A multi-method investigation of the quality and safety of mobile medical apps for the self-care of asthma and diabetes

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Submitted for the degree of Doctor of Philosophy

Declaration of originality

I, Christopher Giles Robert Huckvale, confirm that the work in this thesis is my own.

Both systematic reviews and app assessments reported in this thesis adopted the standard practice of additional, independent reviewers being involved in study/app selection and data extraction in order to maximise search sensitivity and minimize assessment-related biases. For the systematic reviews of asthma and diabetes, work was shared between researchers to make the review process tractable. I confirm that the contributions of these individuals have been fully described. Where information or guidance has been derived from other sources, I confirm that these have been referenced in the thesis.

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Abstract

Background

Mobile medical apps – interactive software tools for consumer mobile devices such as smartphones – offer a novel context to support self-care by individuals with prevalent long-term conditions, such as diabetes and asthma. However, little is known about the quality and safety of available mobile medical apps, their potential to support desired health outcomes, or their acceptability to patients. The contribution of this thesis is to provide a detailed characterisation of issues of quality and safety affecting mobile medical apps for self-care that combines research, clinical and patient perspectives and to use these data to critique recent proposals from the UK National Health Services to offer self-care apps 'on prescription'.

Methods

A multiple methods design to assess the state of research on mobile medical apps for self-care, appraise the quality of publicly-available apps and understand how and why individuals use mobile medical apps for self-care, using asthma and diabetes as representative long-term conditions.

Results

A limited research literature of moderate quality suggests modest benefits of app-supported interventions (defined as those that incorporate mobile medical apps as a major delivery mechanism) for the biochemical control of diabetes and equivalence to existing methods for asthma self-care. Evidence for cost-effectiveness is lacking. Mobile medical apps available through public stores rarely conform to guideline standards for information content or functionality and some, such as insulin dose calculators, pose a safety risk to patients. A range of motivational factors influence patient use of mobile medical apps for self-care, including concrete needs for data arising from changes in health status and the emotional consequences of greater awareness of disease state.

Discussion

Ubiquitous gaps in the quality of apps for self-care represent a potential challenge to healthcare professionals and policy-makers wishing to incorporate them into practice. A stratified response, which extends the principle of proportionality established in medical device regulation, is presented as a potential strategy to address these gaps while recognising resource and capacity constraints. Without such triangulation, the vision of 'mobile medical apps on prescription' is probably unrealistic.

Table of contents

Declaration of originality 2

Copyright 2

Disclaimer 2

Acknowledgements 3

Abstract 4

Table of contents 5

List of appendices 12

Lists of figures, boxes and tables 13

Figures 13

Boxes 13

Tables 13

1 Chapter one: Introduction 15

1.1 Chapter introduction 15

1.2 Self-care, mobile medical apps and quality: opportunity, need and caution 15

1.3 Thesis focus, aims and objectives 17

1.4 Overview of thesis structure 19

2 Chapter two: Context 22

2.1 Chapter introduction 22

2.2 Mobile medical apps 22

2.2.1 Definitions 22

2.2.2 The case for mobile medical apps for patient use 24

2.2.3 Potential disadvantages of mobile medical apps for patient use 29

2.3 Self-care for long-term conditions 30

2.3.1 Definitions 30

2.3.2 Rationale for prioritising self-care 31
2.3.3 Strategies for self-care support 33
2.3.4 How apps could play a role in self-care 34
2.4 Asthma 35
2.4.1 Condition overview 35
2.4.2 Components of asthma self-care 37
2.4.3 How mobile medical apps might play a role in asthma self-care 38
2.5 Diabetes 41
2.5.1 Condition overview 41
2.5.2 Components of diabetes self-care 42
2.5.3 How mobile medical apps might play a role in diabetes self-care 44
2.6 Quality and safety 45
2.6.1 Definitions and origins 45
2.6.2 Safety in healthcare 49
2.7 Quality and safety of mobile medical apps 50
2.7.1 Definitions 50
2.7.2 Policy context 50
2.7.3 Current state of knowledge 50
2.8 Chapter summary 51
3 Chapter three: Justification of aims and methodological approach 52
3.1 Chapter introduction 52
3.2 Rationale for thesis 52
3.2.1 Rationale for focus on self-care using mobile medical apps (synthesis of context) 52
3.2.2 Rationale for dual focus on asthma and diabetes 53
3.2.3 Rationale for breadth of study 54
3.3 Thesis aims and objectives 54

3.3.1 Aim 54
3.3.2 Objectives 54
3.4 Rationale for methodological approach 55
3.4.1 Multiple methods (multimethod) research 55
3.4.2 Selected methods 56
3.4.3 Integration of methods 59
3.5 Chapter summary 60
4 Chapter four: Mobile medical app-supported interventions for asthma and diabetes. A systematic literature review 61
4.1 Chapter overview 61
4.2 Existing literature reviews 61
4.3 Review-specific objectives 63
4.4 Methods 64
4.4.1 Study searches 64
4.4.2 Study selection 65
4.4.3 Data extraction 68
4.4.4 Study quality appraisal 71
4.4.5 Synthesis and reporting 72
4.4.6 Contributions of other researchers 73
4.5 Results 74
4.5.1 Search results 74
4.5.2 Characteristics of included studies 74
4.5.3 Quality assessment 83
4.5.4 Outcomes 85
4.5.5 Ongoing studies 101
4.6 Discussion 101
4.6.1 Summary of results 101

4.6.2 Integration with other findings 102
4.6.3 Review limitations 103
4.6.4 Issues identified for thesis discussion 104
4.7 Chapter summary 105
5 Chapter five: Quality of mobile medical apps for asthma. Results from serial systematic content assessments 106
5.1 Chapter introduction 106
5.2 Study-specific objectives 108
5.3 Methods 108
5.3.1 App selection 108
5.3.2 Assessment criteria development 110
5.3.3 Assessment of asthma information 111
5.3.4 Assessment of self-management tools 118
5.3.5 Other assessment domains 119
5.3.6 Data extraction 121
5.3.7 Statistical analysis 121
5.3.8 Contributions of other researchers 122
5.3.9 Governance 123
5.4 Results 124
5.4.1 Search results 124
5.4.2 Basic characteristics of apps 125
5.4.3 Rating and download data 127
5.4.4 Information apps 129
5.4.5 Self-management tools 134
5.4.6 Therapeutic instructions and tools 135
5.4.7 Content-independent assessment 137
5.4.8 Software issues 139

5.4.9 Research links 139
5.5 Discussion 139
5.5.1 Summary of results 139
5.5.2 Integration with existing research 140
5.5.3 Study limitations 147
5.5.4 Synthesis of issues for thesis discussion 149
5.6 Chapter summary 149
6 Chapter six: Safety of dose calculator apps for diabetes. A systematic content assessment 151
6.1 Chapter introduction 151
6.2 Study-specific objectives 154
6.3 Methods 155
6.3.1 App selection 155
6.3.2 Assessment criteria development 156
6.3.3 Assessment and data extraction 158
6.3.4 Statistical analysis 160
6.3.5 Contribution of other researchers 160
6.3.6 Governance 160
6.4 Results 161
6.4.1 Search results 161
6.4.2 Characteristics of dose calculators 161
6.4.3 Development context 163
6.4.4 Control of accidental error 164
6.4.5 Systematic calculation errors 166
6.4.6 Other software errors 166
6.4.7 Statistical comparisons 166
6.4.8 October 2014 update 167

6.5 Discussion 167
6.5.1 Summary of results 167
6.5.2 Study limitations 169
6.5.3 Synthesis of issues for thesis discussion 170
6.6 Chapter summary 171
7 Chapter seven: How and why do patients use mobile medical apps for self-care? A qualitative interview study 172
7.1 Chapter introduction 172
7.2 Study-specific objectives 173
7.3 Methods 174
7.3.1 Method selection 174
7.3.2 Participants 175
7.3.3 Interview procedures 177
7.3.4 Data analysis methods 180
7.3.5 Ethical issues 181
7.3.6 Contribution of other researchers 182
7.4 Results 182
7.4.1 Characteristics of participants 183
7.4.2 Ways in which mobile medical apps were used 183
7.4.3 Why use an app? – Factors shaping the use of mobile medical apps 194
7.5 Discussion 204
7.5.1 Summary of results 204
7.5.2 Discussion and integration with existing research 205
7.5.3 Limitations of study methods 209
7.5.4 Reflexive issues 211
7.5.5 Issues identified for thesis discussion 213
7.6 Chapter summary 215

8 Chapter eight: Synthesis 216
8.1 Chapter introduction 216
8.2 Summary of results 217
8.3 Implications for healthcare professionals and delivery organisations 219
8.3.1 Do apps have a place? 219
8.3.2 Making mobile medical apps on prescription work 221
8.3.3 Recommendations 224
8.4 Implications for NHS systems and policy-makers 227
8.4.1 Recommendations 231
8.5 Implications for research 232
8.5.1 App-supported intervention research 232
8.5.2 Mobile medical app quality research 234
8.6 Strengths and limitations of work 236
9 Chapter nine: Conclusions 239
Appendices 242
References 307

List of appendices

Appendix 1 Bibliometric analysis methods 242

Appendix 2 Systematic review search strategy 243

Appendix 3 Systematic review screening flowchart 250

Appendix 4 Systematic review data extraction template 251

Appendix 5 Characteristics of excluded studies 253

Appendix 6 Criteria for assessing inhaler technique education 256

Appendix 7 Asthma apps assessment data extraction template 259

Appendix 8 Characteristics of excluded asthma apps 267

Appendix 9 Coverage of educational topic coverage by platform and payment model 272

Appendix 10 Consistency of information apps with evidence by platform and payment model 274

Appendix 11 Summary of ethical disclosures and software issues by platform and payment model. . 276

Appendix 12 Insulin dose calculator test case generation procedures 278

Appendix 13 Characteristics of excluded diabetes apps 281

Appendix 14 Insulin dose calculator app characteristics detail 286

Appendix 15 Insulin dose calculator app formula details 288

Appendix 16 Interview study participant recruitment adverts 292

Appendix 17 Interview study participant information sheet 295

Appendix 18 Interview study consent form 298

Appendix 19 Interview study survey question schedule 299

Appendix 20 Interview study ethics approvals 303

Appendix 21 Interview study indemnity 306

Lists of figures, boxes and tables

Figures

Figure 1-1 Overview of thesis....18
Figure 2-1 Bibliometric analysis using terms relating to mobile medical apps, 2000-2014....24
Figure 4-1 Study selection flowchart....75
Figure 4-2 Summary of risk of bias assessment of included studies....83
Figure 5-1 Flowchart of 2013 app selection process....123
Figure 5-2 Change over time in numbers of asthma apps available through public app stores....125
Figure 6-1 Flowchart of app selection process....161
Figure 7-1 Examples of data summary views in mobile medical apps for asthma and diabetes....187
Figure 7-2 Examples of automated data annotation functions in apps for asthma 191

Boxes

Box 6-1 Details captured during app assessment 158
Box 7-1 Interview topic guide 178

Tables

Table 2-1 Mobile device features and potential functions relevant for self-care....26
Table 4-1 Summary of study eligibility criteria....65
Table 4-2 Overview of information extracted from included studies....70
Table 4-3 Design and recruitment characteristics of included studies 78
Table 4-4 Participant characteristics of included studies....79
Table 4-5 Intervention characteristics of included studies 80
Table 4-6 Risk of bias characteristics of included studies 85
Table 4-7 Observed effects of app-supported interventions on HbA1c in patients with diabetes....87
Table 4-8 Observed effects of app-supported interventions on lung function, fasting glucose, weight, systolic blood pressure, cholesterol....88
Table 4-9 Observed effects of app-supported interventions on healthcare utilisation....91

Table 4-10 Observed effects of app-supported interventions on self-rated symptoms.....95
Table 4-11 Observed effects of app-supported interventions on patient-centred outcomes.....96
Table 5-1 Asthma app selection criteria.....109
Table 5-2 Operational criteria for assessing the comprehensiveness of asthma self-management educational materials.....112
Table 5-3 Management strategies used to assess consistency of asthma information with evidence-base 115
Table 5-4 Ethical disclosure principles for smartphone apps.....119
Table 5-5 Categories of software issue considered during assessment.....120
Table 5-6 Basic characteristics of included apps.....126
Table 5-7 Breakdown of app functions 128
Table 5-8 Comprehensiveness of overage of asthma self-management education topics by information apps.....131
Table 5-9 Consistency of information apps with evidence-based recommendations.....132
Table 5-10 Summary of ethical disclosures and software issues 138
Table 6-1 Diabetes app selection criteria.....156
Table 6-2 Schema and operational criteria used for app issue identification.....157
Table 6-3 Characteristics of included dose calculator apps 163
Table 6-4 Frequency of identified issues, grouped by platform and cost.....165
Table 7-1 Participant selection criteria 175
Table 7-2 Initial analytic framework created during analysis 181
Table 8-1 Summary of study findings.....217

Chapter one: Introduction

1.1 Chapter introduction

Mobile medical apps are software programs that add health-related functions to personal portable devices, such as smartphones. While the range of identified potential uses is extremely broad – spanning diagnosis; condition monitoring and treatment; communication between professionals, patients and carers; public health surveillance and outreach; healthcare administration; and professional education [1-3] – the focus of this discussion, for reasons that will be introduced in this introductory chapter and developed in chapter two, will be on mobile medical apps intended to support self-care. My thesis will argue that it is both timely and necessary to evaluate mobile medical apps for self-care through a lens of quality and safety that reflects established norms around the governance of health technologies intended for patient and public use.

It will present evidence from a series of empirical investigations into the quality and safety of extant apps for the self-care of asthma and diabetes, two prevalent long-term conditions with a substantial burden of morbidity unaddressed by current strategies for self-care. It will draw this evidence together to present a unified critique of quality and safety issues in relation to current mobile medical apps for the self-care of these conditions, and offer recommendations for clinicians, policy-makers and researchers.

This chapter introduces the major themes of mobile medical apps, quality, safety and long-term condition self-care that underpin the thesis and which will be developed in subsequent chapters. It summarizes the thesis aims and objectives and concludes with an overview of the thesis structure.

1.2 Self-care, mobile medical apps and quality: opportunity, need and caution

> *"When we talk about mobile health, we are talking about taking the biggest technology breakthrough of our time and using it to take on one of the greatest national challenges of our time. And while we have a way to go, we can already imagine a remarkable future in which control over your health is always within hand's reach."*
>
> Kathleen Sebelius
> Secretary of US Department of Health and Human Services, 2011[4]

> *"[M]ost countries' health care systems have been slow to recognise and capitalise on the opportunities presented by the information revolution. For example, in Britain 86% of adults use the internet but only 2% report using it to contact their GP. […] In the future we intend to take a different approach. [This will include] an expanding set of NHS accredited health apps that patients will be able to use to organise and manage their own health and care."*
>
> NHS England
> The NHS Five Year Forward View, 2014[5]

> *"The desire to realise the potential of technology to improve the quality and safety of healthcare often leads to the introduction of new IT solutions, on a large or even national scale, with typically only a limited evidence-base in support of the systems' overall effectiveness and safety. […] It is salutary to note that, even when safe, some 50 to 70 per cent of eHealth projects fail."*
>
> Josip Car et al.
> The impact of eHealth on the quality and safety of healthcare,
> Report for the NHS Connecting for Health Evaluation Programme, 2008[6]

Captured in the quotes of Sebelius, a US Secretary of State, and the recently-published Five Year Forward View of the English National Health Service (NHS), above, is the sense of political purpose that underpins current interest in mobile medical apps. The sense of substantial 'national challenge' is neither unique to the United States and the United Kingdom, nor exclusive to developed settings[7, 8]. It reflects growing concern about the sustainability of existing models of healthcare provision in the face of ageing populations, global increases in non-communicable long-term condition prevalence and comorbidity, and costs associated with the growing technical complexity of medical intervention. In the United Kingdom, sustained interest in self-care reflects a calculated triangulation between the scope for reductions in healthcare utilisation and consequent expenditure when individuals take steps to become 'fully-engaged' in their own health, and an ethical imperative to respect the autonomy of individuals and place patients at the centre of decision-making about their health[7, 9]. Long-term conditions justify particular focus both because of the substantial potential life-limiting consequences for individuals whose disease is poorly managed and the concomitant high cost to health systems. In the English NHS, chronic diseases are estimated to account for 70% of budgeted expenditure[5].

According to proponents, mobile medical apps fit into this picture as a delivery mechanism for information and tools that will support the shift towards self-care that has yet to occur at scale[10-12]. A pragmatic case for mobile medical apps (developed in section 2.2.2 below) identifies benefits compared to other intervention strategies in the functional flexibility offered by software to support

a wide range of health-related functions, the rapid population-scale uptake of app-capable smartphones that creates a ubiquitous, if fragmented, platform for intervention, and apparent interest from patients and the public who already look to the internet for health advice and use personal health tracking apps in increasing numbers.

Balancing the sense of opportunity afforded by mobile medical apps is a cautionary perspective, illustrated by the third of the quotes provided above [6, 13], that identifies the potential risks associated with novel technologies when effectiveness is assumed and the scope for harm goes unexplored[14, 15]. Early studies indicating the potential clinical benefit of self-management using apps[16] have been tempered by critical failings in apps performing high-risk functions, such as self-diagnosis of skin cancer[17], and withdrawals of apps, both enforced[18] and voluntary[19], on safety grounds. However, there are also is gap in terms of the availability of work that draws these findings together in a coherent way, recognizing that multiple factors shape the suitability of mobile medical apps for clinical use, characterizes the potential impact of biases in the available data, identifies gaps in knowledge that could inform future inquiry, and guides policy-makers and clinicians. It is towards this gap that my thesis is directed.

A critical exploration of quality and safety holds potential relevance for policy-makers who envisage mobile medical apps being offered 'on prescription' as packaged self-management interventions[20], healthcare professionals who will be responsible for supporting care process involving apps, and patients and the public who will be encouraged – and perhaps expected – to use them[21]. It provides an opportunity to evaluate the approaches being adopted by regulators such as the US Food and Drug Administration[22] who are responsible for eliminating unsafe apps, and accreditation programs, such as that developing within the UK NHS[23], that seek to identify those that are safe and effective.

1.3 Thesis focus, aims and objectives

This section should be read in conjunction with Figure 1-1, below. Numbered items in the text below refer to the numbering in the figure.

My thesis aims to critically evaluate the suitability for routine clinical use of mobile medical apps long-term conditions, using the examples of asthma and diabetes ①. Although mobile medical apps have a broad range of potential uses, the work will focus specifically on apps for self-care intended for patient use ②, for reasons that will be developed in chapter two (see section 2.3).

The question of suitability will be assessed using a lens of quality and safety (3). Contemporary characterisations understand quality as a multi-dimensional construct in which questions of cost, equity, patient experience and safety act to balance a focus on clinical outcomes that was a main feature in earlier definitions[24]. These dimensions also reflect values held by different stakeholders in health, for example the importance to individuals of care that is perceived to respond personal needs and preferences, which contrasts, for example, with more normative questions of social efficiency (fairness) that might operate at policy-making levels.

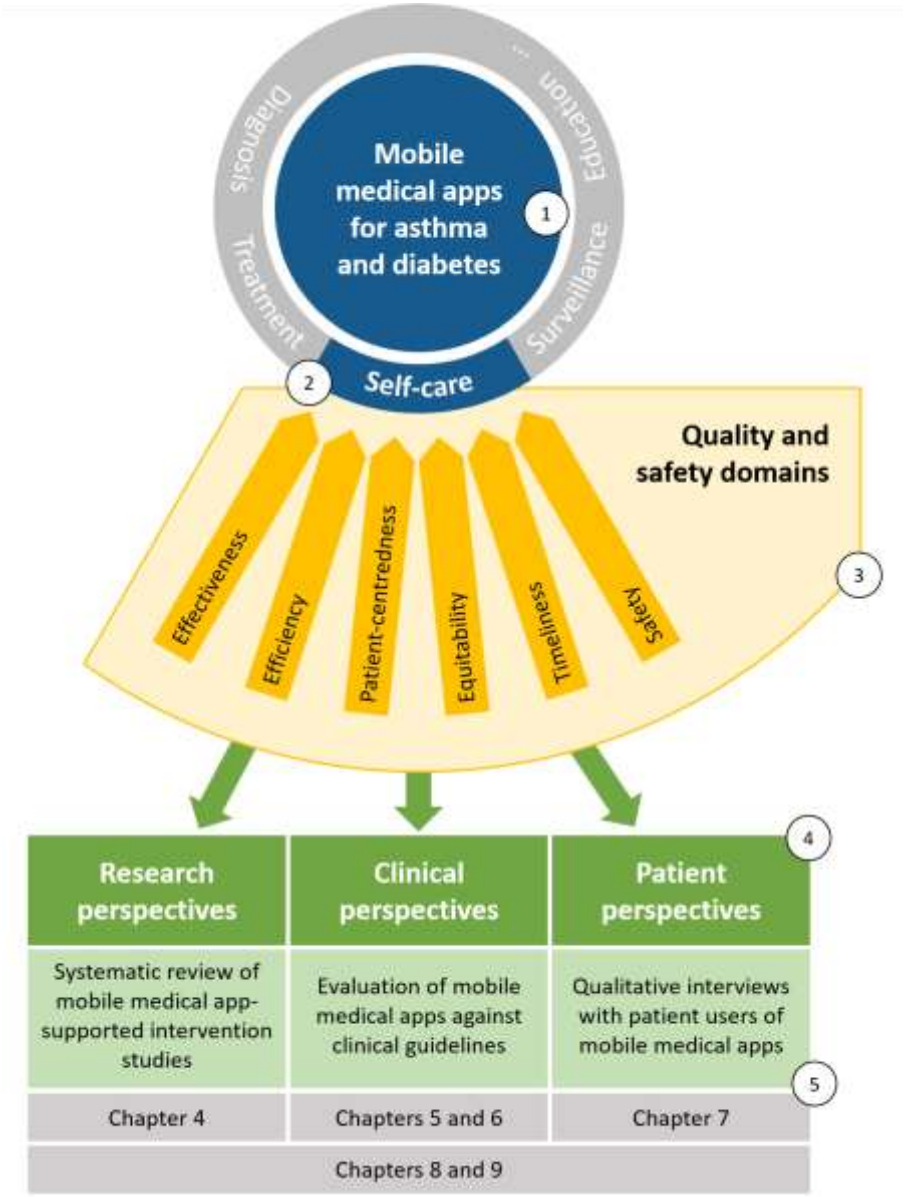


Figure 1-1 **Overview of thesis**

The figure summarises the focus and components of the thesis. See text of section 1.3 for discussion of numbered elements.

To try to respond adequately to this multi-dimensional, multi-value context, the thesis explores quality issues by drawing data from three separate perspectives: academic research; clinical standards and norms and those of patients who are the ultimate users of mobile medical apps ④.

This involves a multiple methods approach ⑤, combining distinct studies that form the basis of subsequent chapters. Together with a final unifying synthesis, exploring these different sources of data (and the perspectives they embody) defines the objectives of the work:

1. To characterise the extent and findings of the experimental evidence base concerning the quality and safety of app-supported interventions for asthma and diabetes.
2. To explore the quality and safety characteristics of mobile medical apps for asthma and diabetes available for use by patients, using established clinical standards and guidelines.
3. To explore the factors that influence how and why individuals choose apps to manage their diabetes and asthma, providing a patient-oriented perspective on issues of quality and safety.
4. To integrate these three perspectives (from research, clinical expectations and patients) to provide an account of quality and safety factors influencing the suitability of apps for long-term conditions and to explore the impact of these findings for patients, clinicians and policy-makers.

The rationale for these aims and objectives, including justification for the use of multiple perspectives and multiple methods, is revisited in detail in section 3.2 below.

1.4 Overview of thesis structure

The thesis is divided into nine chapters. To assist navigation, each chapter opens with a brief introduction which aims to orient discussion within the overall work and concludes with a summary of the content, including – if relevant – any major findings or conclusions from preceding individual studies.

Chapters two and three provide the background and justification for the work. **Chapter two** develops the major themes introduced above. It provides a context within which to understand current interest in mobile medical apps, explores the political and health-related factors motivating a focus on self-care and long-term conditions, and introduces quality as a suitable framework for exploring new health technologies, such as apps. **Chapter three** forms the bridge between this context and the aims and objectives described above. It draws on literature discussed in the previous chapter to justify examination of issues of quality and safety for mobile medical apps for self-care,

the use of a broad rather than focussed lens reflecting both the current state of research and the value of a comprehensive understanding of quality issues, and the focus on asthma and diabetes.

Chapters four through seven describe the individual studies that collectively comprise the thesis and present their individual findings. **Chapter four** is a systematic review of experimental research literature exploring the impact of app-supported interventions for diabetes and asthma (Objective 1). Together with chapter two, this section fulfils the role of a traditional thesis literature review in summarizing the state of research literature about apps for asthma and diabetes self-care. Thus, in addition to addressing the separate clinical and patient perspectives described above, the chapters that then follow can also be understood as a response to gaps identified during the literature review process:

- Responding to a narrow intervention focus revealed in the research literature, **chapter five** takes an observational stance, reporting the results of serial censuses of the entire landscape of publicly-available, commercial apps for asthma. Lacking impact data – since most are designed outside formal intervention or evaluation frameworks – these apps are instead evaluated in terms of compatibility with evidence-based guidelines and clinical best-practice. Judgemental approaches to quality appraisal of health technologies are not new[25], but their application to mobile medical apps for self-care is limited, despite the large numbers of apps that are available. They provide a potential way to anticipate the scope for benefit where formal evaluation is unavailable or infeasible and where there is substantial existing evidence to guide judgement (a sense that is formally captured in current definitions of effectiveness, see section 2.6.1.1 below)
- Recognizing the limited empirical evidence currently available about hazards associated with mobile medical apps of any kind, **chapter six** reports the results of a systematic assessment of a targeted inquiry examining insulin dose calculator apps for diabetes self-medication. Illustrative of the higher-risk activities to which apps may be directed, this study is used to expose potential safety issues relevant for clinical care and policy. Together, chapters five and six address Objective 2.
- To provide a patient-centred counterpoint to the clinical and research approaches underpinning previous chapters, **chapter seven** reports the results of a qualitative inquiry examining factors shaping contemporary use of apps by patients with asthma and diabetes, responding to Objective 3.

Chapter eight brings together the findings presented in earlier chapters in a structured synthesis (Objective 4). Returning to the overall study aim, the findings are then discussed in light of the implications for routine use and their potential impact for the public, patients, healthcare professionals and policy-makers. The chapter also discusses limitations of the current work and identifies opportunities for further study.

Finally, **chapter nine** presents the overall conclusions that may be drawn from the work.

Tables and figures are presented in place. A small number of complex data tables are available only online (via published manuscripts). Supplementary material, including study approvals and data tables that provide additional detail not central to the discussion are presented as appendices. All external tables and appendices are referenced in the main text.

Chapter two: Context

2.1 Chapter introduction

This chapter introduces three topics central to the subsequent discussion: mobile medical apps, self-care and healthcare quality.

It provides a perspective about the political, clinical and social factors shaping interest in mobile medical apps, current interest in self-care and the use of quality as a framework to judge the performance of healthcare interventions.

2.2 Mobile medical apps

2.2.1 *Definitions*

Mobile apps and app stores

A contraction of the term application software, 'app' is a generic term for any software program that is designed to help a user accomplish one or more specific tasks. Although not new, the term was popularized in public discourse by marketing for an early mass-market touchscreen smartphone, the Apple iPhone[26]. Smartphones combine a mobile telephone with the capabilities of a general-purpose computer and sophisticated input and sensing capabilities such as touchscreens, voice-recognition and geolocation. As general-purpose computers, smartphones can perform any function that can be expressed in software and, as a result, the range of tasks that can be performed using a device can be extended simply by storing and executing appropriately designed programs.

As part of a business strategy intended to commodify this extensibility, the term 'app' was appropriated as a marketing device to communicate the concept to non-technical consumers. This, in turn, was assisted by the development of digital distribution platforms to automate the installation and configuration of apps, making the process of adding new device functions as simple as making a free or paid selection in an online 'app store'; a searchable marketplace hosting apps produced by a range of commercial and non-commercial developers. The success of app stores in providing an alternative to the historically complicated process of manual software distribution, installation and update has been illustrated both by the volume of app installations and the way that marketplaces have subsequently been introduced into existing computer operating systems.

One consequence of this, and the recent introduction of new computing platforms such as wearable devices, has been a broadening of the common usage of the word 'app' to be closer to the nonspecific definition of application software. Apps and app stores are now available not only for

major desktop operating systems but also computing accessories such printers, gaming consoles, domestic appliances and cars. However, for reasons that will be developed in the next section, this discussion is focussed on 'mobile' apps that run on personal portable devices such as smartphones and tablet computers. In the subsequent text, the term 'mobile mobile app' and 'app' are used synonymously. The impact of app stores as a development closely associated with, but not formally recognized in the definition of an app, highlights the scope for a characterization of the potential benefits and harms associated with apps that is broader than one simply concerned with the function of software. The nature and importance of these related factors will be a recurring theme in my thesis.

Mobile medical apps

Mobile medical apps are any app intended to fulfil a function related to the diagnosis, treatment, self-care or prevention of disease. Design intent, rather than efficacy in achieving this goal, identifies apps as falling into this category.

App-supported interventions

In healthcare, an intervention is a set of clinically-recognized actions intended to contribute to a specified objective with one or more anticipated benefits for health. Examples of interventions include drug therapy, surgery, health promotion, screening and talking therapies.

Health technologies, such as websites and mobile medical apps, have been characterised as 'delivery mechanisms' for the content of interventions[27]. For self-care, this arises because of the multiple ways in which information and skills may be communicated and supported. For example, asthma skills adhering to an evidence-based curriculum intended to promote certain self-care outcomes (intervention content) may reasonably be taught by face-to-face methods (delivery method), self-directed online learning (delivery method) or by suitably-designed interactive apps (delivery method). The term 'app-supported' interventions will be used to describe both situations where a mobile medical app is the main method through which a patient experiences an intervention and those where apps play only a small role. In practice, most interventions incorporating an app will also be 'complex' interventions, in which there are multiple components with potential impacts on desired outcomes, because of the requirement to educate individuals about how to use the app and integrate app use into care processes.

It may not always be appropriate, however, to describe mobile medical apps as interventions. For example, apps available in public marketplaces may be developed without explicit clinical framing of desired outcomes. Similarly, individuals may initiate the use of mobile medical apps with only

limited articulation of the goals they are seeking. (The extent to which this may or may not be the case is explored in the qualitative interview study of patient app users in Chapter 7)

In the subsequent text both app-supported interventions and mobile medical apps that do not clearly meet this definition are considered. This reflects the expectation that, although most uses where apps are recommended by a clinician to a patient will probably fall within some kind of intervention structure, individuals are also free to select mobile medical apps to meet their own perceived self-care needs. Questions of quality and safety are no less relevant to these latter uses.

2.2.2 *The case for mobile medical apps for patient use*

Bibliometric analysis highlights that interest in mobile health in general, and mobile medical apps in particular, is a recent and evolving phenomenon in the medical literature (Figure 2-1). References to mHealth as a conceptual grouping for emerging networked health technologies first appeared in 2004[28] [29], and the first references to smartphones appeared in 2005[30]. However, bar a single reference in 2006[31] and despite the launch of commercial app stores in 2008[26], it wasn't until 2010 that studies started to refer to apps in the sense of mobile software with potential health uses.

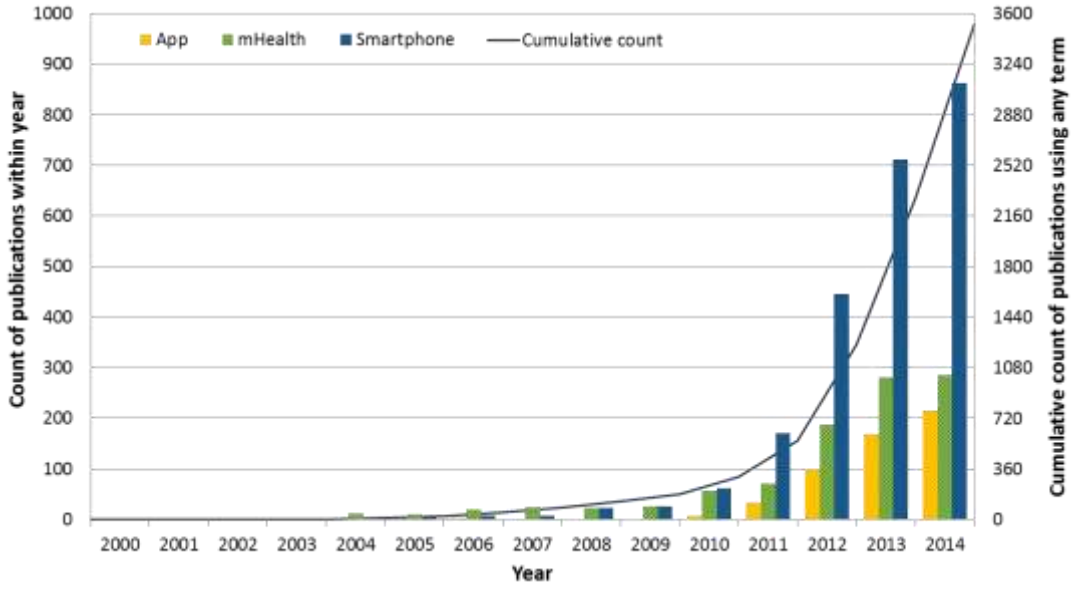


Figure 2-1 **Bibliometric analysis using terms relating to mobile medical apps, 2000-2014**

The figure plots the count by year of publications indexed in MEDLINE, EMBASE and PsycINFO containing the terms 'app', 'mHealth' and 'smartphone' in the title or abstract (bars, left axis), and the overall cumulative count of app-related publications (line, right axis). Methods are detailed in Appendix 1.

Since then, the numbers of studies have grown steadily, with over 200 published references to mobile medical apps in 2014. The analysis highlights the way that increases in references to mHealth have paralleled the rapid growth in studies reporting apps and smartphones, having previously been published in low numbers. At the end of 2014, biomedical databases indexed at least 3500 papers on smart mobile technologies, of which just over 520 included references to mobile apps in a title or abstract.

It is worth considering what might be driving current interest in mobile medical apps, particularly when the number of empirical studies providing direct evidence of impact is low. In the bibliometric analysis described above, fewer than 50 citations were randomized studies (1.3%, n=48/3671). Synthesis of perspectives offered by clinical, technology and policy commentators suggests that a range of factors are relevant. Collectively, these propositions offer an *a priori* justification for both the empirical investigations of mobile medical apps that are now emerging in research literature and the work underpinning this thesis:

1. *Functional flexibility enabling breadth of clinical applications*

   App flexibility arises from a combination of the generic expressive capacity of software running on a network-connected, general-purpose computer and mobile hardware that either already contains, or can be supplemented with, technologies for sensing and interacting with users. Table 2-1 illustrates potential uses, relevant to self-care, that are connected to specific features of current mobile devices. Functional breadth is highlighted by taxonomy-building studies[32-37] that have mapped potential uses for mobile medical apps across a range of disciplines, including self-care for long-term conditions. Technology advances mean that mobile software can provide experiences equivalent to those historically available on desktop or through the web, established technologies that are routinely used to provide and manage health information. Observational studies[33, 38] (including those described in chapter five) suggest that textual and, to a lesser extent, multimedia information content is a common feature in commercially-available mobile medical apps, highlighting a potential role for apps that complements existing channels for providing health information to patients and the public. However, there are also large numbers of apps offering interactive features such as diaries and medication management tools[35, 39-41], as well as examples of apps incorporating diagnostic and therapeutic functions[17, 33, 42], such as those intended to assist health behaviour change[3, 43, 44], using techniques such as remote interaction with healthcare professionals, peer-to-peer support and automated feedback.

Table 2-1 **Mobile device features and potential functions relevant for self-care**

Feature	Potential functions
Image processing	Analysis of images taken by a device camera for analysis of calorie intake in diet-controlled conditions; tracking wound healing e.g. diabetic ulcers.
Decision support	Use of diary and contextual information to help patients make decisions about self-management, reflect on disease state and set personal goals.
Telephony	Enables telephone consultation to augment other services; e.g. as part of an integrated annual review for a long-term condition.
Notifications	Automated reminders for drug compliance, appointments and reviews; allows patients to track and reinforce personal goals for their condition.
Data services	Shares long-term condition monitoring data with regular practitioners; acts as a store for summary information about a long-term condition to be shared with clinicians in emergencies, e.g. emergency pain relief schedule for Sickle Cell Disease.
Video	Enhances telephony with video to enable non-verbal communication during clinical reviews; can display demonstrations of self-management skills; e.g. inhaler technique.
Text-to-speech services	Allows people with limited eyesight and those with reading difficulties to access support for their condition.
Connected sensors	Monitoring data from glucose, blood pressure and other sensors can be collected automatically using wireless technology. Built-in sensors like accelerometer can be used to track activity when exercise goals have been set as well as specific events, such as falls in the elderly.
Touchscreen	Enables intuitive ways to capture information about the condition, for example diary data about a long-term condition.
Location services	Enables contextual reminders about possible risks (e.g. triggers for condition) and present information about local opportunities to support condition.
Internet access	Connects a user to social networks and peers to access support about their condition.

2. *Usage culture enabling targeted interaction*

Empirical data describing the way that devices are used by individuals has been used to argue that mobile devices create specific opportunities for health intervention[45, 46], providing a counterpoint to the generic flexibility described above. Survey data suggest that over two thirds of adults carry a personal mobile device with them at all times, leaving it switched on throughout waking and sleeping hours[47]. In addition to the communication uses traditionally characteristic of mobile phones, smartphones increasingly act as integration hubs for personal information, agenda management, social networking and entertainment, such as eBooks, videos, and games.

From the point of view of self-care, this creates potential opportunities for targeted, timely interaction, such as medication reminders[32], as well as unobtrusive data collection either by individuals, for example logging a blood glucose immediately after a measurement, or automatically using device sensors. Arguments from health psychology suggest that contextual interactions may be more effective in assisting behaviour change initiation and maintenance[45], for example by providing contextually appropriate choices tailored to an individual[48]. In addition, because smartphones are almost always personal[47], in contrast to desktop computers which are often shared, it has been proposed that they may offer a more acceptable platform for interacting with sensitive data. The biometric and integrated authentication methods increasingly supported by smartphones may simplify the process of secure data access compared to alternative technologies; tackling a potential barrier to health information exchange while also satisfying the requirement to protect information adequately.

3. *Scale of potential app audience*

By 2020, forecasts derived from sales data suggest that most adults in developed settings will own a personal smartphone capable of installing and running apps[49]. Ownership of mobile devices varies substantially according to setting, with the highest rates seen in developed Asian countries such as Korea[50]. In the United Kingdom in 2014, over two thirds of adults owned a smartphone[51], similar to the United States[52] and Australia[53]. Scope for population-scale delivery of healthcare interventions is balanced by platform fragmentation, with multiple devices and operating systems for which customized solutions and support may be necessary. While mobile device ownership does not escape concerns about inequality[54], for example, the ability to service costs associated with mobile contracts and data charges, there is limited evidence that it is *more* inequitable than alternative technologies. In addition, a small number of survey-based studies have indicated that smartphones may be preferentially adopted by user groups for whom previous computing technologies, such as laptops, have historically proven too costly, such as those from disadvantaged socioeconomic backgrounds[55-57].

4. *Scale of actual app adoption*

Widespread smartphone adoption is complemented by evidence of substantial interest in apps from consumers. In the United Kingdom in 2014, approximately half of adults in consumer surveys reported knowing about and using apps of any kind[51]. Data from 2012 found that a fifth of US adults had downloaded a health or fitness app, increasing amongst

people with recent changes in health status[58]. The pool of consumer mobile medical apps has been estimated to exceed 15,000[59] and commercial forecasts suggest that there may be over a billion users by 2018[60]. Evidence for clinical translation is suggested by a recent survey of US clinicians across healthcare settings in which over a third reported having recommended an app to a patient in the preceding year[61]. Patients appear to be receptive: in 2013 90% of US adults stated that they would consider using an app issued 'on prescription' by a healthcare professional[62].

5. *Putative impact on costs of healthcare delivery*

Prevalent in contemporary policy discourse are concerns about the sustainability of projected increases in expenditure which are, in turn, cited as justification for investigating alternative mechanisms for healthcare delivery[9, 63-65]. Most arguments hinge on anticipated reductions in healthcare expenditure resulting from greater emphasis on self-care, discussed further in the following section, for which apps are identified as a candidate support mechanism[66]. Specific potential advantages of apps compared to alternative ways of supporting self-care are found in:

- Automation that enables tailored support (maximizing effectiveness) at costs lower than those required by conventional programs involving expert professional input.
- The re-use of consumer-grade personal devices, potentially avoiding capital costs associated with bespoke hardware development and, for providers, the purchase and maintenance of devices, compared to traditional telehealth-type interventions.
- The established infrastructure provided by app stores and mobile operating systems, mitigating opportunity costs associated with deploying interventions.

6. *Potential benefits of trans-disciplinary innovation*

It is possible that the rapid development models that inform current approaches to commercial software development and the commoditisation of apps operating in a consumer rather than traditional health environment will provide a means to escape factors, such as vested interests and power structures, that might typically act to limit the adoption and spread of new health technologies[67]. While there are a range of issues that may legitimately challenge this perspective, such as the need to ensure that care is safe, the slow speed of technology adoption is nevertheless a recognised problem in healthcare.

2.2.3 *Potential disadvantages of mobile medical apps for patient use*

A number of authors have identified potential disadvantages associated with a switch to mobile apps as a delivery mechanism for supporting healthcare[68-70].

A reliance on information technology introduces complexity that may not be present in alternative methods, such as written materials for supporting self-management education and monitoring. Potential cost savings associated with eliminating physical resources may be offset by costs of providing support and the requirement for technical – in addition to clinical – expertise to modify mobile medical apps to meet needs that may vary by patient population, location and over time[71]. Experience from past information technologies highlights the importance of ensuring that there is adequate support for professionals expected to adopt and integrate the use of technologies appropriate and safely into routine practice[6].

While the growth in networked technologies may confer benefits in terms of the ability to exchange health information and support patients with remote monitoring, it highlights the way that apps may introduce new risks that must be managed appropriately[12, 72]. Monitoring systems must be robust if actionable signs of deterioration are not to be missed. The exchange of electronic data may jeopardise patient confidentiality if appropriate security and privacy controls are not in place[70]. Experience with managing patient interaction with health data at large scales is currently limited. Beyond scenarios where there is scope for direct clinical oversight, automated functions of apps may pose particular risks to patients who lack clinical knowledge to filter inappropriate diagnosis or treatment advice[73, 74]. While apps may be actively harmful, for example by making an incorrect mediation dose recommendation, they are also susceptible to failures that may limit their health impact, for example by perpetuating advice that is known to be ineffective or encouraging individuals to engage in behaviours with no clear health benefit[18]. While apps designed in a clinical setting may be largely free from these kinds of failures, commercial apps which may compete with traditional methods for supporting patients may lack this kind of input. Finally, apps may introduce unexpected risks through the changes they introduce into healthcare systems, for example by displacing established methods for monitoring health status for which controls have been refined over time.

Apps may perpetuate inequalities if availability varies across different classes of smartphones which assort by demographic or socioeconomic background[56, 57], or if they fail to incorporate design features that reflect variations in individual function such as literacy, numeracy, vision and manual dexterity[75, 76]. However, the impact may also be offset by greater standardization and availability of features such as large-format interfaces, text-to-speech and audio-described interfaces.

The rapid evolution of mobile technologies may itself present a challenge compared to other technologies and methods for healthcare support[77, 78]. Device upgrades and obsolescence creates a recurring resource requirement to test and validate apps to ensure that they continue to remain available and safe. Regular device upgrades also necessitate mechanisms to assist users in transitioning from one device to another. Related to this, it is currently unclear if patients are willing to sustain use of apps over the periods of time that would justify long-term monitoring strategies[79], of if shorter-duration, targeted interventions would be more feasible[80],. The advent of a future technology may mean that current consumer interest in smartphones changes unexpectedly, disrupting clinical systems that are structured around app use.

2.3 Self-care for long-term conditions

2.3.1 *Definitions*

While the concept has existed in academic discourse for at least three decades[81], contemporary definitions of 'self-care' concern the abilities of, and actions taken by, individuals to maintain health, prevent and manage illness in themselves or those they care for[82, 83]. There is no single, widely-accepted definition[84, 85], and the concept has evolved from a focus on steps taken to prevent illness[86, 87] to one concerned additionally with the role of health in everyday life, the response to disease, and responsibilities towards dependents, such as children [83, 88, 89]. In 2009, the WHO provided an update to definitions of self-care that were first advanced in 1983[87], stating that:

> *"Self-care is the ability of individuals, families and communities to promote health, prevent disease, and maintain health and to cope with illness and disability with or without the support of a health-care provider." [83]*

In the UK, a comprehensive definition was articulated by the Department of Health in 2005:

> *"Self-care is a part of daily living. It is the care taken by individuals towards their own health and well-being, and includes the care extended to their children, family, friends and others in neighbourhoods and local communities. Self-care includes the actions individuals and carers take for themselves, their children, their families and others to stay fit and maintain good physical and mental health; meet social and psychological needs; prevent illness or accidents; care for minor ailments and long-term conditions; and maintain health and wellbeing after acute illness or discharge from hospital." [88]*

When originally focussed on prevention, self-care was proposed to be distinct[86] from 'self-management', which describes the abilities of people with long-term conditions to manage aspects their illness including symptoms, treatment and psychosocial and lifestyle impacts[90]. However,

this differentiated usage was inconsistent[89, 91, 92], with some key authors, such as Wanless[9], describing self-*care* in similar terms. Building on recent definitions, this discussion assumes that self-care effectively encompasses the narrower focus of self-management[85, 92].

While recognizing that, in the context of a discussion focussing on long-term conditions, many apps may correctly be described as focused on self-management, the term self-care is preferred here for two reasons. Firstly, in addition to care for diagnosed long-term illness, it recognizes activities that seek to prevent both complications and primary disease, such as lifestyle modification in type 2 diabetes[93, 94], both of which could reasonably be supported by apps. Secondly, it explicitly allows the possible involvement of third parties, such as professionals, parents or carers, who might use remote monitoring or communication capabilities in apps to support the care of a patient or dependent.

The term 'self-care support' has been used to describe strategies to assist individuals in acquiring and performing self-care skills including, but not restricted to[89], self-management education[95]. Some authors have suggested that self-care support additionally describes a 'fundamental' conceptual shift towards greater partnership between clinicians and patients[96] and should incorporate systems and organisation-level changes intended to facilitate this[9]. However, this strategy risks conflating self-care with patient-centredness; a set of principles guiding communication between patients and professionals[97, 98]. Furthermore, apps (and a range of other strategies, such as self-help books and websites) test this expanded definition, since patients may select these without recourse to a professional, and their adoption may have limited impact on health service configuration. As a result, I have chosen to avoid definitional assumptions about the role of professional involvement in favour of explicit descriptions of the contexts in which apps are, or could be, used. Where relevant, the possible impact on patient-clinician interaction is evaluated in terms of the potential objectives or outcomes, or both, of suitably-designed interventions involving apps.

2.3.2 *Rationale for prioritising self-care*

Self-care, with a specific focus on long-term conditions, has been a key feature of healthcare policy in the UK for at least a decade[66, 82, 88, 91, 99-101], demonstrated most recently by the NHS Constitution, published in 2013:

> *"The NHS aspires to put patients at the heart of everything it does. It should support individuals to promote and manage their own health. NHS services must reflect, and should be coordinated around and tailored to, the needs and preferences of patients, their families and their carers. [99]"*

Self-care also features in health policy in a range of other settings, including other European countries, such as Denmark[102], Canada[103], the United States[104] and Australia[105].

In England, self-care policy has been shaped by both government-commissioned and independent research examining both the suitability and capability of health systems to adapt to changing health needs[9, 106, 107] and changing expectations amongst professionals and patients about how healthcare should be organised[95, 98, 108]. Within policy-related discourse, three motivating arguments are apparent:

1. A pragmatic view which anticipates substantial increases in healthcare demand arising from extended lifespan and greater long-term condition comorbidity[109], and asserts that self-care strategies as a viable option for mitigating future cost[9]. This builds on the observations that much of the experience of health, and long-term illness in particular, occurs outside a healthcare context and that there are often opportunities for individual action that might limit subsequent healthcare utilisation, such as self-medication in response to signs of deteriorating asthma[110]. In the UK, it is estimated that the 15.4 million individuals with a long-term condition use 50% of appointments and 70% of inpatient bed days, and through direct and indirect costs, consume up to 70% of the NHS budget[109]. Globally, the consequential impacts of non-communicable disease, including lost productivity, are estimated at around 2.35 trillion USD per annum, disproportionately affecting high-income countries[111].

   Modelling has highlighted the potential for cost savings with self-care targeted at those with mild and moderate illness[9] (anticipating alternative approaches, such as case-management be required for those with more complex care needs[107].) However, empirical evidence concerning impact on expenditure is mixed. While self-care for long-term conditions may reduce hospital use, short-term cost-savings are not guaranteed[112]. In addition, evidence on the comparative cost-effectiveness of different implementation strategies, including new technologies, remains limited. Consequently, within the broader objective of assessing the state of research literature, one of the purposes of this thesis is to summarize what is known about the potential cost impact of apps for asthma and diabetes.

2. Recognition of the potential positive impact of self-care on clinical outcomes and patient-reported health status[92, 112]. Although of variable magnitude, evidence for benefit is broadly supported by empirical studies[112]. Intervention strategies to support this, and an

overview of the state of supporting evidence in relation term to long-term conditions is discussed in the following sections.

3. A value-based perspective, present in more recent policy documents[66, 82, 99], which identifies autonomy and choice as principles that should shape the design of health services. Self-care is constructed as targeting both, enabling appropriate day-to-day health decisions without necessitating clinical input, sitting within a broader framework in which personal care goals and strategies are decided in partnership with professionals[95].

2.3.3 *Strategies for self-care support*

While there is no definitive taxonomy, authors have used both content and theoretical approaches to try to organise strategies for supporting self-care.

Using existing programs to structure analysis, Pearson et al.[113] propose a division between self-management education and supportive elements that focus on psychosocial aspects of managing illness. Condition-specific self-management education typically combines information addressing basic aspects of a disease with skills training targeting medication use, such as in inhalers for asthma, and other aspects of behavioural regulation, such as dietary changes for diabetes[92]. Education may also be used to reinforce healthy lifestyle behaviours, such as smoking cessation[114]. A distinct role for psychosocial support derives from behavioural models of illness, such as the Health Belief Model[115] and Social Cognitive Theory[116], which identify emotions and self-efficacy – perceived capacity to achieve particular goals[117] – (or related concepts) as key mediators of whether people will change health behaviour. Psychosocial components may also include education intended to help individuals develop problem-solving skills, but can also include goal-setting, feedback about performance, and support for coping with emotional aspects of illness[95, 118].

A complementary categorization considers the setting and actors involved in self-care support. Pearson et al. identify four models in the literature: primary-care based support, disease management programs involving face-to-face care provided by specialist staff, disease management programs based on call centres and remote support using technology automation[113]. In addition, Elissen et al. [114] highlight the use of different delivery modes to distinguish one-to-one and group-based support.

Others[95, 119] have attempted to integrate these components, arguing that the form and content of education should be tailored in response to joint planning involving a patient and professional which identifies specific barriers to self-management and specifies the attainment of particular skills and knowledge as personal goals. Lorig and Holman[118] present self-management education as a

process of matching tasks and skills in which tasks are grouped into three core domains: medical management, role management and emotional management, but no specific distinction is made between psychosocial and practical skills.

The extent to which psychosocial integration and tailoring occurs in routine practice is unclear[120]. Nevertheless, these examples serve to illustrate the scope for intervention designs which address a variety of psychosocial and practical needs *and* that combine these in different ways, providing a context to understand the substantial heterogeneity that exists in practice[114, 121]. Some authors have argued that heterogeneity is not just desirable, but necessary, if the spectrum of patient needs and preferences are to be adequately addressed[92].

2.3.4 *How apps could play a role in self-care*

A combination of multimedia, interactive and communication capabilities means that apps could conceivably play a range of roles as part of self-care support. Evidence from online interventions suggests that it is possible for technology-based interventions not only to support the acquisition of knowledge and skills but also address motivational and emotional aspects of self-care[122-124]. Mobile medical apps could support the kind of automated feedback already used in the design of web-based programs, augmenting this with behavioural tailoring and feedback only feasible with a portable device, such as medication reminders. However, automation is not the only possible role. Communication capabilities offer scope for interaction between patients and sources of support. These might include text, voice and video messaging services in scenarios similar to call-centre based disease management models or, alternatively, connecting individuals to provide peer group support.

Edwards et al.[27] have argued that technologies such as apps be viewed as a type of delivery mechanism, equivalent to written or face-to-face instruction, for the content that makes up interventions. While this is helpful to the extent that it underlines the flexibility with which interventions may be configured, this does not remove the need for accounts that critically examine the role of delivery mechanism in shaping the outcomes that are observed. As a result, my view is that the right level of comparison is one in which the relevant contribution of mobile medical apps to self-care outcomes can be isolated from other components within what are almost always complex interventions. Reflecting the range of possibilities and the early stage of research, the approach in this thesis will be to characterise, rather than prescribe, the roles that apps may play in modifying self-care support strategies, and without making assumptions that apps are a neutral delivery mode for intervention content.

Finally, it is worth reiterating that the intervention-based perspective, rooted in both research literature and clinical practice, may not adequately capture all relevant uses of mobile medical apps for self-care support. Individuals may find value – 'support' – from apps that they have chosen without attaching, or the app providing explicit support for, the kind of objectives that would define a clinical intervention. In the context of exploratory work defining the bounds of how apps may be used, I have remained open to this possibility, since these uses may still give rise to issues of quality and safety that are relevant concerns for professionals with a duty of care for such individuals.

2.4 Asthma

2.4.1 *Condition overview*

Asthma is a common respiratory condition with a diverse clinical phenotype. It is characterized by paroxysmal episodes of cough, wheeze, shortness of breath and subjective sensations of chest tightness[125], known as 'asthma attacks', that occur against a background of variable, and at least partially reversible, decreases in lung function. The Global Burden of Disease Study 2010[8] estimated global prevalence of asthma at 4.9% with a patient population of up 334 million people. However, there is substantial variation by setting. For example, when partitioned into high, middle and low income countries, the prevalence of adult physician-diagnosed asthma is estimated at 9.4%, 5.2% and 8.2%, respectively[126]. After Australia (32.8%), the United Kingdom has one of the highest rates of adult asthma prevalence in the world (16.8%)[126]. Child prevalence is higher (up to 29.7%[127]), and the disparity reflects a proportion of people whose symptoms resolve spontaneously prior to adulthood. For most, however, asthma is a chronic condition. While asthma prevalence increased during the latter half of twentieth century, there is some evidence that this rise is now being attenuated, possibly as a result of better management in some settings, including the UK[127, 128].

Although asthma is a clinical diagnosis[125], the underlying pathological mechanisms involve immune-mediated inflammation and airway hyper-responsiveness, in which lung changes seen normal individuals in response to common environmental exposures or 'triggers', such as airborne allergens, cold air or infectious agents, are inappropriately exaggerated[129]. Changes in airway function involve both acute responses, such as narrowing and increased mucus production, and longer-term airway remodelling[130]. While sustained exposure to certain triggers is known to increase the risk of asthma, for example from occupational chemical exposure[131], variations in location-specific prevalence, person-specific triggers and symptom patterns suggest a multifactorial

origin that involves interaction between both environmental exposures[132] and genetic factors[133], particularly during childhood[134].

Inter- and intra-individual symptom variation means that some individuals may experience no day-to-day symptoms, while others live with substantial disability. Previously stable individuals may relapse unexpectedly. Reflecting this, the proportion of individuals undergoing active treatment in primary care in England is estimated at 5.9%[135], lower than prevalence estimates. As a result, it has been suggested that, in the future, asthma may be better understood as an umbrella term for a group of related conditions having distinct pathophysiological mechanisms[133, 136] which, in turn, might enable improved treatment choices, behavioural management and prognostication[137]. At present, however, although a number of distinct clinical phenotypes are recognised based on life stage and symptom patterns, such as cough-variant asthma[138], these continue to be managed within a common framework[125, 139, 140] and, for most people, a precise cause is not definitively established.

Clinical asthma management uses a combination of pharmacological and behavioural components and relies substantially on self-care[125, 139, 140]. A step-wise approach to drug therapy uses fast-acting 'reliever' agents, such as beta-agonists, that target airway musculature which are supplemented, if necessary, with slower-acting mediators of inflammation, such as steroids. Drugs are commonly inhaled using a variety of commercially available pre-packaged devices, although oral therapy may be used in more severe asthma and during exacerbations. Behavioural adaptation is a key feature of self-care, and is discussed further below.

The availability of effective management strategies means that symptom control with minimal lifestyle limitation should be a realistic goal for asthma management in primary care[125]. Despite this, the condition remains a major cause of morbidity. In the UK, the number of years lived with disability for asthma (490 per 100,000) is higher than diabetes (337 per 100,000) [141], affecting lifestyle and resulting in lost work and school time[142]. While asthma is not a significant cause of global mortality[143], it is a persistent cause of avoidable deaths, particularly in young children and the elderly[144]. Of around 1200 annual deaths in England and Wales[145], many appear to be preventable, arising from inadequate clinical management (in 62% of cases) and patient/carer behaviour (in 65%) include delays in seeking help[144]. In the UK, annual healthcare costs associated with asthma mostly reflect medication use, accounting for 11% of the total prescribing budget (£0.7 billion) [146]. Additional costs reflect routine management in primary care (up to £311 million) and unplanned secondary care utilisation (up to £83 million) [146], and appear to be increasing[142].

2.4.2 *Components of asthma self-care*

In addition to education addressing the basic mechanisms of environmental-trigger-related symptoms[110], evidence-based approaches[125, 139, 140] to asthma self-care identify a set of core skills and behaviours for which patients should receive targeted education and support. These skills address specific gaps that have been identified in observational studies and in practice:

- *Trigger identification and avoidance*

  Recognition of personal triggers enables individuals to avoid situations in which exposures may occur that precipitate subsequent asthma symptoms. Multilevel evidence indicates clinical benefit from behavioural strategies for controlling exposure to tobacco smoke, air pollution during exertion and specific allergens identified by clinical tests, but is equivocal about the benefits of environmental modifications, such as air filters, targeting mould, dust-mite, pet and cockroach allergens which are either ubiquitous or resistant to control measures that are potentially costly[125, 139, 140].

- *Appropriate self-medication*

  Most individuals with nontrivial asthma have a baseline treatment regime which must be taken regularly to be effective, as well as rescue medication which must be used promptly in response to symptoms. Relevant skills include appropriate device-specific inhaler technique and planning to sustain medication schedules and ensure that inhalers are available when needed. Despite potential benefits of therapy, treatment non-adherence is seen in up to three fifths of adults[147]. Complex determinants include forgetfulness, characteristic variability in disease state with some individuals experiencing extended periods with subclinical disease, concern about steroid-associated side-effects[148], stigma associated with inhaler use in public settings[149] and illness burden[150]. Poor inhaler technique appears to be a particularly common issue; seen in up to two fifths of individuals[147, 151, 152]. The steps involved in preparing and actuating devices present multiple opportunities for problems that interfere with adequate delivery of drugs to the lungs; wasting medication and increasing the risk of suboptimal long-term control or inadequate therapy during acute attacks[151]. Historical data suggest that running out of inhalers is a contributory factor in around 1 in 10 (8%) of emergency admissions for asthma in the UK[153].

- *Self-monitoring*

Both peak-flow and symptom-based monitoring are effective strategies[154] for identifying changes in the state of asthma necessitating further action. Individuals must either be able to collect and interpret peak flow values appropriately or use a criterion-based approach to interpret symptoms. Logged data may be used by professionals to inform treatment decisions and provide feedback. Action plans, written instructions that detail actions to be taken under specific contingencies, are an effective strategy[155] for assisting individuals in interpreting self-monitoring information and then acting appropriately by:

- *Responding to signs of deterioration*

  Multiple studies have highlighted the risk of latency between initial asthma symptom onset and deterioration requiring urgent care[144, 156]. A major contributory factor appears to be the failure of individuals (or carers) to respond appropriately, even when symptoms are recognized. Low rates of implementation of action plans are a potentially contributory factor. Recent data indicate that fewer than a third of UK patients have written action plans[144, 157].

- *Personal goal setting*

  Both qualitative interview and survey data have highlighted the potential negative psychosocial impacts of asthma, which may confer substantial lifestyle limitations[147, 148]. These stem, in part, from low expectations of symptom control despite evidence indicating the feasibility of minimal lifestyle limitation for most individuals. Goal setting as part of a personalised approach to care planning and decision making is advocated as offering a motivating connection between desired personal outcomes and self-regulatory activities necessary to achieve those outcomes with moderate potential benefits for both physical and psychological health[158, 159].

2.4.3 *How mobile medical apps might play a role in asthma self-care*

Empirical characterisation of mobile medical apps for asthma is one of the aims of the thesis. Data from both systematic review and surveys of commercial apps form the basis of results presented in chapters four and five. However, in a similar mode to the arguments justifying interest mobile medical apps that were introduced in section 2.2.2 above, it is also possible to anticipate the kinds of uses that may be possible in light of the components of self-care described above and evidence of (unmet) needs. This characterisation of potential roles for apps in asthma self-care aims to provide

a counterpoint against which those apps which are actually available may be subsequently compared.

Mobile medical apps may be used as a conduit for providing self-management educational information. While substantial quantities of health information are already available through the internet, there appears to be interest in mobile access from patients, 31% of whom report having used the *mobile* web to answer a health query[47]. The ability to blend textual and multimedia information, and to customize this according to user characteristics and preferences, raises the prospect of tailoring that seeks to optimize knowledge acquisition while compensating for variations in functional and health-specific literacy[160]. Interactive designs such as quizzes and games, are also feasible and may be integrated with other components to provide ongoing or contextual education, such as pop-up tips about performing specific self-care skills. A 2007 systematic review of nine computerized interactive education programs found potential benefits for asthma knowledge and symptoms, although impacts on unscheduled care use and lung function were only seen in one and two studies, respectively[161]. Because apps offer a way to package information so that it can be accessed without needing a network connection, there are opportunities for apps that target situations that may arise only infrequently, such as what to do in an asthma attack.

Mobile medical apps provide a mechanism for generating reminders. These might be used to address the risk of forgetfulness-related medication non-adherence, support related tasks such as ordering replacement inhalers, and reduce missed asthma reviews and other routine healthcare appointments. A systematic review of six telephone and text-message based medication reminder systems targeting asthma found improvements in adherence, although the impact of clinical outcomes was equivocal[162]. A separate review of eight trials of appointment reminders found low-to-moderate quality evidence of a positive impact on appointment attendance[163]. Potentially relevant modifiers include findings indicating that the frequency of reminders may be an important factor in determining their acceptability and effectiveness if perceived 'information overload' means that individuals consequently choose to ignore them[164]. There is also evidence, for reasons that are unclear, that reminders may be less effective for certain types of tasks. For example, text-message-based prompts were found to be ineffective in increasing peak flow monitoring[165]. However, apps can support features missing in other reminder modalities, such as 'snoozing' to handle unexpectedly delayed doses[164], and these may test the inferences that can be drawn from studies dominated by text messaging.

A third major class of potential uses concerns the collection and manipulation of symptom and peak flow data. Consistent with the role of smartphones as a repository for personal contact, email and

social networking information, mobile medical apps may also act as hubs for medical data. Interest in these capabilities is indicated by the recent integration of tools designed to assist app developers within smartphone and tablet operating systems[166]. Apps may be targeted to address current low rates of action plan coverage, providing a low-cost alternative to current-generation paper versions that are available wherever a mobile device is taken. Much has been made of the potential for mobile medical apps to interrogate wireless sensors using low-power technologies, such as Bluetooth[2]. Future apps may connect to wireless peak flow meters, but it seems likely that manual data entry capabilities enabled by appropriately-designed interfaces will also be important, not least because of the requirement to track symptoms in addition to lung function measurements.

There remain open questions about whether such tracking is useful as a long-term activity, particularly in those with mild asthma, as opposed to being a targeted response to changes in asthma state[125]. Suitably-designed apps may address this by supporting different models in which routine data collection is more or less emphasised, and offering decision support to assist individuals in stepping-up their self-monitoring activities consistent with guideline recommendations[125]. Scope for decision-support capabilities ranges from simple flagging of out-of-range values to automatically excerpting portions of actions plans by using the criteria that a patient would otherwise have to apply manually. There may be opportunities for more sophisticated interrogation of longer-trends in data that non-clinical users may find hard to discern, such as changing diurnal variability[167], which might, in turn, assist understanding of condition state or recognition of particular personal triggers. The efficacy and acceptability of such strategies in asthma is largely unknown, however. Studies of a range of information technologies highlight the potential for unanticipated safety risks if, for example, patients are reassured inappropriately, and the unnecessary worry and potential impact on healthcare utilization caused by overly-conservative flagging[13].

At the boundary between self-care and disease management, there are a range of possibilities involving clinician support in which apps may play a role. Secure messaging offers a way for patients to solicit feedback from healthcare professionals (or, potentially, peers) and to transfer data to inform clinical review. Structured monitoring scenarios are also possible in which there is an element of routine review and feedback. A systematic review of telehealth studies (n=21) found potential clinical benefits in interventions directed towards those with moderate or severe, but not mild, asthma[168].

Finally, mobile medical apps may incorporate specific strategies for addressing psychosocial aspects of self-care. These may include capabilities to log progress against personal asthma goals and

motivational elements such as badges and rewards intended to sustain interest in self-care. In addition to variable adherence to recommended treatment[147], attrition of engagement to eHealth interventions is a recognized issue in intervention studies[169] and affects up to a quarter of participants in chronic disease self-management programs[170]. A recent systematic review of behavioural components for asthma care identified potential benefits of interventions in which participants were actively involved but also highlighted the potential negative effects on subjective symptom perception of strategies focussing on stress management[171]. There is also the possibility of app-supported interventions targeting emotional aspects of long-term illness, such as anxiety and depression, including those use using formal techniques such as cognitive behavioural therapy[172]. Understanding of the potential effectiveness of these types of interventions is limited by the quality of available studies and the lack of research specifically targeting asthma.

2.5 Diabetes

2.5.1 *Condition overview*

Diabetes mellitus (hereafter: diabetes) is a group of endocrine disorders of glucose regulation characterized by persistent high blood glucose levels and altered fat storage that, if sustained, result in systemic impairments arising from vascular and end-organ damage[173, 174]. Two main forms of the condition are recognized: type 1 and type 2 diabetes. The dominant form of the condition, in 90%[175], is adult-onset type 2 diabetes which involves the failure of adaptive mechanisms to compensate for lifestyle and diet-associated nutrient excess which has been termed 'chronic fuel surfeit'[174]. In the UK, the highest proportion of diagnoses occur in the 60-65-year-old age group[176], although condition onset may predate this by several years[177]. Less than ten percent of cases are type 1 diabetes, which typically manifests in childhood and results from immune-associated destruction of pancreatic islet cells involved in production of the hormone insulin, the major regulator of cellular glucose uptake and thus blood glucose levels[178]. Global diabetes prevalence is estimated at 6.4% (285 million individuals), higher than asthma, and modelling forecasts an increase of up to 1.3% by 2030 driven mostly by increases in type 2 prevalence in developing settings undergoing urbanisation and a shift towards Western diet and lifestyle[179].

Independent of the underlying disease subtype, the short-term, reversible effects of elevated blood glucose include polyuria and polydipsia arising from osmotic effects on kidney function and increased risk of infection by bacteria able to metabolise sugar present in body secretions. However, raised blood glucose also has a range of additional pathological effects which, if uncontrolled, ultimately contribute to long-term complications. These include microvascular damage to eyes,

kidneys and the nervous system, and macrovascular damage contributing to large vessel atherosclerosis and an increased risk of myocardial infarction and stroke[174, 178]. Visceral fat deposition seen in type 2 diabetes may also directly cause tissue damage[180].

Like asthma, treatment approaches for diabetes combine medication-based therapy with behavioural regulation and lifestyle modification. However, unlike asthma, which focusses on symptomatic relief and minimal short-term disability, the short-term consequences of hyperglycaemia may be limited, and therapy is directed mainly towards avoiding long-term complications. Drug therapies include agents which act to either increase insulin secretion or promote its activity in peripheral tissue, and exogenous insulin, which must be injected or infused, to replace lost endogenous production. Large-scale observational studies have demonstrated the benefit of anti-hyperglycaemic drugs in reducing morbidity and mortality in uncomplicated type 1 and type 2 diabetes[181-183]. While insulin has always been a mainstay of type 1 diabetes therapy, a current clinical focus on tight glycaemic control[184, 185] has resulted in a greater proportion of UK patients with type 2 diabetes being started on insulin therapy [186]. As a result, there is overlap between the self-care approaches that are now used for both conditions, meaning that some interventions, including apps, may be reasonably designed to be subtype agnostic. Nevertheless, there are important differences, such as typical age of onset, which may be relevant factors in intervention design.

Diabetic complications confer a substantial burden of premature mortality and negative impacts on lifestyle and mood. In the UK, retinopathy is the main cause of acquired blindness[187], while almost half of limb amputations occur in those with diabetes[188]. The impact on life expectancy varies by age of onset and associated comorbidity, such as obesity, and has been falling[189]. In the US, an adult diagnosed at 40 might be expected to die between 5 and 6 years earlier than someone without diabetes[190]. The direct and indirect costs of diabetes are estimated at £9.8bn and £13.8bn per year, respectively, of which 79% (£7.7bn) is directed towards the management of complications[191]. Direct costs are forecast to grow to £39.8bn by 2035, reflecting an increase from 10 to 17% of NHS expenditure[191].

2.5.2 *Components of diabetes self-care*

Like asthma, evidence-based strategies for diabetes self-care[192, 193] incorporate education about the condition and skills addressing a number of domains:

- *Healthy eating*

Blood glucose levels are directly influenced by dietary carbohydrate intake. Control strategies include reductions in refined sugar intake, caloric restriction and formal counting methods which attempt to precisely quantitate carbohydrate intake. Systematic reviews of trials of carbohydrate counting in type 1[194, 195] diabetes indicate the potential for modest but clinically-relevant benefits compared to unstructured methods for diet regulation.

- *Appropriate self-medication*

  Oral antidiabetic, multiple daily injected (MDI) and continuous subcutaneously infused (CSI) insulin therapies require skills to avoid missed medication and, for insulin, appropriately tailor doses. This additionally necessitates skills for sampling blood glucose, caring for injection/infusion sites to protect body tissues and to manage and configure delivery devices, such as auto-injectors and infusion pumps. Planning skills are also needed to ensure medication and glucose test strips are available when required. Like asthma, treatment non-adherence is a recognized problem in diabetes with negative potential consequences including increased risk of mortality[196]. A 2004 systematic review found the proportion to patients of adherent to prescribed regimens ranged from 36-93% for oral antidiabetic agents and identified a single study of patients with type 2 diabetes in which compliance with insulin was estimated at 63%[197]. Contributory factors include the potential complexity of insulin medication regimes[198] creating a risk of self-medication error[73, 199], psychosocial factors related to coping, particularly amongst younger patients[197], and clinical inertia that does not emphasise the importance of consistent therapy, particularly in patients with type 2 diabetes[200].

- *Self-monitoring*

  Identification of short term changes and longer-term variability in blood glucose potentially enables early intervention in the form of medication and dietary changes that may prevent longer-term complications[201, 202]. Like asthma, logged data have value for both patients and responsible professionals. Although emphasised as a component of daily self-care, adherence to self-monitoring is variable, with meta-analysis suggesting that at least two fifths of patients do not engage in routine monitoring[203].

- *Problem solving*

  While unexpected deterioration in condition control is a featured shared with asthma, appropriate responses for diabetes may require prompt identification of the underlying

cause and are less amenable to stereotyped action plans. Although stereotyped skills are still required to deal with specific, common, problems, such as unexpected hypoglycaemia, there is an emphasis on problem-solving that can be used to respond flexibly to changes in condition state. A systematic review of heterogeneous studies of problem-solving[204], targeting either adults (study n=17) and children (n=7), identified potential benefits including compliance with self-care in children/adolescents and reduced rates of depression in adults. Positive impact on clinical outcomes appears to depend on the type of problem-solving interventions and is more clearly seen in multi-session and structured approaches that break problem-solving into steps.

- *Risk reduction*

  Risk reduction behaviours include foot and eye care, weight loss and/or healthy weight maintenance, which modifies visceral fat deposition and insulin resistance in type 2 diabetes, and exercise, smoking cessation and healthy eating to modify cardiovascular risk[203].

- *Healthy coping*

  Like asthma, the substantial long-term risk of life-changing complications presents a psychosocial burden that individuals with diabetes must manage[205].

2.5.3 *How mobile medical apps might play a role in diabetes self-care*

Mobile medical apps for diabetes have potential roles that are similar to those available for asthma, discussed in section 2.4.3 above, reflecting the broad overlap of self-care activities relating to behavioural regulation, self-medication and self-monitoring. However, there are important differences with potential implications for the design of apps targeting diabetes.

Compared to asthma, there is greater complexity of skills required for both routine self-care and reactive problem solving. This presents challenges for patient education, which needs to incorporate multiple structured sessions and regular reinforcement in order to be effective[206]. There are number of ways in which mobile medical app designs might respond to this additional complexity. Apps might offer a structured curriculum that can be completed at a pace suited to each individual. Alternatively, there may be benefits in blended designs that incorporate other delivery methods, such as face-to-face sessions, for which apps provide knowledge summaries or refreshers within larger educational interventions.

Technical complexity creates opportunities for tools specifically intended to simplify tasks, such as calculators designed to determine an appropriate insulin dose. Recently it has been suggested that apps could act as integration hubs for behavioural data which would be used by a combined glucose-meter and pump-system to act as a form of 'artificial pancreas'[207].

Evidence from web-based interventions suggests that, like asthma, the use of behavioural changes techniques as part of mobile medical app design may be associated with improved outcomes[208].

2.6 Quality and safety

2.6.1 *Definitions and origins*

Healthcare quality is an abstract, multidimensional construct concerned with the 'goodness' of health interventions, services and systems. While authors and organizations vary in their commitment to objective excellence versus more situated standards[209], definitions are united by the idea that it is possible to define and measure the degree to which aspects of healthcare satisfy specified expectations. Perhaps the most widely-cited early definition is that of the Institute of Medicine (IoM):

> *"Quality consists of the degree to which health services for individuals and populations increase the likelihood of desired health outcomes and are consistent with current professional knowledge." [210]*

Acknowledging the origins of quality discourse in commerce[211], others have proposed a third component that acknowledges the subjective perceptions of the 'marketplace' of users in addition to the standards defined by professional best practice and specified health outcomes[209]. Some authors have explicitly acknowledged the role of healthcare context and intended audience in determining the most appropriate approach for framing quality, emphasising the consequential value of information about quality in making improvements to healthcare delivery[212]. Yet another perspective emphasises the dynamic balance between what might be desired and what is feasible when accounting for the constraints placed by available health technologies and resources[213].

Partly as a result of these differing perspectives, contemporary definitions identify multiple conceptual domains within which judgements about quality may occur, providing a framework, rather than a prescriptive approach, to structure evaluations of quality[214-216]. This flexibility allows for the possibility of tensions between domains that arise both from differing perspectives, but also the multiple ways that healthcare demand may be met. As a result, quality frameworks

provide both a means to judge quality in isolation, but also a structured way to assess the relative quality impact of different strategies for achieving similar goals.

This discussion will adopt the IoM framework for quality and safety, published in 2001[214] as a follow-up to a landmark 1999 report exposing the scale of iatrogenic harm[217]. This identified six domains of quality: effectiveness, efficiency, patient-centredness, equitability, timeliness and safety. These domains are consistent with those recognized by the WHO framework, which subsumes timeliness within a domain of accessibility and emphasises that patient-centredness should incorporate assessments of acceptability but is otherwise identical[215]. The IoM framework is a superset of a three-domain approach incorporating effectiveness, patient-centeredness and safety adopted by both the OECD quality indicator project[216] and the UK NHS Next Stage Review[218]. The framework has also been adapted for previous evaluations of healthcare information communication technology[13]. While some recent definitions have recognized additional domains not represented by the IoM, it is not clear that these constitute additional categories orthogonal to those that already exist. Rather, they are specific facets of existing domains, such as appropriate use of resources[219] (which fits within the IoM domain of efficiency), or indicators, such as baskets of care outcomes[220], which appear to have been prioritised for strategic reasons in the context of particular programmes.

Five of the six IoM domains are summarized below, and the sixth – safety – is discussed in the following section. While discussion of each domain may be framed at multiple levels, from the experience of specific individuals to the aggregate performance of health systems, the approach here will be to adopt an intervention-focussed perspective (section 2.2.1.3 above) reflecting the way in which apps are likely to be introduced.

Effectiveness

Effectiveness concerns the ability to generate desired health outcomes; measurable changes in health status of individuals and populations arising, in the case of long-term conditions, from the modification of disease-related impairment[24]. This framing allows strategies ranging from those intended to eliminate (functional) impairment, such as the use of steroid inhalers to suppress asthma-related inflammation, to those intended to modify the potential consequences, such as foot care to prevent skin breakdown in diabetes. Although there is no definitive set of outcomes applicable to all health interventions, common measures have evolved to enable discussion and comparison. At a per-condition level, these include objective measures of function, such as peak flow – a measure of lung function – in asthma, and subjective measures of symptoms, disability and disease-specific quality of life assessed using standard instruments. Condition-independent

outcomes also assess morbidity, such as disability-adjusted life years[221], but additionally include hard endpoints, such as years of life lost.

A second sense of effectiveness is consistency with existing biomedical knowledge, rooted in the argument that it is unethical and wasteful to implement healthcare strategies that are known either to be ineffective or less effective than those that are, given available resources, feasible[24]. For newly developed intervention classes, such as apps, where relative effectiveness is unknown, this principle suggests that it is not enough to measure health impact. Rather, the design of new interventions should, to the extent that it is feasible, incorporate existing knowledge in order to maximise the likelihood of effectiveness.

Efficiency (including cost-effectiveness)

Efficiency is concerned with minimizing waste and maximizing the productive use of material and human resources. It recognizes that health systems are subject to constraints which may necessitate trade-offs in other areas of quality. Taxonomy-building work has identified three types of efficiency that are expressed in terms of their impact on health outputs, the combination of quality outcomes and measures of the performance of services necessary for generating those outcomes within a target population, such as reach[222].

- Productive efficiency exists where health outputs of a particular standard cannot be delivered at lower cost. Where financial resources place a hard constraint, the dependency may be inverted to require that better outcomes cannot be delivered given available resources. Measures of cost-effectiveness fit within this approach, for example the cost per quality-adjusted life year cost-utility adopted by the UK National Institute for Health and Care Excellence (NICE)[223].
- Technical efficiency recognizes that health outputs draw from a limited pool of material and human resources, and recommends strategies that reduce waste. As highlighted in the discussions of asthma and diabetes, medication use is particular target. Strategies relevant to self-care include ensuring that individuals adhere to recommended prescriptions and know how to use their medications to maximum benefit, for example by using inhalers appropriately.
- Social efficiency reflects an allocation of resources across populations of patients that optimally conforms to social norms and values. While some issues may be uncontroversial in most settings, for example the application of high-risk preventative procedures to low-risk patients, the situated nature, and propensity for change, in social values is a particular

challenge for measures of social efficiency. Social efficiency is rarely measured directly[222], but motivates strategies for long-term care, such as the NHS Health and Social Care Model, that recommend self-care for those with mild or moderate disease while reserving disease and case-management approaches for those with the most complex needs[107]. This stratification does not remove the need to consider other determinants of need, such as health literacy and ability to access care, highlighting the potential overlap between social efficiency and equitability (discussed below).

Patient-centredness

Patient-centred care identifies individual patient values and preferences as important factors in clinical decision making[224]. In intervention design, patient-centredness may necessitate mechanisms for soliciting personal preferences and strategies for tailoring particular intervention components. The flexibility and customization potential of information technology-based approaches has been proposed as a potential enabler of access and patient-centred care. However, technology may also have unintended consequences, for example by reducing the opportunities for face-of-face decision-making involving patients and professionals. In addition, technology non-use is a valid preference from a patient-centred point of view, and this possibility must be reconciled with strategic goals, such as those seeking to standardise approaches to care. Tension is visible in the contrast with both effectiveness, which emphasises normative outcomes, and (social) efficiency predicated on collective, rather than individual, values.

Equitability

Whereas patient-centredness emphasises the scope for variation that reflects individual preference, equitability seeks to eliminate variation arising from factors that cannot be justified[24]. These include access to, and experience of, care that varies by gender, age, ethnic background, sexuality, socioeconomic status or geographic location. Like patient-centredness, technology may seek to address issues of equitability, for example by improving access to support outside traditional clinical contexts, but also unintentionally compound them, for example by requiring that individuals have access to technologies that carry financial cost, such as mobile phone contracts.

Timeliness

Related to efficiency, timeliness recognizes the specific harmful effect of delays during diagnosis and therapy. Appropriate intervention designs may facilitate timely care, for example by enabling access to professional advice, or, in the context of long-term condition self-care, allowing individuals to recognize early signs of changes in their condition state and take appropriate action.

2.6.2 *Safety in healthcare*

Recognition of the scale of harm arising from medical error was one of the major factors influencing the development of the IoM framework for quality[217]. In healthcare, safety can be defined as the freedom from accidental or preventable harms that are arise from the experience of medical care[225]. Harms may reflect both human errors (slips, mistakes and lapses[226]) which may include acts of commission or omission[227], and latent system-level failures[228].

There is some debate about the appropriate way to frame safety in relation to quality. Under the IoM framework, safety represents a sixth quality domain; a "subset of the larger, much more complex and multidimensional concept of quality."[209] Others agree the categorical separation, but argue a more fundamental distinction of objectives between quality described and evaluated in terms of the presence of desirable attributes and safety characterized as the absence of harm. The idea that harms act to negate other aspects of health quality is present in definitions where safety is presented as 'underpinning' quality[24]. An alternative view identifies a balancing, rather than strictly negating, role for safety considerations in relation to quality[6]. This perspective, which underpins approaches to medical technology regulation and which is being applied to mobile medical apps by regulators[229], recognizes that harms are not absolute, but differ in terms likelihood and impact, and the interventions may be explicitly designed to mitigate known safety risks[230]. This balancing perspective has informed the approach used in my thesis, and is the reason why safety is identified separately from quality in both title and text.

2.7 Quality and safety of mobile medical apps

2.7.1 *Definitions*

Building on the IoM framework described above (section 2.6.1), an appropriate definition of quality and safety might be:

> *"The quality of mobile medical apps for self-care concerns the degree to which they: increase the likelihood of desired health outcomes in a way that is cost-effective; are consistent with current professional knowledge; are clinically safe and handle personal sensitive information appropriately; enable patient-centred care that is acceptable to individuals and equitable at a population-level; are usable by intended patient groups; and are feasible for integration into routine clinical practice."*

Within this definition, the potential risks to privacy posed by information technology are explicitly incorporated as a relevant safety consideration, since the compromise of personal information is a potential source of harm. Similarly, the definition recognises the usability of apps as a factor linking domains of acceptability and effectiveness. The ISO defines usability as "the extent to which a product can be used by specified users to achieve specified goals with effectiveness, efficiency and satisfaction in a specified context of use.[231]"

2.7.2 *Policy context*

In the UK, specific interest in mobile medical apps was first articulated by a Secretary of State for Health in 2012[20], who suggested a vision for future primary care in which apps would be offered 'on prescription'. Subsequent policy documents have specifically referred to the use of apps as part of a digital strategy that emphasises self-care[5].

While plans for implementation, which will be coordinated by a newly-established National Information Board, have not yet been announced, there have been other concrete developments. These include the establishment of an NHS-based accreditation program for mobile medical apps in 2013[232] and clarification in 2014 of the regulatory requirements for mobile medical apps by the UK Medicines and Healthcare Regulatory Authority[233], paralleling announcements by the US Federal Drug Administration after a year-long consultation process[229].

2.7.3 *Current state of knowledge*

As suggested in chapter one, while there is acknowledgement of the importance of understanding quality and safety issues in relation to mobile medical apps[11, 32, 77, 234], there is currently limited co-ordinated synthesis.

Systematic assessments of apps for long-term conditions[40], pain-relief[42] and health behaviour change[43, 44] have highlighted the possibility that many current apps do not conform to evidence-based recommendations. Poor diagnostic sensitivity has been identified in apps that offer screening for skin cancer[17], raising the possibility of missed or delayed diagnosis. Apps intended for therapeutic purposes[18] and drug calculation[19] have been withdrawn.

2.8 Chapter summary

This chapter has introduced the concepts of mobile medical apps, self-care and quality and described the political and health-related context shaping current interest in each.

The evidence presented here underpins the rationale for the thesis. Rather than present a detailed summary here, the major points raised in this chapter are recapitulated in section 3.2.1 below as part of the justification of aims and methods.

Chapter three: Justification of aims and methodological approach

3.1 Chapter introduction

This chapter draws together themes identified in the previous chapter in order to describe the rationale behind the thesis and its specific aim and objectives.

It presents an overview and justification of the methodological approach selected to respond to these objectives. Detailed descriptions of specific methods used for the six studies compromising this thesis are provided in subsequent chapters.

3.2 Rationale for thesis

3.2.1 *Rationale for focus on self-care using mobile medical apps (synthesis of context)*

A focus on self-care apps reflects a combination of arguments from policy and clinical need that were detailed in the previous chapter.

The following serves as a brief summary of the relevant arguments:

- A political focus on self-care as a mechanism for improving outcomes while addressing concerns about the sustainability of healthcare expenditure associated with traditional models of provision.
- Concerns from patient advocates, also reflected in changing patient expectations, about the limited extent to which individuals are currently involved in healthcare decision making and self-care.
- Evidence for substantial unmet needs and limited implementation of self-care within long-term conditions such as asthma and diabetes.
- Existing evidence from intervention strategies not incorporating apps hat self-care can be effective and acceptable strategy for improving health outcomes.
- Concerns that existing models, such as chronic disease management and expert patient programs are not scalable to population-level interventions required to address prevalent conditions such as diabetes.

- A case for apps that identifies their flexibility as a delivery mode for supporting a wide range of activities relevant for self-care coupled with high rates of adoption amongst consumers that make smartphones a credible, ubiquitous delivery device.
- Mixed evidence about the potential benefit of computerised self-management support justifying further research which attends, in particular, to issues of equity and cost-effectiveness.

3.2.2 *Rationale for dual focus on asthma and diabetes*

The dual focus on asthma and diabetes sought to enable a richer commentary about quality issues relating to long-term condition self-care than that possible by focussing on either condition alone. Both conditions are prevalent and associated with substantial morbidity for which comprehensive self-care strategies have been devised but with variable patterns of implementation and recognized opportunities for improvement. However, there are important differences. Diabetes brings a greater requirement for daily monitoring and greater technical complexity in problem solving that contrast with the more variable symptoms of asthma that can nevertheless be managed by more stereotyped self-care. Asthma is commonly diagnosed in childhood, while (type 2) diabetes is a disease of middle age. Asthma symptoms broadly correlate with underlying disease activity, while individuals with diabetes must sustain control in the face of the future threat of complications while experiencing few day-to-day symptoms. It was hoped that these contrasts – of day-to-day self-management, task complexity, demographics, and illness experience would provide a useful basis for comparing findings with potential relevance for other long-term conditions. For example, the experience of diabetes may have implications for the management of other conditions in which secondary prevention is a major component, such as cardiovascular disease rehabilitation, while experiences from asthma may be relevant for discussions about conditions with variable phenotypes and the risk of unexpected deterioration, such as relapsing remitting forms of multiple sclerosis.

Pragmatic considerations were also relevant. Scoping work highlighting limitations in the scope of literature addressing either condition alone. There were similar concerns about the practicability of a qualitative study of app use targeting a single condition when the potential size of the target population of app users was unknown.

3.2.3 *Rationale for breadth of study*

The decision to retain a comprehensive focus rather than iteratively focussing on particular dimension(s) of quality and/or safety reflected several considerations:

- The potential difficulty of justifying a targeted focus in a discussion invoking quality. This theoretically-informed perspective arises because current multidimensional constructions of quality afford no particular privilege to any individual quality domain. They also explicitly recognize the possibility of dynamic balance between domains which might be compromised by the exclusion of particular components.
- The desire to generate commentary that may practically contribute to discussion about the introduction of apps into routine care. This can be understood as a pragmatic translation of the first perspective. It responds to the review of policy and clinical commentary which suggests that all the dimensions of quality will need to examined if apps are to be introduced with the confidence that they can support high quality care.
- Recognition of the feasibility of synthetic approaches seeking to provide a comprehensive overview of quality and safety issues in relation to information technology, based on previous work[13, 235].
- Calibration of the likely volume of research available given the emerging status of mHealth as research discipline. Identification of the landscape of addressed and unaddressed topics around quality and safety holds potential value for informing priorities for research that, in turn, may contribute to rational adoption of apps as part of care processes.

3.3 Thesis aims and objectives

3.3.1 *Aim*

To critically evaluate the dimensions of quality and safety that may affect the suitability of mobile medical apps for routine use to support the self-care of long-term conditions, using the examples of asthma and diabetes.

3.3.2 *Objectives*

1. To characterise the extent and findings of the experimental evidence base concerning the quality and safety of app-supported interventions for asthma and diabetes.
2. To explore the quality and safety characteristics of mobile medical apps for asthma and diabetes available for use by patients, using established clinical standards and guidelines.

3. To explore the factors that influence how and why individuals choose apps to manage their diabetes and asthma, providing a patient-oriented perspective on issues of quality and safety.

4. To integrate these three perspectives (from research, clinical expectations and patients) to provide an account of quality and safety factors influencing the suitability of apps for long-term conditions and to explore the impact of these findings for patients, clinicians and policy-makers.

3.4 Rationale for methodological approach

3.4.1 *Multiple methods (multimethod) research*

Multiple methods research describes a methodological approach in which a research problem is decomposed into a series of smaller projects each of which targets a specific objective using a suitably optimized method[236]. It has been argued that multiple methods research offers an alternative paradigm to both quantitative and qualitative research by emphasising a pragmatic approach to epistemology that rejects either dogmatic commitments to either post-positivist or constructivist research philosophies or frank scepticism[237]. Two major types of multiple methods research are recognized[238]. 'Mixed method' studies "combine quantitative and qualitative methods, approaches, concepts or language"[239] within an overall research question having a particular qualitative or quantitative theoretical orientation. In multiple methods or 'multimethod' studies, a series of self-contained projects are conducted and, in a final step, triangulated to form a coherent synthesis[238]. Multimethod research confers no specific requirement that both quantitative and qualitative techniques be used.

A multimethod approach was adopted to structure this thesis. Although incorporating both quantitative and qualitative components, each study was designed as a self-contained element answering a specific research question. This approach reflected an iterative approach to the development of the PhD in which previous studies were used to influence decisions about subsequent work. A unifying synthesis that triangulates the findings of these studies is a specific objective of the thesis and underpins the discussion presented in the closing chapters of the thesis.

There are two potential benefits of a multiple methods approach for a discussion focussed on the quality and safety apps for self-care. The first recognizes that particular methods may be optimized towards examining specific facets of quality and safety, given its multidimensional character. The value of multimethod evaluation of complex information technology interventions on these grounds

has been recognized for at least three decades[240-242]. The methods exposition (section 3.4.2 below) highlights the way that specific methods were chosen to respond to identified gaps framed both at the level of particular objectives and within specific quality domains. The second is the opportunity for triangulating synthesis that compares individual studies and explores the implications of tensions and inconsistencies in light of the strategic goal of introducing apps into routine care. This is discussed in the final section of this chapter (section 3.4.3 below).

3.4.2 *Selected methods*

This section provides an overview of the rationale behind the choice of the three major methods used in the thesis. Conceptual limitations associated with each method, and those arising from the specificities of the work that was undertaken, are discussed in their respective results chapters (see sections 4.6.2, 5.5.3, 6.5.2 and 7.5.3 below)

Systematic literature review

In order to provide a comprehensive characterisation of the research literature examining quality and safety in relation to apps for asthma and diabetes (**Objective 1**), a systematic literature review was performed.

Systematic reviews aim to provide an unbiased synthesis of research studies that explicitly considers how the quality and breadth of available evidence influences not only the conclusions that may be drawn about particular phenomena but also their validity and relevance to particular populations and settings[243]. This necessitates methods both to assess biases arising from the conduct of included studies and to control bias and error that might be inadvertently introduced during the conduct of the review itself. As a result, systematic reviews combine a formal protocol-based approach, including a pre-specified research question and strategy for identifying literature, with standard methods for selecting, critically appraising and synthesizing studies. Each stage of assessment may be replicated by multiple investigators in order to minimize assessment bias and error. A range of synthetic approaches are possible depending on the types of study and data being combined. For quantitative data, meta-analysis may be used to combine data across studies to generate a pooled estimate of an effect. Since the feasibility of this approach depends on the degree of clinical heterogeneity and methodological diversity present in those studies contributing to a synthesis, systematic reviews typically incorporate formal criteria for judging when quantitative synthesis will be conducted.

Methodological robustness[244] was the major factor influencing the choice of systematic review compared to less formal methods for literature synthesis. However, the ability to explicitly and

reliably characterize gaps in knowledge was also important. A relative lack of identified literature addressing app safety, exploring patient-centred perspectives on app use or explicitly relating intervention effects to components of self-care informed the development of objectives two and three and the studies that respond to these. The existence of unanswered research questions also has direct implications for proposals to introduce apps into routine care as well as any future research agenda and these are topics that are developed in the discussion.

Systematic appraisal of published apps

To characterise mobile medical apps available through commercial app stores and evaluate their clinical and safety characteristics (**Objective 2**), a systematic appraisal method was developed. This method combined a census of all available apps meeting study-specific criteria with a criterion-based approach to assessment of compliance with clinical standards. It underpins the studies described in chapters five and six.

Although an observational, rather than synthetic, technique, the method adapted principles from systematic review to minimize bias and error. In order to maximise sensitivity of app identification, a search strategy was developed for each study, piloted and then customized for each app store. Searches were executed by two authors, combined and de-duplicated. In order to minimize selection-related bias and accidental error, candidate apps identified by the search were filtered using pre-specified selection criteria. At least two authors reviewed each app, working independently, any decisions to retain or exclude apps were made based on consensus. Finally, to avoid assessment-related bias and accidental error, quality criteria were pre-specified for each study and applied by at least two authors whose independent judgements were then combined.

It may be possible to define robust sampling-based approaches to app appraisal that replace the census-based method described here, which is time and resource intensive. In addition to the fact that, at the time the studies were conducted, an exhaustive app search was a feasible option, two factors additionally influenced its use. Firstly, it avoided problems associated with defining and implementing an unbiased sampling strategy. In particular, the way that commercial app stores process search queries appears to create a risk of sampling bias arising from the opaque criteria used to filter and order search results. During pilot searches for the studies included in this thesis, it became clear that different authors would receive different orderings of search results. Without understanding the criteria involved (which might reasonably incorporate factors such as user-ratings or download counts that are plausibly covariate with quality) it is hard to argue that any given sampling approach is unbiased. Secondly, it enabled quantitation of the dynamics of app release, update and withdrawal that have potential implications for discussions about quality; for example,

in relation to the resources required to ensure that apps available to patients are safe. These dynamics are explored in relation to apps for asthma in Chapter five.

Qualitative interviews of app users

In order to explore factors influencing how and why patients with asthma and diabetes are currently using apps, a qualitative interview study was undertaken (Objective 3). In contrast to the deductive approach underpinning the systematic methods described above, qualitative research adopts an inductive stance, which seeks to generate accounts of how and why social behaviours and phenomena occur. Qualitative research makes no claim to provide exhaustive, or statistically bounded, descriptions. Instead it seeks to provide plausible, coherent explanations that can provide insight into complex phenomena that cannot be generated easily by quantitative methods in general, and experimental studies, in particular[245]. As noted above, this was borne out in the relative lack of experimental studies addressing patient perspective identified by systematic review. This, together with the requirement to explore issues of patient-centredness and equity (as top-level quality domains) and the observation that patient use or non-use of apps will substantially influence their effectiveness in practice[21] were the key factors motivating this study.

As for deductive research, accounts of human behaviour are potentially subject to bias, although the determinants are different. Particular challenges include the varying ability of individuals to access and communicate true factors shaping their behaviour, and the subjective character of interpretation by research staff whose own perspectives may be shaped by personal, cultural and situational factors. As a result, a range of qualitative methods have been developed to try to mitigate against bias and, through transparency, enable external critical appraisal.

For this work, a semi-structured contextual interview method was paired with a Framework analysis. In a contextual interview, individuals are asked to model a relevant behaviour, for example the use of an app, in a controlled setting in which a researcher acts as both observer and interviewer, asking questions to clarify and probe behaviour. In addition to characterising the detail of specific functions of apps used by patients, the method provided a way to generate explanations for why these were valued that grounded in actual behaviour.

Ethnographic observational methods were discounted because of the impracticality of observing multiple individuals whose app use might be distributed throughout each day and change substantially over time. The Framework Method[246] is a type of thematic analysis, a family of analytical methods for identifying patterns within qualitative data, such as that generated through interviews. Three factors shaped the choice of the method. Firstly and in contrast approaches such

as grounded theory which emphasize theory generation, Framework is appropriate for analysis where conceptual domains that might shape analysis have already been identified, such as the how and why dichotomy identified above in relation to mobile medical app use[247]. Secondly, the method emphasizes the value of exploring similarities and differences between and across individual accounts. It was felt that, given the early stage of research, generating a balanced account of the breadth of ways in which apps might be used would be important. This also informed the sampling strategy used to identify potential participants which is described further in Chapter five. Finally, Framework emphasizes procedural transparency and is therefore consistent with a methodological commitment to strategies that enable external critique which also motivated the choice of the systematic review and appraisal methods described above.

The possibility of a similar study exploring clinician perspectives was also considered but ultimately not performed because of the limited integration of mobile medical apps for patient use into current practice sufficient to provided accounts grounded by experience rather than opinion. This could be a target of future studies once apps start to be used in routine care in the United Kingdom and other settings.

3.4.3 *Integration of methods*

In addition to ensuring coverage sufficient to meet the overall aim of a comprehensive exploration of quality and safety issues, a multiple method approach also presents opportunities for synthesis and contrast.

Topics which substantially depend on the ability to integrate findings from multiple sources, and which are discussed in Chapter 8, include:

- The potential tension between patient perspectives about desirable features in apps and those framed from clinical and research perspectives.
- Contrasts that may be drawn between asthma and diabetes which contribute to a broader discussion of the potential relevance of findings to other long-term conditions.
- Differences in issues affecting app-supported-interventions that are likely to already be embedded in a clinical context compared to those that are not part of targeted interventions but may nevertheless play a role in self-care, such as apps that individuals select themselves from public app stores.
- The contrast between the volume and types of apps that are commercially available, those evaluated by research literature, combined with evidence of dynamic app turnover which

tests that argument that tests the argument that all apps need to be subject to empirical evaluation.

- The role for differentiated strategies for introducing self-care apps into routine care to reflect different patient/condition-specific needs and different app types.

These are discussed in light of their potential relevance for policy-makers and regulators, app accreditation programs, healthcare professionals and patients.

3.5 Chapter summary

Chapter three presented the rationale for my thesis, building on the specific political and health-related needs identified in the previous chapter.

It identified specific concerns about breadth and condition focus that have acted to shape both the thesis objectives and the selection of a multi-method approach which combines systematic review of research literature, systematic content assessment of published apps and qualitative inquiry. In the following chapters (4-7) each of these methods will be revisited as the findings of the studies that compromise the thesis are presented and discussed. The first of these is a systematic review of experimental studies using apps for asthma and diabetes.

Chapter four: Mobile medical app-supported interventions for asthma and diabetes. A systematic literature review

4.1 Chapter overview

Chapter four presents the combined results of two systematic literature reviews of experimental studies evaluating mobile medical app-supported self-care interventions (see section 2.2.1.3 for definition) for asthma and diabetes. It presents an outcomes-focussed perspective on quality, summarising the clinical, patient-centred and safety related impacts measured as outcomes during the conduct of these studies. It extends and completes the discussion of context presented in chapter two by summarising the state of the research literature in respect of app-supported interventions.

The chapter opens with a brief review of existing systematic reviews addressing mobile health-based interventions, highlighting the gaps that informed the development of this work. It continues by laying out the review-specific objectives, methods and results, and concludes with a discussion of findings and limitations, using a structure that will be repeated in each subsequent results chapter (chapters 5-7).

4.2 Existing literature reviews

While there have been a number of systematic literature reviews examining interventions on mobile devices, most have focussed on diabetes, and none have specifically focussed on apps to the exclusion of other intervention modalities, such as short message service (SMS) text messages. The text below provides a brief overview of these reviews and their findings.

Krishna et al. (2008) [248] examined cell-phone use in diabetes self-care up to 2007 and found significant improvements in HbA1c in 9 out of 10 studies that reported it with mixed results for short-term blood glucose, cholesterol and weight. The heterogeneity of studies – which included all types of cell phone intervention and was dominated by text-message-based (SMS) solutions – precluded systematic synthesis of process of care measures like convenience and satisfaction but the authors did suggest these were generally favourable. The review did not recognise the six studies that involved some form of phone-accessible software as a distinct intervention category and the focus

on cellular phones excluded the broader range of mobile devices. Because the review was based solely on MEDLINE data and was restricted to RCTs, quasi-experimental and pre-post designs, relevant studies may have been overlooked. A similar review by the same authors looking at cell phone use for chronic conditions more generally had the same limitations [249].

Russell-Minda et al. (2009) [250] performed a systematic review of studies examining health technologies for monitoring and managing diabetes up to 2008. While they identified cell phone-based interventions as a distinct category, these were primarily SMS-based. Two studies involved app-supported interventions. Kumar et al. (2004) [251] examined the impact of a game add-on to a PDA based diabetes management software on data collection and outcomes. Knowledge improved and more data were submitted when the game was used but there was no significant change in HbA1c. In the second, included in the current review, Quinn et al (2008) [16] reported results of small pilot (n=30) of an app for type 2 diabetes. They found the intervention to be acceptable to clinicians as well as improvements in HbA1c associated with changes in insulin doses in those using the management software compared to controls.

Polisena et al. (2009) [252] examined home telehealth for diabetes management and identified two studies out of 21 in which cellular apps were used for data collection. A Chinese study comparing an intervention based on electronic diary with feedback against usual care found a non-significant improvement in HbA1c [252]. Separately, Vähätalo et al. (2004) [253] (included in the current review) evaluated a cell-phone software extension allowing patients to submit glucose readings to a clinician and found higher rates of recording but no impact on HbA1c outcomes. The search strategy requirement that studies index both of the terms 'home' and 'telehealth' may have limited the scope for identifying mobile device studies nor were apps were not identified as distinct intervention category within this review.

More recently, Peterson (2014)[254] examined 14 reports of mobile tools for type 1 diabetes management and found one study (of 14) evaluating the additional benefit of tailored feedback in addition to self-care using a mobile phone. Peterson concluded that the results offered some evidence for improved glycaemic control, echoing findings of earlier meta-analysis Liang et al. (2011)[255] which identified a mean excess reduction in HbA1c (a measure of glycaemic control) of 0.3% (95% CI 0.0 to 0.5% from 11 studies) in patients using a mobile intervention. Liang also examined studies addressing type 2 diabetes and found greater evidence for benefit, with a mean reduction in HbA1c of 0.8% (95% CI 0.5 to 1.1%). The meta-analysis incorporated 5 studies examining mobile medical apps for self-care, but no subgroup analysis differentiated these from other delivery mechanisms. The findings differed, however, from a review of type 1 and 2 diabetes studies

performed by Baron et al. (2012)[256] which was equivocal, citing methodological issues in included studies, but identified 8 reports of app-supported interventions.

For asthma, McLean et al. (2010)[168] evaluated telehealth interventions and identified one study in which a mobile technology (SMS) was used to support individuals, but no app-supported interventions. The review concluded that telehealth may be of benefit for individuals with more severe asthma at risk of hospital admission but questioned the value of telehealth in those with mild disease.

The findings above highlight a number of gaps to which the work presented in this chapter is directed:

- A lack of reviews examining the impact of mobile technology on asthma, specifically.
- A lack of reviews focussing only the effect of apps on mobile devices, which may operate substantially differently from communication-based modalities such as SMS.
- Inconsistencies in the conclusions of recent reports combining different technologies, recommending further work.
- Conduct limitations, such as the use of only the MEDLINE citation database to identify studies, potentially omitting relevant research.
- The importance of explicitly considering quality issues when synthesising reports of app-supported interventions.

4.3 Review-specific objectives

The primary objective of the combined reviews was to assess the impact on quality-related outcomes of app-supported interventions supporting self-care by individuals with asthma and diabetes.

Relevant outcomes were those falling within any of the six IoM quality domains articulated in chapter two. Because a broader purpose of the work was to explore the state of current knowledge, these were not pre-specified. However, anticipated measures included those relating to clinical effectiveness, patient-centred impacts such as self-related quality of life, intervention acceptability, cost effectiveness and safety.

Secondary objectives were:

- To explore whether the impact of app-supported interventions can be sustained in the medium or longer term.

- To identify aspects of the design and implementation of app-supported self-care interventions that maximise the likelihood of desired outcomes.
- To identify gaps in knowledge relevant for broader the thesis discussion about the feasibility of integration of self-care apps into routine care.

4.4 Methods

Systematic review conduct was informed by the process devised by the Cochrane Collaboration which emphasises methods to control bias during study selection and extraction, formal assessment of bias in included studies and reporting transparency[257].

4.4.1 *Study searches*

Scoping searches conducted in January 2012 highlighted a contemporary lack of standard terminology and keywords in intervention studies addressing mobile apps. Potentially eligible studies were also located in both medical and information technology literature. Together these recommended a broad-based strategy to maximise search sensitivity (at the potential expense of specificity necessitating manual review of large numbers of citations). A three-component Boolean search strategy was devised containing terms addressing mobile health; mobile devices and software, respectively. The complete search plan is documented in Appendix 2. Searches were not restricted by language, setting, study design or condition focus (these were applied during subsequent screening). Documents written prior to 1992 were not included because neither smartphones nor personal digital assistants existed prior to this date[1].

Structured Boolean searches were conducted using the following electronic databases:

- *Medically-focussed resources*

  MEDLINE, EMBASE, PsycINFO, CINAHL, CENTRAL, the Cochrane Library, CAB Direct Global Health, WHO Global Health Library

- *Information technology-focussed resources*

  ACM Digital Library, IEEExplore, Compendex (Engineering Index),

- *General resources*

  CiteSeer^{X}, ProQuest Dissertations, ERIC, Google Scholar

In addition, manual searches were performed to identify other potentially relevant studies:

- Mobile Active, a user-populated directory of mobile health solutions (now defunct).
- The reference lists of included studies and related systematic reviews.
- The personal web pages of study authors.
- Pilot studies and those reporting ongoing work were followed-up by contacting study authors to see if more recent or final data had subsequently been published.

Search results were staged using reference management software (EndNote X4, Thomson Reuters Corporation, New York, USA) and merged to remove duplicate records of the same report.

4.4.2 *Study selection*

Eligible studies were those satisfying criteria defined under five domains addressing the research population, intervention design, comparisons, outcomes and study methods (collectively 'PICOS'). These are summarised in Table 4-1 and described in detail below.

Table 4-1 **Summary of study eligibility criteria**

Population	Studies including individuals from any demographic background with either type 1 or 2 diabetes mellitus or asthma, in any setting (healthcare or otherwise)
Intervention	Studies evaluating any type of self-care intervention involving a mobile (e.g. targeting smartphone or tablet) medical app
Comparisons	Studies comparing intervention versus usual care (including routine self-care)
Outcomes	Studies reporting outcomes relevant to effectiveness, cost-effectiveness, acceptability, patient-centredness, timeliness, equity and safety.
Study types	Experimental study designs. Qualitative studies developing the findings of linked experimental studies.

Population

Eligible studies were those incorporating individuals with type 1 or type 2 diabetes or asthma, whether exclusively or as an analysable subgroup. It was felt to be infeasible to require that diagnosis be confirmed according to a normative definition of each condition. Participants were therefore included on the basis of whatever diagnostic criteria were established by each study. No participant was excluded on the basis of any other socio-demographic characteristic (e.g. age; gender; ethnicity; marital status; geographic location; employment status; education; income or health status). The review also considered interventions intended for used by someone acting in place of a patient, such as a patient or carer, but in practice no such studies were found.

Intervention

Eligible interventions were those defining self-care as the content of the intervention and using a mobile medical app. Operational criteria were defined for each of these elements:

- *Self-care content*

  Any intervention intended to support any aspect of self-care behaviour recognized for asthma (see section 2.4.2 above), such as action plan and peak flow-based treatment self-titration, or diabetes (see section 2.5.2 above), such as engaging in exercise.

- *Mobile medical app*

  Any discrete piece of software accessible wholly through a mobile device, whether or not the software was installed on that device (e.g. software accessible through a web browser on a mobile phone). Interventions using a mobile phone only as transmitter for data for clinical review, rather than offering interactive features intended for patient use, were not included. Apps did not need to be available from a public app store. Studies were included regardless of whether the app was the sole means by which an intervention was delivered or where it was supplemented by other components, such as telephone support.

- *Mobile device*

  Any consumer-grade mobile device available commercially at the time of study conduct, such as smartphones, feature phones or personal digital assistants (PDA). The rationale for inclusion of older device types was that the numbers of studies addressing only post-2007 smartphones was likely to be small, and that such devices share characteristics identified as modifiers of how app-based interventions might work (portable, instant-on, always-carried, see section 2.2.2 above). Reflecting the pragmatic focus on the feasibility of intervention implementation, experimental hardware, such as 'artificial pancreas' systems, bespoke devices or studies of consumer hardware that had been physically modified were not included.

No restrictions were placed on the setting within which interventions were offered or received.

Comparisons

Eligible studies compared app-supported interventions with controls based on usual care incorporating standard self-management practices. Because the focus of the current work was to explore the benefit apps might offer over routine methods of supporting self-care, the small number of studies comparing apps with other novel intervention modalities (n=4) were not included.

Outcomes

Outcomes were not pre-specified, but were required to relate to the six IoM domains of quality. Scoping work identified potential outcomes within each domain (these were not used to restrict analysis but are provided here for illustrative purposes):

- Effectiveness, measured by:
    - Impact on clinical disease control with predictive impacts on disease outcomes such as percentage of glycosylated haemoglobin (HbA1c) in diabetes, or peak flow in asthma.
    - Patient reported impacts on symptoms and self-care behaviours.
    - For asthma: utilisation of health services, a key indicator of disease control. For diabetes this is less commonly reported as an outcome. Unplanned service utilisation also overlaps with issues of safety.
- Cost-effectiveness, quantitating comparative per-patient (or similarly standardised) costs of real-world intervention delivery compared to usual care.
- Patient-centred care, measured using patient-reported instruments such as self-rated quality of life and self-efficacy.
- Equity, measured by patient-reported assessments of acceptability segregated according to differing health status and demographic background.
- Safety, measured by adverse events relating to the intervention, such as hypoglycaemic episodes in diabetes, and unplanned utilisation of emergency care for both conditions.
- Timely processes of care, measured by ability to access support promptly enabled by intervention compared to usual care.

Because of the risk of error arising from bespoke measures of health status, patient-reported outcomes were only included if they had undergone validation.

Study types

Study selection aimed to minimise false inferences arising from the risk of bias inherent in particular research designs by excluding studies without randomisation or an independent control group for comparison. Randomized crossover studies were included but only the first period analysed to eliminate the possible impact of carry-over effects between intervention and control periods. In addition, any linked qualitative studies describing either the development, or analysis of the effects, of trials satisfying the criteria above were also included with the intention of being able to provide

a richer account of factors influencing the effectiveness of app-based interventions. In practice, only accounts of intervention development were identified.

Study selection followed the process established by the Cochrane Collaboration and was partitioned into two phases. An initial screening process reviewed study titles and abstracts to eliminate obviously irrelevant articles. A subsequent review of the full text of retained studies was used to identify the final set of studies for inclusion in the review. To minimise error and selection bias, both stages were performed by at least two researchers (see section 4.4.6 below), working independently. To ensure consistency, a standardised decision tree was used to structure both stages of selection (Appendix 3) and an initial pilot was performed using a sample of 100 citations. Any disagreements about study eligibility were resolved by discussion.

4.4.3 *Data extraction*

Study data were extracted using a structured form to capture details of the study methods, participants, intervention design and outcomes. Components of the extraction process are summarised in

Table 4-2 (detailed description of data items in Appendix 4). Extraction was performed by pairs of reviewers, working independently, whose data were then reconciled to eliminate errors. Data were extracted into a common grid (Microsoft Excel 2013, Microsoft Corporation, Redmond, Washington, USA) for subsequent analysis.

Table 4-2 **Overview of information extracted from included studies**

General information	• Title • Authors • Source and publication status • Date published • Language • Date of review
Study methods	▪ Aim of study ▪ Study design ▪ Method of recruitment and setting ▪ Inclusion and exclusion criteria ▪ Details of control and comparison groups ▪ Incentives for participation
Risk of bias assessment	See section 4.4.4 below
Participants	▪ Description ▪ Geographic setting ▪ Place where intervention delivered ▪ Study numbers (at recruitment, eligibility screening, randomisation and follow-up, by intervention group), details of power calculation ▪ For the pooled set of participants (pooled controls and interventions): - Demographic characteristics (mean age; %female; %BME groups) - Disease characteristics - Comorbidities ▪ Assessment of baseline imbalance between groups
Providers	▪ Details of the health care worker(s) or systems responsible for providing or supporting the app
Intervention	▪ Name ▪ Hardware and software technologies used ▪ Key software functions ▪ Software installation process ▪ Main receiver of intervention (patient; carer; healthcare worker) ▪ Mode of data entry (manual; wireless e.g. from a connected monitoring device; etc.) ▪ Training offered to patients ▪ Frequency, duration and intensity of interaction with intervention ▪ Other intervention components ▪ Security arrangements ▪ Measures of adherence and protocol deviation
Control	▪ Nature of control group care
Measurements	▪ Details of measurement instruments and unit systems ▪ Quantitative details of outcomes concerning:

- Within-group changes in mean values between baseline and conclusion of study assessed for intervention and control groups separately
- Between-group differences between intervention and control in mean values assessed at the conclusion of the study period

▪ All measures were extracted with associated statistical uncertainty, if reported.

4.4.4 *Study quality appraisal*

In addition to content extraction, the quality of included studies was evaluated in order to identify issues potentially impacting interpretation of their findings. Assessment of experimental studies was performed using a modified version of the Cochrane Collaboration's tool for assessing the risk of bias[257] which examines five domains:

- Selection biases arising from either inappropriate methods for randomisation (random sequence generation) or visibility of the allocation of patients to intervention or control group enabling potential manipulation of allocation (allocation concealment)
- Performance bias when participants or personnel (or both) are un-blinded to intervention or control status during study execution, enabling potential manipulation. Blinding is not possible for technology-based interventions and so this domain was not assessed.
- Detection bias when study investigators are not blinded to group allocation during analysis, which may influence the way data are handled.
- Attrition bias when the reasons that individuals leave the study may be related to aspects of the intervention under study and subsequent analysis does not adequately compensate for these, for example through imputation.
- Reporting bias when one or more planned outcomes is not reported, raising the prospect that unfavourable data have not been reported.

The risk of bias was evaluated for each domain separately and summarised as either 'low' (indicating a low risk of bias), 'high' (indicating a high risk of bias) or 'unclear' (indicating an uncertain risk of bias). In addition, studies were evaluated for their incorporation of a sample size calculation, ethical approval and disclosures of funding sources. As for screening and data extraction, quality assessment was performed by pairs of researchers (see section 4.4.6 below), working initially independently. Where study processes were insufficiently described to assess bias or protocol

deviation, the original study protocol was requested from the study authors. The possibility of reporting biases at the publication level was also explored when evaluating whether to combine quantitative outcomes for meta-analysis (see section 4.4.5.2 below).

4.4.5 *Synthesis and reporting*

The study selection process was summarised using an adapted PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-analyses) flowchart. Studies excluded after initial were detailed in a table of characteristics of excluded studies that includes the reason for exclusion. Multiple reports of the same research were combined into a single unit for analysis.

A narrative synthesis incorporating simple descriptive statistics was used to summarise the characteristics of included studies, participants and interventions, grouping studies by condition and, where appropriate, intervention types. Qualitative study outcomes were also reported in this way.

Quantitative study outcomes were analysed by converting data to a common effect size, assessing the validity of generating a pooled effect estimate by combining data in a meta-analysis and, if appropriate, generating the pooled estimate. These steps are discussed further below.

Effect size standardisation

To enable comparison and discussion, mean within-group and between-group measures were standardised. For clinical measures, such as blood glucose, this involved unit conversion, if required, to SI units to enable mean differences observed for these outcomes to be reported in their native scales. For patient reported outcomes and other instruments involving non-standard scales, mean comparisons were converted to the standardised mean difference (SMD, Cohen's D [258]) to facilitate comparison across instruments with different ranges and score variances. Effect size standardisation also addressed differences in the direction of patient reported outcome scales such that, in presented data, greater positively-valued numbers are always associated with greater clinical or patient-reported benefit. (This convention is not applied to clinical measures, such as weight.) Measures of uncertainty, such as standard errors and confidence intervals were converted to the standard deviation (SD) for reporting.

Feasibility of meta-analysis

For each outcome, the possibility of generating a pooled estimate of effect was considered. The following criteria informed the decision whether to perform a meta-analysis or not:

- The availability of at least two studies without substantial risk of bias identified during quality assessment;
- The extent to which diversity of population and intervention characteristics within applicable studies would challenge a common estimate of effect;
- Statistical evidence for heterogeneity generated by calculating the I^2 statistic [259]. A result greater than 0.5 was considered as indicating a violation of homogeneity recommending that meta-analysis not be conducted;
- Where more than ten studies were available, evidence for publication bias at the study-level (e.g. non-reporting of unfavourable data) explored visually using a funnel plot of the mean difference against its standard error [260] . When fewer than ten studies were present, it was assumed that publication bias could exist [261] and a funnel plot was not performed.

In practice, limitations in the number of outcomes (and studies) satisfying these criteria meant that meta-analysis was ultimately only performed for two outcomes, both for diabetes: HbA1c and weight.

Meta-analysis procedures

Meta-analysis was performed using an inverse variance random-effects model[262]. To assess the robustness of the pooled effect estimate, sensitivity analyses were performed to explore the impact of any discrepant intervention or participant characteristics. For HbA1c, a *post hoc* subgroup analysis was also performed to compare the effect of interventions including professional feedback with those involving only automated interaction because the requirement for human intervention may substantially impact the feasibility and cost of app-supported interventions.

4.4.6 *Contributions of other researchers*

I developed the original study protocols and search strategy for the reviews. In order to make the subsequent review process tractable, work was divided by condition. I led the conduct of the diabetes-specific review, while the asthma-specific review was coordinated by a colleague and fellow PhD student, José Marcano Belisario (JMB). To satisfy the requirement for dual independent study selection, data extraction and quality appraisal, both reviews involved contributions from a number of additional colleagues. For the diabetes review, I was assisted in these aspects of the review process by colleagues Lambert Felix, Michelle van Velthoven and Lucinda Cash-Gibson. For the asthma review, colleague Geva Greenfield also assisted selection and extraction in addition to

myself and JMB. Oversight of the studies was provided by my supervisor, Josip Car and colleague Laura Gunn.

The asthma-specific review has been published as a Cochrane review:

> Marcano Belisario JS, Huckvale K, Greenfield G, Car J, Gunn LH: Smartphone and tablet self management apps for asthma. Cochrane Database Syst Rev 2013, 11.

The analysis of diabetes studies and the combined synthesis presented in this chapter is my work alone.

4.5 Results

4.5.1 *Search results*

Searches were originally performed in January 2011 (for diabetes) and June 2012 (for asthma) and updated in April 2015. Figure 4-1 shows the combined study selection process. From an original pool of 17013 unique studies, 31 published reports[16, 263-288] [71, 289-291] of 15 unique studies (n=13 diabetes, n=2 asthma) were ultimately selected for inclusion in the review.

Of the 57 reports excluded at full-text review, almost half (n=27) did not employ a randomised study design and a sixth (n=10) described a mobile intervention using a technology other than apps, such as SMS. In ten cases there was insufficient information to evaluate the study despite attempts to obtain clarifying information. Details of excluded studies are provided in Appendix 5.

4.5.2 *Characteristics of included studies*

Study design

Basic design characteristics of the included studies are summarised in Table 4-3. The majority of studies (n=11/13 diabetes, n=2/2 asthma) were randomized controlled trials. Two studies, both for diabetes, used an alternative design (n=1 cluster randomised controlled trial, n=1 randomised crossover study, for which the first period only was analysed). Study duration ranged from 3 to 13 months (mean 7 months, median 6 months).

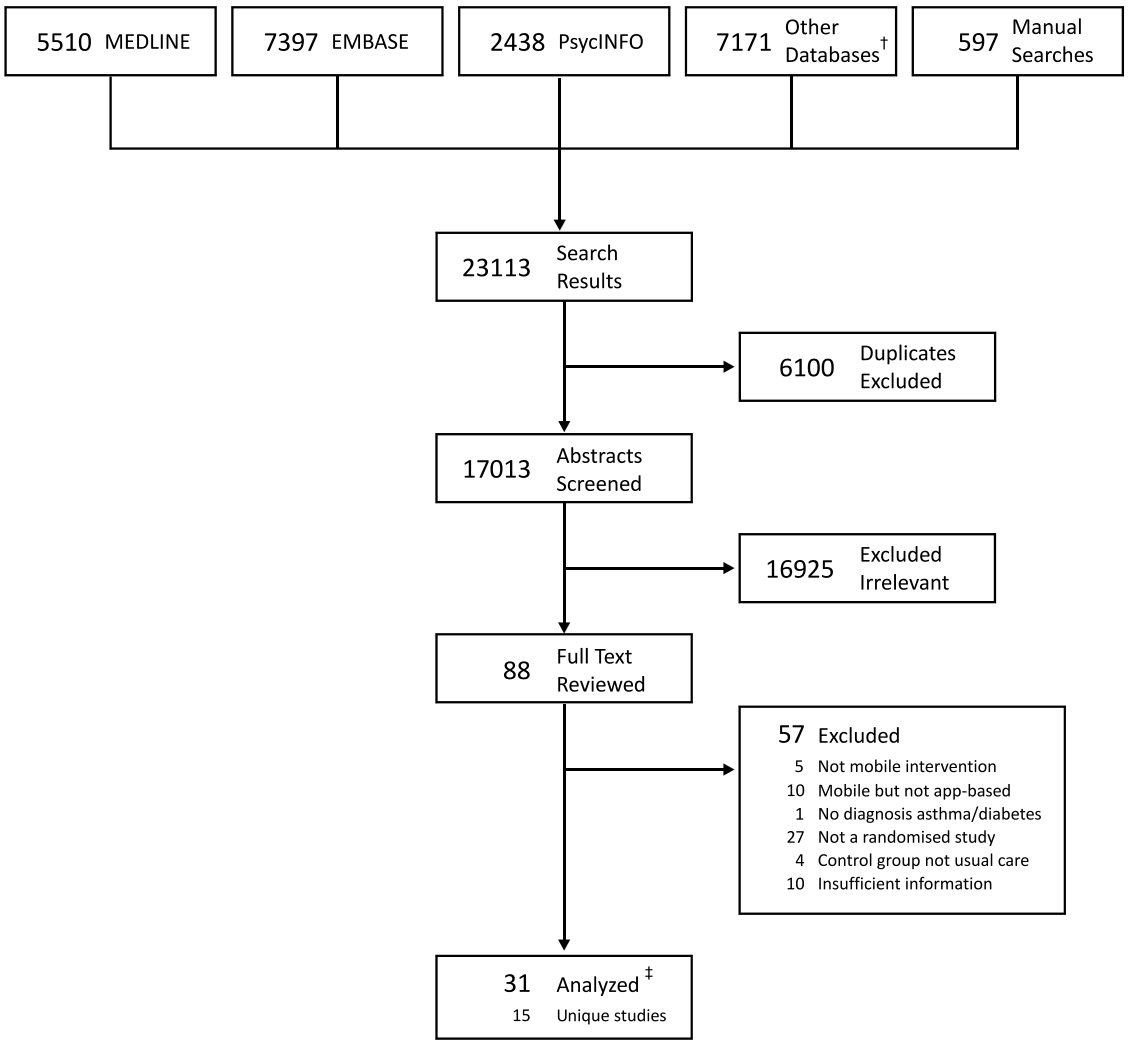


Figure 4-1 **Study selection flowchart**

† Other database search results: ProQuest n=486, ERIC n=238, Global Health Library n=830, IEEExplore n=391, ACM n=1198, CAB n=1193, CINAHL n=1955, CiteSeerX n=99, Cochrane n=169, Compendex n=423, CTR n=189

‡ Analysed: Diabetes n=27, Asthma n=4, Unique studies: Diabetes n=13, Asthma n=2

Participants

Details of participants are summarised in Table 4-4. Included studies incorporated 2239 participants (mean=149, median=137, range=20-298). Of thirteen studies addressing diabetes including 1831 individuals, participant numbers were approximately balanced between six focussing only on type 1 diabetes (n=870 participants) and five on type 2 diabetes (n=804). Two studies (n=157 participants) did not restrict participants by diabetic type and it was not possible to disaggregate individuals by condition. Participants in the diabetes studies had a mean average baseline Hba1c of 8.52%±0.55 SD

(n=13, range = 7.49 to 9.28, median 8.48), indicative of minimally poorly controlled diabetes. The mean number of years after diagnosis for diabetes, an indicator of likely comorbid burden, ranged from 6.6 to 23.0 years (n=13, mean of means = 13.6±4.86 SD, median 13.1). Eight studies incorporated participants with known diabetes-related complications, such as neuropathy and retinopathy. Two studies for asthma included a combined number of 408 participants. No metric equivalent to years since diagnosis was reported for individuals with asthma, however both studies attempted to recruit participants with poor or difficult-to-control asthma. Ryan et al. (2012)[71] selected participants based on a self-rated symptom score of greater or equal to 1.5 on the Asthma Control Questionnaire, indicative of poor control. Liu et al. (2011)[291] did not define precise criteria for participant selection of those with 'moderate-to-severe persistent asthma', however mean baseline peak flow was measured at 351.11±59.97L/min, a low value even after controlling for differences in gender and body size.

The mean age of participants ranged from 32[280] to 59[281] years (mean of means = 46, median = 49). No intervention exclusively targeted children or adolescents, and most studies (n=14/15) excluded children. In their study of an app-supported intervention for asthma, Ryan et al. (2012)[71] incorporated adolescents (aged 12 or over) in addition to adults. Although at an aggregate level study recruitment was balanced by gender (mean of means = 51% female, median = 52%), the proportion ranged from 36%[281] to 65%[16].

Half (n=6/13) of studies for diabetes were conducted in European centres (n=2 France, n=1 Italy, n=1 Norway, n=1 UK, n=1 multicentre Italy/Spain/UK), and four took place in the USA. Of the remaining three studies, one was based in Australia, one in China and one in South Korea. Of the two studies for asthma, one was UK-based and the other recruited participants in Taiwan. Of the five studies that provided information about recruitment by ethnic group, two involved majority White study populations[71, 288], one a majority Black population[16], and two were approximately equitable between recruitment of either Black and White[264], or Asian, Black and White[269], participants, respectively.

Interventions

The 15 studies involved 12 distinct app-supported intervention strategies (Table 4-5). In three cases, involving six studies[16, 264, 273, 276, 277, 281], the same intervention for diabetes was evaluated in a second population and these studies were treated as separate units for analysis.

Half of studies (n=7/15, all for diabetes) were based on a commercially-available smartphone. Six (n=4/13 diabetes, n=2/2 asthma) used an older generation feature phone, and two diabetes studies

were based on a personal digital assistant (PDA). In most cases (n=13/15), participants were supplied with a device, rather than using their own mobile phone. However, one diabetes study was conducted solely using participants' own devices[292], and both studies of asthma (n=2) allowed participants to use a personal device if compatible with the app being evaluated[71, 291], although the proportion of participants such devices was not reported. Only three apps, iBGStar, Glucose Buddy and WellDoc for diabetes were available in public app stores.

All studies incorporated a basic intervention design involving self-monitoring of one or more condition-specific parameters, entered into an app, based on which participants could make decisions about their treatment. Autonomous decision making was augmented, in most cases, with feedback generated either automatically (n=6) or involving support form a health professional (n=2) or both (n=5). Automated feedback strategies ranged from simple strategies, such as flagging of out-of-range values (n=3), to those offering specific dose adjustment recommendations (n=6). Clinician feedback was provided either promptly through messaging services (n=5), such as SMS, or through scheduled contacts (n=3). Most studies incorporating remote monitoring included provisions for emergency intervention, irrespective of their routine management protocol.

No study reported a theory-informed approach to intervention design, although Quinn et al. (2011) [264] used the Diabetes Stages of Change model [293] to assess intervention impact on participant readiness to change their health-related behaviours. For diabetes, the most commonly collected parameters were blood glucose (n=12/13), information about carbohydrate intake (n=11/13) and physical activity (n=7/13). Smaller numbers of apps also collected information about insulin dose (n=5/13), other medication use (n=4/13), weight (n=2/13) and blood pressure (n=1/13). Both studies of asthma apps collected information about peak flow, symptoms and inhaler dose, while Liu et al. (2011)[291] also incorporated self-reported assessment of impact on daily activities. In most cases, data collection relied on manual entry by individuals, however four diabetes studies supported either wired (n=1) or wireless (n=3) automatic transfer of blood glucose measurements from a sensor device into an app for analysis.

Interventions varied in the extent to which they established expectations about the frequency of data collection. For diabetes, over two thirds (69%, n=9/13) either did not provide guidance to participants (n=7) or advised participants to follow practices recommended by their usual clinician. Two studies asked patients two monitor blood glucose at least twice daily, one diet-focussed study required data to be recorded at every meal, and one study adopted a tailored approach to establishing a monitoring schedule. For asthma, participants were asked to monitor their condition either daily (n=1/2) or twice daily (n=1/2). Three fifths of studies (60%, n=9/15) included app-based

Table 4-3 **Design and recruitment characteristics of included studies**

					Numbers randomised					
					App-supported intervention			Control		
Study	**Condition** [a]	**Study type** [b]	**Duration** [c]	**Numbers recruited**	n	Completed (%) [d]		n	Completed (%)[d]	
Charpentier et al. (2011) [277-279]	T1	RCT	6M	180	60	56	(93%)	61	60	(98%)
Franc et al. (2014) [281]	T2	RCT	13M	190	64	64	(100%)	63	63	(100%)
Garg et al. (2014) [282]	T1	RCT	6M	100	50	50	(100%)	50	50	(100%)
Garg et al. (2008) [288]	T1	RCT	12M	123	61	42	(69%)	60	38	(63%)
Holmen et al. (2014) [283-286]	T2	RCT	12M	298	51	39	(76%)	50	41	(82%)
Istepanian et al. (2009) [269-272]	T1/T2	RCT	9M	137	72	48	(67%)	65	55	(85%)
Kirwan et al. (2013) [287]	T1	RCT	6M	197	36	25	(69%)	36	28	(78%)
Quinn et al. (2008) [16]	T2	RCT	3M	30	15	13	(87%)	15	13	(87%)
Quinn et al. (2011) [264-268]	T2	cRCT	12M	163	38	23	(61%)	62	56	(90%)
Rossi et al. (2010) [273-275]	T1	RCT	6M	143	67	58	(87%)	63	61	(97%)
Rossi et al. (2013) [276]	T1	RCT	6M	127	63	55	(87%)	64	57	(89%)
Tsang et al. (2001) [280]	T1/T2	Crossover	3M	20	10	10	(100%)	10	9	(90%)
Yoo et al. (2009) [263]	T2	RCT	3M	123	62	57	(92%)	61	54	(89%)
Liu et al. (2011) [291]	A	RCT	6M	120	60	43	(72%)	60	46	(77%)
Ryan et al. (2012) [71, 289, 290]	A	RCT	6M	288	143	116	(81%)	145	124	(86%)

· = Data not available (not collected or not stated in paper or not supplied by authors on request).

[a] Diagnosis: T1/T2 = type 1/2 diabetes, A = asthma

[b] Study type: RCT = randomized controlled trial; cRCT = cluster RCT, Crossover = randomized crossover trial (only first period analysed)

[c] Intervention duration, in months

[d] Numbers of patients retained in study at conclusion of intervention period.

Table 4-4 **Participant characteristics of included studies**

				Ethnicity							
Study	**n**	**Mean age [a]**	**% Female**	Asian	Black	White	Other [b]	**Setting**	**Condition**	**Mean dx [c]**	**Comorbidities**
Charpentier et al. (2011) [277-279]	180	33.8	63%	·	·	·	·	France	Type 1 diabetes	16.4	Clinical neuropathy, nephropathy, retinopathy
Franc et al. (2014) [281]	190	58.7	36%	·	·	·	·	France	Type 2 diabetes	13.1	·
Garg et al. (2008) [288]	123	32.8	54%	·	·	93%	·	USA	Type 1 diabetes	17.2	·
Garg et al. (2014) [282]	100	38.5	48%	·	·	·	·	USA	Type 1 diabetes	23.0	·
Holmen et al. (2014) [283-286]	298	57.0	41%	·	·	·	·	Norway	Type 2 diabetes	10.3	Foot ulcers, retinopathy
Istepanian et al. (2009) [269-272]	137	58.6	·	31%	31%	34%	0%	UK	Type 1/2 diabetes	12.5	Cardiovascular disease, nephropathy, retinopathy
Kirwan et al. (2013) [287]	197	35.2	61%	·	·	·	·	Australia	Type 1 diabetes	18.9	·
Quinn et al. (2008) [16]	30	51.0	65%	·	62%	38%	·	USA	Type 2 diabetes	9.3	Coronary artery disease, hyperlipidaemia, hypertension, microvascular complications
Quinn et al. (2011) [264-268]	163	53.0	49%	0%	47%	48%	5%	USA	Type 2 diabetes	8.4	Coronary artery disease, hyperlipidaemia, hypertension, microvascular complications
Rossi et al. (2010) [273-275]	143	35.7	57%	·	·	·	·	Multicentre [d]	Type 1 diabetes	16.5	Clinical neuropathy, lower-limb complications, nephropathy, retinopathy
Rossi et al. (2013) [276]	127	36.3	53%	·	·	·	·	Italy	Type 1 diabetes	15.6	Clinical neuropathy, retinopathy
Tsang et al. (2001) [280]	20	32.4	37%	·	·	·	·	China	Type 1/2 diabetes	8.4	·
Yoo et al. (2009) [263]	123	58.3	41%	·	·	·	·	South Korea	Type 2 diabetes	6.6	Hypertension, obesity
Liu et al. (2011) [291]	120	52.3	51%	·	·	·	·	Taiwan	Asthma	·	·
Ryan et al. (2012) [71, 289, 290]	288	49.0	63%	·	·	98%	·	UK	Asthma	·	Smoking

· = Data not available (not collected or not stated in paper or not supplied by authors on request).

[a] Mean age in years. [b] Chinese, mixed or other ethnicities. [c] Mean years since diagnosis. [d] Centres = Italy, Spain, UK.

Table 4-5 **Intervention characteristics of included studies**

	App-supported intervention							
Study	Name	Platform	Patients' device?	Data collection	Feedback mechanisms	Reminders	Other intervention components	**Control intervention**
Charpentier et al. (2011) [277-279] Franc et al. (2014) [281]	Diabeo	Smartphone	No	Items: BG (Manual), Diet, Physical Activity, Frequency: At Least Twice Daily	HCP feedback: None, Automated feedback: Insulin Dose Suggestion, Frequency: NS	Yes	Web Portal, Two HCP Visits	Paper-Based SMBG, Two HCP Visits
Garg et al. (2008) [288]	ACCU-CHEK Advisor	PDA	No	Items: BG (Manual), Insulin Dose, Diet, Frequency: NS	HCP feedback: No , Frequency: NS, Automated feedback: Insulin Dose Suggestion, Frequency: NS	·	Tailored Insulin Dosing Schedule, Multiple Study Clinic Visits	Usual Care, Multiple Study Clinic Visits
Garg et al. (2014) [282]	iPhone Plus BGStar (iBGStar)	Smartphone	No	Items: BG (Automatic), Insulin Dose, Diet, Medication, Physical Activity, Frequency: NS	HCP feedback: None, Automated feedback: BG Coding (Out of Range), Frequency: NS	Yes	iBGStar Meter	SMBG with ACCU-CHEK Nano Meter
Holmen et al. (2014) [283-286]	Few Touch Application (FTA)	Smartphone	No	Items: BG (Automatic), Diet, Weight, Physical Activity, Frequency: NS	HCP feedback: None, Automated feedback: BG Coding (Low/Normal/High), Frequency: NS	Yes	Goal Setting, Diabetes Information, Annual HCP Visit, Technical Support	Usual Care, Annual HCP Visit
Istepanian et al. (2009) [269-272]	Mobile Disease Management System	Feature Phone	No	Items: BG (Automatic), Frequency: Personalised Schedule	HCP feedback: Tailored Treatment Recommendation Letters, Frequency: NS, Automated feedback: None	Yes	Technical and Clinical Telephone Support, Data Sent, Usual HCP	Usual Care
Kirwan et al. (2013) [287]	Glucose Buddy	Smartphone	Yes	Items: BG (Manual), Insulin Dose, Medication, Diet, Physical Activity, Frequency: NS	HCP feedback: Tailored SMS, Frequency: NS, Automated feedback: None	Yes	Glucose Buddy Website, Usual Care, 3-Monthly HCP Visits	Usual Care, 3-Monthly HCP Visits
Quinn et al. (2008) [16] Quinn et al. (2011) [264-268]	WellDoc	Smartphone	No	Items: BG (Manual), Diet, Medication, Frequency: Per Usual HCP Recommendation	HCP feedback: Tailored Messages, Frequency: NS, Automated feedback: Insulin Dose Suggestion, Tailored	Yes	Web Portal, Patient Action Plans, Usual HCP Visits, Data, Usual	SMBG, Usual Care

Study	App-supported intervention							Control intervention
	Name	Platform	Patients' device?	Data collection	Feedback mechanisms	Reminders	Other intervention components	
					Messages, Frequency: NS		HCP (2008), Usual HCP Visits (2011)	
Rossi et al. (2010) [273-275] Rossi et al. (2013) [276]	Diabetes Interactive Diary (DID)	Feature Phone	No	Items: BG (Manual), Insulin Dose, Diet, Physical Activity, Frequency: NS	HCP feedback: Tailored Messages, Frequency: , Automated feedback: Insulin Dose Suggestion, Frequency: NS	·	Food Database, Diabetes Complications Information, Two-Way Messaging, As-Needed HCP Visits (2013)	Usual Care, Standard Education Program
Tsang et al. (2001) [280]	Diabetes Monitoring System (DMS)	PDA	No	Items: Diet, Frequency: Every Meal	HCP feedback: None, Automated feedback: Meal Composition Information, Frequency: NS	·	Manual Data Synchronisation	Usual Care
Yoo et al. (2009) [263]	Ubiquitous Chronic Disease Care System (UCDC)	Feature Phone	No	Items: BG (Semi-Automated), Weight, Blood Pressure, Frequency: Twice Daily (BG, BP), Once Daily (Weight)	HCP feedback: Tailored Messages, Frequency: NS, Automated feedback: Tailored Messages, Frequency: NS	Yes	SMS Exercise Logging, SMS-Based Healthy Diet and Exercise Information	Usual Care
Liu et al. (2011) [291]	Mobile Telephone-Based interactive Asthma Self-Care System	Feature Phone	If possible	Items: Peak flow (Manual), Symptoms, Inhaler Dose, Impact on Activities, Frequency: Daily	HCP feedback: None, Automated feedback: Assessment of Asthma Status, Frequency: NS	·	Self-Care Education, Web Portal, Data, Clinicians, Usual Clinic Visits	Self-Care Education, Action Plan, Daily Paper Diary
Ryan et al. (2012) [71, 289, 290]	t+Asthma	Feature Phone	If possible	Items: Peak Flow (Manual), Symptoms, Inhaler Dose, Frequency: Twice Daily	HCP feedback: Teleconsultation, Frequency: NS, Automated feedback: Peak Flow Coding (Traffic Light), Target Peak Flow, Frequency: NS	·	Web Portal, Action Plan, Self-Care Education, Monthly HCP Review	Twice Daily Paper Diary, Self-Care Education, Monthly HCP Review

· = Data not available (not collected or not stated in paper or not supplied by authors on request).

Abbreviations: BG = blood glucose, BP = blood pressure, HCP = Healthcare professional, NS = Not Specified

reminders to encourage participants to adhere to their recommended self-monitoring schedule (the remaining six studies provided insufficient information to determine if reminders were used). A similar proportion (n=8/15) also incorporated initial training to assist participants in learning how to record data and receive feedback, although reporting limitations in six studies may mean that the proportion receiving training was higher. In only one case[292] was training explicitly not provided, as part of a pragmatic evaluation strategy intended to assess the extent to which individuals could embark on self-monitoring without professional support.

Interventions adopted a combination of feedback strategies. Most (n=11/13 diabetes, n=2/2) incorporated an automated mechanism for providing feedback about supplied data. Four studies provided summary information about overall condition state, derived from data, by either annotating readings, for example by colour coding (n=2/13 diabetes, n=1/2 asthma), or providing an automatically generated textually summary of asthma status (n=1/2). Five diabetes studies also used user-supplied data in order to generate an insulin dose suggestion intended to guide therapy. One study used planned food intake information to provide feedback about meal composition as part of a dietary intervention for diabetes. Three diabetes studies generated additional automatic textual messages providing tailored guidance, motivational messages or general healthy living advice. Six studies incorporated some form of mechanism for human feedback by a study clinician (n=3) or a usual health professional (n=3). While a small number of apps (n=4) supported messaging functions, most professional feedback involved communication mechanisms external to the app, such as teleconsultations initiated by the health professional (n=2), messages sent by SMS (n=1) or letter (n=1). The frequency of professional feedback was rarely clearly specified, but most studies (n=3/5 where details provided) appeared to adopt an *ad hoc* approach in which professional intervention was used only to supplement self-monitoring and automated feedback when clinically indicated, such as in response to deteriorating condition control. Two studies did not incorporate any form of automatic feedback and relied on professional feedback instead.

While all studies constituted control groups based around accepted care practices, such as self-monitoring of blood glucose, studies varied in the extent to which these components were specified. Five studies (n=3/13 diabetes, n=2/2 asthma) precisely articulated components defining standard care. A further seven diabetes studies specified certain control group components, such as the requirement to attend visits with a healthcare professional (n=3), perform self-monitoring (n=2) or complete a standard education programme during study entry (n=2), but did not otherwise specify 'usual care'. Three studies of diabetes did not specify any additional components other than those

routines already engaged with by control-group participants and the monitoring requirements created by study participation.

4.5.3 *Quality assessment*

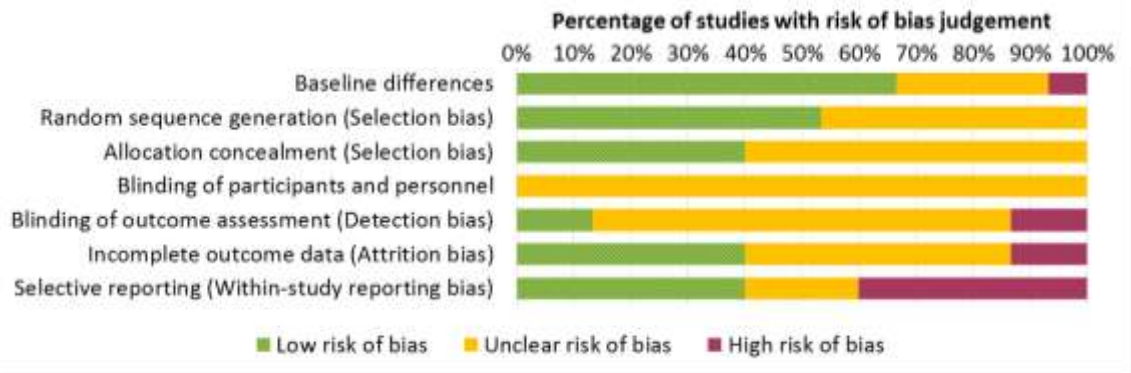


Figure 4-2 **Summary of risk of bias assessment of included studies**

Figure 4-2 summarises the results of the quality appraisal of included studies and Table 4-6 provides a per-study breakdown. Two thirds of included studies (80%, n=12/15) provided evidence permitting characterisation of differences between intervention and control groups at baseline. In all but one (n=11/12), reported participant characteristics were sufficiently similar to suggest a low risk of bias arising from differential selection. Although Kirwan et al. (2013)[292] was randomized, there was a significantly greater proportion of women and higher baseline HbA1c in the intervention group. Since incremental reductions in HbA1c are harder to achieve, this created a risk of bias for comparison of within-group changes in HbA1c, but not direct endpoint comparisons where the effect would likely be conservative. While no studies were judged at high risk of bias for the process of randomization of participants, assessment was limited by the availability of data. Just under half (47%, n=7/15) of studies did not provide a clear account of the process by which participants were randomized (sequence generation), and three fifths (60%, n=9/15) did not describe processes to protect the process from accidental or deliberate interference by study staff (allocation concealment). Just over half (53%, n=8/15) of studies detailed a power calculation to inform recruitment targets. In one asthma study, Liu et al. (2011)[291], a power calculation was not performed and two fifths (40%, n=6/15) did not provide enough information to assess strategies to control Type II error. The nature of app-based interventions made it impossible to blind either participants or investigators to allocation status during the study, however fewer than a third of studies (27%, n=4/15) detailed whether the process of data analysis was blinded. In two cases, Holmen et al. (2014)[283] and Quinn et al., (2011)[264], analysis indicated that blinding had not been

used. Similar variability was observed when it came to reporting. While two fifths (40%, n=6/15) of studies described an appropriate method to account for unexpected attrition or withdrawal of participants, such as intention-to-treat analysis, almost half (47%, n=7/15) did not provide adequate information and two studies (13%) described approaches that would put analysis at risk of bias. Garg et al. (2008) performed a complete case analysis, excluding any participants who did not complete the study protocol. Istepanian et al. (2009)[269] handled participant attrition by carrying forward last known measurements. Both approaches create a substantial risk of bias if, for example, participant attrition does not occur at random[294]. A higher proportion of studies failed to report all the outcomes study in study methods, protocol or trial registration. While two fifths (40%, n=6/15) studies provided complete reporting, the same proportion omitted data about at least one stated outcome. A fifth of studies (20%, n=3/15) did not clearly detail intended outcomes.

Two thirds of studies (67%, n=10/15) provided transparent declaration of funding sources with a low associated risk of bias, however one study, Garg et al. (2014)[282] received sponsorship from the manufacturer of the app under evaluation and was reported only in abstract form, without detail about the role of the sponsor in data analysis and reporting. Four studies (27%) omitted funding details. The majority of studies (87%, n=13/15) provided details indicating that ethics review had taken place. Two studies, Franc et al. (2014)[281] and Rossi et al. (2010)[273] lacked this information.

There was no clear pattern of differences in the quality of reporting between studies in asthma and diabetes. However, all of the studies judged at higher risk for outcome reporting, including both attrition and selective reporting biases, were performed in diabetes.

Table 4-6 **Risk of bias characteristics of included studies**

		Risk of Bias Domain										
Study	**Condition** [a]	Baseline differences	Random sequence generation (Selection bias)	Allocation concealment (Selection bias)	Blinding of participants and personnel	Blinding of outcome assessment (Detection bias)	Incomplete outcome data (Attrition bias)	Selective reporting (Within-study reporting bias)		**Funding sources clear**	**Study ethics approval**		**Sample size calculation**
Charpentier et al. (2011) [277-279]	T1	+	+	?	?	+	+	-		+	+		+
Franc et al. (2014) [281]	T2	?	?	?	?	?	?	-		+	?		?
Garg et al. (2008) [288]	T1	+	+	+	?	?	-	?		+	+		?
Garg et al. (2014) [282]	T1	+	?	?	?	?	?	-		-	+		?
Holmen et al. (2014) [283-286]	T2	+	+	+	?	-	+	-		+	+		+
Istepanian et al. (2009) [269-272]	T1/T2	+	+	?	?	?	-	?		?	+		+
Kirwan et al. (2013) [287]	T1	-	+	+	?	?	+	+		+	+		+
Quinn et al. (2008) [16]	T2	?	?	?	?	?	?	-		+	+		?
Quinn et al. (2011) [264-268]	T2	+	?	?	?	-	?	-		+	+		+
Rossi et al. (2010) [273-275]	T1	?	+	+	?	?	+	+		?	?		+
Rossi et al. (2013) [276]	T1	+	+	+	?	?	+	+		?	+		+
Tsang et al. (2001) [280]	T1/T2	?	?	?	?	?	?	+		+	+		?
Yoo et al. (2009) [263]	T2	+	?	?	?	?	+	+		+	+		?
Liu et al. (2011) [291]	A	+	?	?	?	?	?	?		?	+		-
Ryan et al. (2012) [71, 289, 290]	A	+	+	+	?	+	?	+		+	+		+

+ = Low risk of bias, ? = Unclear risk of bias, - = High risk of bias

[a] Diagnosis: T1/T2 = type 1/2 diabetes, A = asthma

4.5.4 *Outcomes*

Effectiveness

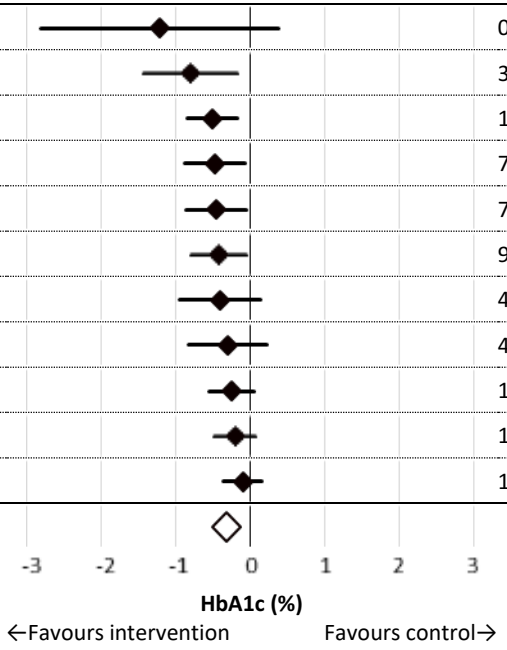
Included studies reported a range of clinically-relevant outcomes. Most studies of diabetes (85%, n=11/13) reported HbA1c as a primary outcome, with secondary measurements of both weight and lipid/glucose metabolism. The two studies of asthma reported utilisation of health services as key endpoints, although Liu et al. (2011) also reported the impact on peak flow.

Table 4-7 summarises the observed effect on HbA1c of app-supported interventions for diabetes. Intervention was associated with a significant reduction in HbA1c (mean of mean reductions -0.74%, range -1.60 to 0.00) in 8 of 11 studies reporting the outcome. In all studies, the direction of effect suggested a modest additional benefit of intervention over control, although at a per-study level, this difference was significant in only five studies. A random effects meta-analysis incorporating 1078 participants (n=529 intervention vs 549 control), justified by a low degree of statistical heterogeneity with an observed I^2 of 0%, demonstrated a combined effect of a 0.32% (95% CI -0.44 to -0.21, P < 0.001) improvement in HbA1c in intervention participants compared to controls. A sensitivity analysis showed this effect to be robust to exclusion of two studies at high risk of attrition bias, with a pooled effect in the nine remaining studies of a 0.33% reduction in HbA1dc (95% CI -0.46 to -0.19, P < 0.001). A second sensitivity analysis considering only those studies using smartphones released post 2007 (n=5) found no difference in effect (-0.41%, 95% CI -0.59 to -0.22, P<0.001, n = 218 intervention vs 256 control).

P*ost hoc* analysis suggested no clear difference in observed effects between studies incorporating patients with either type 1 (mean pooled effect favouring intervention -0.27%, 95% CI -0.43 to -0.12, P < 0.001, n=264 intervention vs 261 control from 5 studies) or type 2 diabetes (mean pooled effect -0.41%, 95% CI -0.61 to -0.21, P < 0.001, n=183 intervention vs 214 control from 4 studies). Comparison was also made between studies incorporating some form of remote feedback to patients to guide self-care (n=8) versus those where patients made treatment decisions without support (n=5). (In two studies, Charpentier et al. (2011)[277] and Holmen et al. (2014)[283] there were two separate subgroups that were disaggregated for this analysis but combined for the overall pooled estimate.) Although both groups experienced a reduction in HbA1c, there was no clear benefit for those receiving advice (-0.31%, 95% CI -0.46 to -0.16, P<0.001, n=482 intervention vs 466 control), compared to those without (-0.51%, 95% CI -0.72 to -0.27, P<0.001, n=170 intervention vs 204 control), where the magnitude of reduction was greater, although the difference was not significant. Analysis of six studies with apps incorporating automated insulin dose suggestion suggested no additional benefit, with a pooled reduction of HbA1c of -0.28% (95% CI -0.44 to -0.13, P<0.001, n=315 intervention vs 344 control).

Table 4-7 **Observed effects of app-supported interventions on HbA1c in patients with diabetes**

					Baseline versus endpoint, Negative change favours intervention					
					Within-group change App-supported intervention		Between-group change App-supported intervention versus control			
Study	**Dx [a]**	**Intervention [b]**	**T [c]**	**n [d]**	MD (95% CI) [e]	P Value [f]	MD (95% CI) [e]	P Value [f]	Forest Plot, MD (95% CI)	Weight [g]
Tsang et al. (2001) [280]	T1/T2	DI	3M	19	-1.01 (-2.77, 0.75)	0.263	-1.21 (-2.81, 0.39)	0.138		0.50%
Quinn et al. (2011) [264-268]	T2	SM+IDS+AF	12M	79	-1.60 (-2.44, -0.76)	<0.001*	-0.80 (-1.42, -0.18)	0.012*		3.30%
Yoo et al. (2009) [263]	T2	SM+PF+AF	3M	111	-0.50 (-0.81, -0.19)	0.002*	-0.50 (-0.84, -0.16)	0.004*		11.30%
Charpentier et al. (2011) [277-279]	T1	SM+IDS	6M	116	-0.49 (-0.88, -0.10)	0.013*	-0.47 (-0.88, -0.06)	0.023*		7.90%
Kirwan et al. (2013) [287]	T1	SM+PF	6M	72	-1.11 (-1.56, -0.66)	<0.001*	-0.46 (-0.86, -0.06)	0.026*		7.90%
Garg et al. (2008) [288]	T1	SM+IDS	12M	80	-0.73 (-1.11, -0.35)	<0.001*	-0.42 (-0.79, -0.05)	0.028*		9.30%
Holmen et al. (2014) [283-286]	T2	SM+AF	12M	80	-0.31 (-0.79, 0.17)	0.211	-0.40 (-0.94, 0.14)	0.145		4.50%
Istepanian et al. (2009) [269-272]	T1/T2	SM+PF	9M	137	0.00 (-0.49, 0.49)	1.000	-0.30 (-0.82, 0.22)	0.262		4.80%
Franc et al. (2014) [281]	T2	SM+PF+IDS	13M	127	-1.51 (-1.85, -1.17)	<0.001*	-0.25 (-0.55, 0.05)	0.104		14.20%
Rossi et al. (2013) [276]	T1	SM+PF+IDS	6M	127	-0.49 (-0.77, -0.21)	0.001*	-0.20 (-0.48, 0.08)	0.158		16.90%
Rossi et al. (2010) [273-275]	T1	DI+SM+PF+IDS	6M	130	-0.40 (-0.67, -0.13)	0.004*	-0.10 (-0.36, 0.16)	0.456		19.40%
Random effects model	n=529 intervention, n=549 control, heterogeneity: I^2 = 0%						-0.32 (-0.44, -0.21)	<0.001		



[a] Diagnosis: T1/T2 = type 1/2 diabetes

[b] Intervention content: DI = dietary intervention, SM = self-monitoring of blood glucose, IDS = insulin dose suggestions, AF = other automated feedback, PF = health professional feedback

[c] Measurement end point in months, equivalent, study intervention duration.

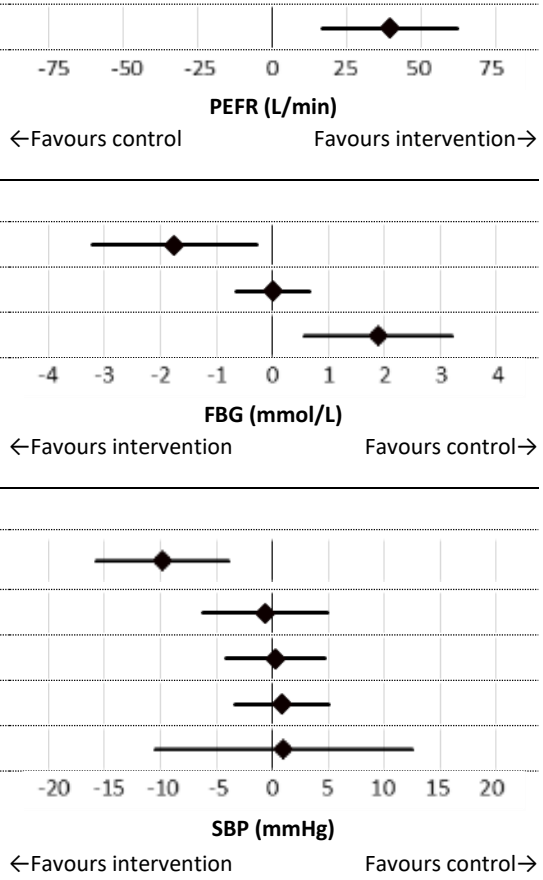
[d] Sum of individuals analysed in intervention and control groups.

[e] Mean difference, reported in native percentage units, with associated 95% confidence interval and [f] exact P value ('*' highlights values significant at the 5% threshold).

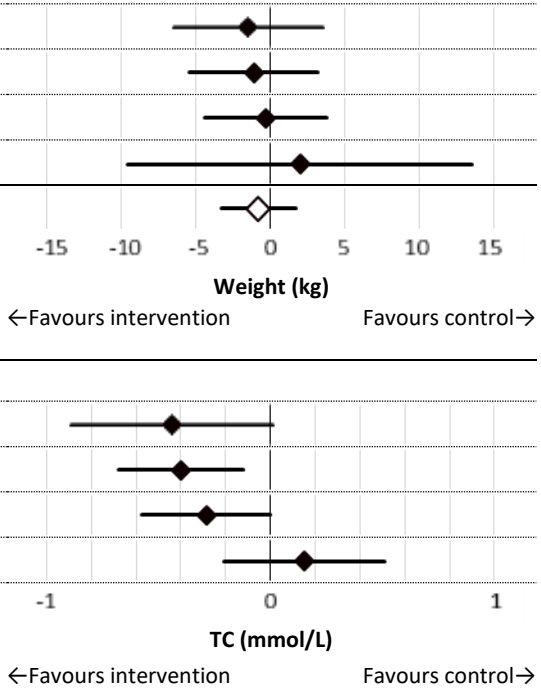
[g] Study weighting contributing, meta-analysis.

Table 4-8 **Observed effects of app-supported interventions on lung function, fasting glucose, weight, systolic blood pressure, cholesterol**

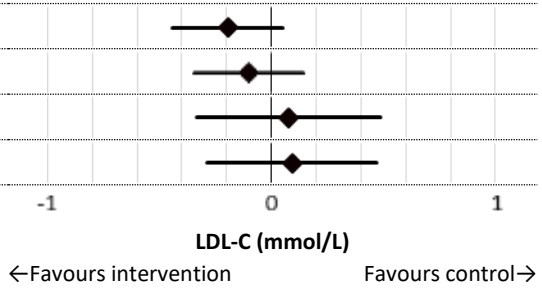
					Baseline versus endpoint, Negative change favours intervention				
					Within-group change App-supported intervention		Between-group change App-supported intervention versus control		
Study	**Dx [a]**	**Intervention [b]**	**T [c]**	**n [d]**	MD (95% CI) [e]	P Value [f]	MD (95% CI) [e]	P Value [f]	Forest Plot, MD (95% CI)
Peak expiratory flow rate (PEFR, L/min)									
Liu et al. (2011) [291]	A	SM+AF	6M	89	30.50 (4.20, 56.80)	0.023*	39.20 (16.58, 61.82)	0.001*	
Fasting blood glucose (FBG, mmol/L)									
Rossi et al. (2010) [273-275]	T1	DI+SM+PF+IDS	6M	130	-1.22 (-2.83, 0.39)	0.137	-1.75 (-3.23, -0.28)	0.020*	
Yoo et al. (2009) [263]	T2	SM+PF+AF	3M	111	-0.40 (-1.03, 0.23)	0.212	0.00 (-0.66, 0.66)	1.000	
Rossi et al. (2013) [276]	T1	SM+PF+IDS	6M	127	-0.09 (-1.56, 1.37)	0.910	1.89 (0.57, 3.22)	0.005*	
Systolic blood pressure (SBP, mmHg)									
Istepanian et al. (2009) [269-272]	T1/T2	SM+PF	9M	137	-6.50 (-11.43, -1.57)	0.010*	-9.80 (-15.72, -3.88)	0.001*	
Yoo et al. (2009) [263]	T2	SM+PF+AF	3M	111	-6.90 (-13.33, -0.47)	0.035*	-0.70 (-6.26, 4.86)	0.817	
Rossi et al. (2013) [276]	T1	SM+PF+IDS	6M	127	-0.72 (-4.89, 3.45)	0.748	0.30 (-4.13, 4.73)	0.903	
Rossi et al. (2010) [273-275]	T1	DI+SM+PF+IDS	6M	130	-0.80 (-5.13, 3.53)	0.731	0.80 (-3.38, 4.98)	0.721	
Quinn et al. (2011) [264-268]	T2	SM+IDS+AF	12M	79	4.00 (-8.59, 16.59)	0.545	1.00 (-10.48, 12.48)	0.874	



Study	Dx [a]	Intervention [b]	T [c]	n [d]	Baseline versus endpoint, Negative change favours intervention Within-group change App-supported intervention MD (95% CI) [e]	P Value [f]	Between-group change App-supported intervention versus control MD (95% CI) [e]	P Value [f]	Forest Plot, MD (95% CI)
Weight (kg)									
Rossi et al. (2013) [276]	T1	SM+PF+IDS	6M	127	0.38 (-4.61, 5.37)	0.890	-1.50 (-6.49, 3.49)	0.567	
Yoo et al. (2009) [263]	T2	SM+PF+AF	3M	111	-1.10 (-5.73, 3.53)	0.654	-1.10 (-5.41, 3.21)	0.629	
Rossi et al. (2010) [273-275]	T1	DI+SM+PF+IDS	6M	130	0.70 (-3.30, 4.70)	0.744	-0.30 (-4.38, 3.78)	0.894	
Holmen et al. (2014) [283-286]	T2	SM+AF	12M	69	-1.30 (-12.74, 10.14)	0.835	2.00 (-9.53, 13.53)	0.747	
Random effects model	n=220 intervention, n=217 control, heterogeneity: I^2 = 0%						-0.76 (-3.24, 1.73)	0.550	
Total cholesterol (TC, mmol/L)									
Quinn et al. (2011) [264-268]	T2	SM+IDS+AF	12M	79	-0.78 (-1.29, -0.26)	0.003*	-0.44 (-0.89, 0.01)	0.055	
Yoo et al. (2009) [263]	T2	SM+PF+AF	3M	111	-0.50 (-0.78, -0.22)	<0.001*	-0.40 (-0.68, -0.12)	0.005*	
Rossi et al. (2010) [273-275]	T1	DI+SM+PF+IDS	6M	130	-0.09 (-0.36, 0.17)	0.497	-0.29 (-0.57, 0.00)	0.049*	
Rossi et al. (2013) [276]	T1	SM+PF+IDS	6M	127	0.10 (-0.23, 0.42)	0.567	0.15 (-0.21, 0.51)	0.411	



Study	Dx [a]	Intervention [b]	T [c]	n [d]	Baseline versus endpoint, Negative change favours intervention Within-group change App-supported intervention MD (95% CI) [e]	P Value [f]	Between-group change App-supported intervention versus control MD (95% CI) [e]	P Value [f]	Forest Plot, MD (95% CI)
Low density lipoprotein cholesterol (LDL-C, mmol/L)									
Rossi et al. (2010) [273-275]	T1	DI+SM+PF+IDS	6M	130	-0.09 (-0.33, 0.16)	0.492	-0.20 (-0.44, 0.05)	0.121	
Yoo et al. (2009) [263]	T2	SM+PF+AF	3M	111	-0.40 (-0.64, -0.16)	0.001*	-0.10 (-0.34, 0.14)	0.428	
Quinn et al. (2011) [264-268]	T2	SM+IDS+AF	12M	79	-0.23 (-0.69, 0.22)	0.322	0.08 (-0.33, 0.49)	0.722	
Rossi et al. (2013) [276]	T1	SM+PF+IDS	6M	127	0.21 (-0.11, 0.54)	0.203	0.09 (-0.29, 0.47)	0.649	



[a] Diagnosis: T1/T2 = type 1/2 diabetes, A = asthma

[b] Intervention content: DI = dietary intervention, SM = self-monitoring of blood glucose, IDS = insulin dose suggestions, AF = other automated feedback, PF = health professional feedback

[c] Measurement end point in months, equivalent, study intervention duration.

[d] Sum of individuals analysed in intervention and control groups.

[e] Mean difference, reported in native percentage units, with associated 95% confidence interval and [f] exact P value ('*' highlights values significant at the 5% threshold).

Table 4-9 **Observed effects of app-supported interventions on healthcare utilisation**

Study	Dx [a]	Intervention [b]	T [c]	n [d]	App-supported intervention			Control			Odds Ratio (95% CI)		P Value
					n	with Outcome (%)		n	with Outcome (%)				
GP consultations													
Ryan et al. (2012) [71, 289, 290]	A	SM+PF+AF	6M	281	140	51	(36%)	141	41	(29%)	1.40	(0.85, 2.31)	0.188
Unscheduled primary care consultations													
Ryan et al. (2012) [71, 289, 290]	A	SM+PF+AF	6M	281	140	45	(32%)	141	62	(44%)	0.60	(0.37, 0.98)	0.039*
Unscheduled emergency department (A&E) attendances													
Liu et al. (2011) [291]	A	SM+AF	6M	89	43	2	(5%)	46	9	(20%)	0.20	(0.04, 0.99)	0.049*
Ryan et al. (2012) [71, 289, 290]	A	SM+PF+AF	6M	281	140	3	(2%)	141	0	(0%)	. [e]	.	.
Hospital admissions													
Liu et al. (2011) [291]	A	SM+AF	6M	89	43	1	(2%)	46	0	(0%)	. [e]	.	.
Ryan et al. (2012) [71, 289, 290]	A	SM+PF+AF	6M	281	140	3	(2%)	141	1	(1%)	3.07	(0.32, 29.88)	0.338
Acute exacerbations													
Ryan et al. (2012) [71, 289, 290]	A	SM+PF+AF	6M	281	140	43	(31%)	141	45	(32%)	0.95	(0.57, 1.57)	0.853
Steroid courses													
Ryan et al. (2012) [71, 289, 290]	A	SM+PF+AF	6M	281	140	28	(20%)	141	30	(21%)	0.93	(0.52, 1.66)	0.818

[a] Diagnosis: A = asthma

[b] Intervention content: DI = dietary intervention, SM = self-monitoring of blood glucose, IDS = insulin dose suggestions, AF = other automated feedback, PF = health professional feedback

[c] Measurement end point in months, equivalent, study intervention duration.

[d] Sum of individuals analysed in intervention and control groups.

[e] Odds ratio not estimable because of zero event rate in at least one group.

The impact of diabetes interventions on other biochemical measures (Table 4-8) was less consistent. No clear impact was seen in measurements on Fasting Blood Glucose (FBG) in three studies that reported this outcome. Rossi et al. (2010)[273] found a significant endpoint reduction in 1.75mmol/L (95% CI -3.23 to -0.28, P=0.020) in FBG at six months in intervention versus control. However, a 2013 study by the same authors[276] of a new cohort demonstrated the opposite, with a 1.89mmol/L (95% CI 0.57 to 3.22, P =0.005) excess FBG between intervention and control at six months. Yoo et al. (2009)[263] found no impact on FBG at 3 months (endpoint difference 0.00mmol/L, 95% CI -0.66 to 0.66, P = 1.0). In five studies reporting systolic blood pressure (SBP) as an outcome, three demonstrated minimal change with endpoint differences ranging from 0.30 to 1.00 mmHg. However, a significant within group reduction of -6.50mmHg (95% CI -11.43 to -1.57, P = 0.01) driving a relative improvement of -9.80mmHg (95% CI -15.72 to -3.88, P = 0.001) was observed by Istepanian et al (2009)[269], who incorporated blood pressure measurement and telemedicine-based blood pressure management feedback to patients in addition to blood glucose management. In Yoo et al., a within-group reduction of similar magnitude was seen in the intervention group (-6.90mmHg, 95% CI -13.33, -0.47, P = 0.035) but this was matched by improvements in control patients. The study demonstrated a 9.8mmHg (95% CI -15.72 to -3.88, P=0.001) improvement in SBP in intervention participants compared to control. No significant changes were observed in end point measurements of body weight in any of the four studies which reported this outcome. A random effects pooled analysis of n=220 intervention and n=217 control participants, justified on the basis of low heterogeneity (I^2 = 0%), demonstrated a non-significant reduction favouring intervention of -0.76kg (95% CI -3.24 to 1.73, P = 0.550). Significant improvements in total (TC) but not low density lipoprotein (LDL) cholesterol were observed into two of four studies incorporating diet in addition to glucose management. Yoo et al. demonstrated a relative reduction of -0.40mmol/L (95% CI = 0.68 to -0.12, P=0.005) in TC but of only -0.10mmol/L (95% CI -0.34 to 0.14, P = 0.428) in LDL cholesterol. Rossi et al. (2010) demonstrated an improvement of -0.29mmol/L (95% CI -0.57 to 0.00, P = 0.049) in TC but not in LDL cholesterol (0.08mmol/L, 95% CI -0.33 to 0.49, P = 0.722).

For asthma, Liu et al. (2011)[291] found a significant 39.20 L/min (95% CI 16.58 to 61.82, P = 0.001) improvement in the peak flow measurements of intervention group participants compared to control at 6 months. Both Liu et al. and Ryan et al. (2012)[71] reported indicators of healthcare utilisation as proxy outcomes for asthma control (Table 4-9). Liu et al. demonstrated a significant reduction in the number of patients with unscheduled emergency department attendances in intervention group patients (5%, n=2/43) versus control (20%, n=9/46) at six months (OR 0.20, 95% CI 0.04 to 0.99, P = 0.049). At six months, Ryan et al. experienced a lower attendance rate in the intervention group (2%, n=3/140) than Liu et al., but also experienced no events in the control group

(n=0/141), precluding statistical comparison. Ryan et al. quantified the number of patients with hospital admissions over the study period, and found no significant difference between intervention and control groups, who experienced low rates of 2% (n=3/140) and 1% (n=1/141) respectively (OR 3.07, 95% CI 0.32 to 29.88, P = 0.338). Liu et al. measured a similar rate in their intervention group (2%, n=1/43) but observed no admissions in their control group (n=0/46). In addition to hospital encounters, Ryan et al. also quantified primary care attendances. Almost two fifths (36%, n=51/140) of patients in the intervention group arranged a GP consultation for asthma compared to control (29%, n=41/141, OR 1.40, 95% CI 0.851 to 231, P = 0.188). Although the difference in routine consultations was not significant, the proportion of patients with an emergency attendance was significantly lower in the intervention group (32%, n=45/140) compared to control (44%, n=62/141, OR 0.60, 95% 0.37 to 0.98, P = 0.039).

Patient-centred outcomes

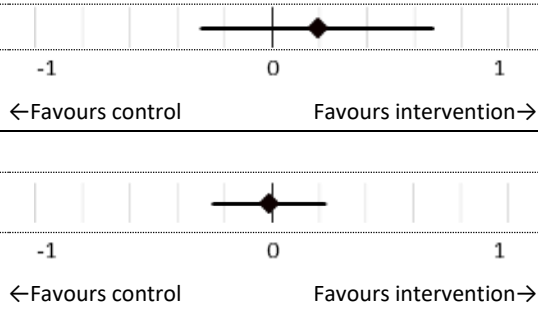
Two studies reported self-rated symptom perception scores (Table 4-10). Quinn et al. (2011)[264] found no significant improvement in standardized mean difference (SMD) in diabetes symptoms collected via a self-reported patient outcome instrument (validation data not found) at 12 months in patients with type 2 diabetes (SMD 0.19 intervention versus control, 95% CI -0.38 to 0.68, P =0.565). Similarly, Ryan et al. (2012) demonstrated no difference in asthma symptoms scored using the Asthma Control Questionnaire between intervention and control at 6 months (SMD -0.01 intervention versus control, 95% CI = -0.24 to 0.23, P = 0.942), although both groups experienced significant improvement (within group change SMD 0.86, 95% CI 0.62 to 1.11, P < 0.001).

None of three studies (n=2 type 1 diabetes, n=1 asthma) reporting overall quality of life demonstrated significant differences between intervention and control at six-month end points (Table 4-11). For Ryan et al. (2012)[71], a significant improvement in quality of life in intervention participants (SMD 0.66, 95% CI 0.37 to 0.95, P < 0.001), measured using the mini Asthma Quality of Life Questionnaire[295], was matched by improvements in the paper-based self-care control group. Ryan et al. observed a similar pattern for self-efficacy, measured using the KASE-AQ instrument [296], where a significant pre-post improvement was seen in intervention participants (SMD 0.47, 95% CI 0.21 to 0.74, P = 0.001), but without additional benefit over paper-based controls (SMD 0.13, 95% -0.12 to 0.39, P = 0.313).

Across seven studies assessing emotional impact, the results were substantially mixed. Two studies demonstrated significant improvements in emotional status at 6 months associated with app-supported care. In a study of type 1 diabetes, Kirwan et al. (2013)[292] found an SMD of 0.54 (95% CI 0.07 to 1.01, P=0.024) for emotional state measured using the Diabetes Quality of Life instrument favouring intervention over control. For asthma, Liu et al. (2011)[291] emotional state assessed using the disease-independent SF-12 instrument was also better in the intervention group (SMD 0.71, 95% 0.28 to 1.14, P = 0.001). However, in three studies, the direction of change favoured the control group, although the results were not significant. A more consistent pattern favouring intervention was seen for self-rated function, assessed using a variety of instruments, where the direction of change favoured intervention in five of six studies. A significant improvement versus control was seen in only two: the study of type 1 diabetes by Charpentier et al. (2011) [277] (SMD 0.40, 95% CI 0.03 to 0.77, P = 0.032) and of asthma by Liu et al. (2011) [291] (SMD 0.57, 95% CI 0.14 to 0.99, P = 0.009).

Table 4-10 **Observed effects of app-supported interventions on self-rated symptoms**

					Baseline versus endpoint, Negative change favours intervention					
					Within-group change App-supported intervention			Between-group change App-supported intervention versus control		
Study	**Dx [a]**	**Intervention [b]**	**T [c]**	**n [d]**	SMD (95% CI) [e]		P Value [f]	SMD (95% CI) [e]		P Value [f]
Diabetes symptoms (Self-Completion Patient Outcome Instrument - Symptom Measure) [297]										
Quinn et al. (2011) [264-268]	T2	SM+IDS+AF	12M	79	0.18	(-0.40, 0.75)	0.565	0.19	(-0.30, 0.68)	0.450
Asthma symptoms (Asthma Control Questionnaire) [298]										
Ryan et al. (2012) [71, 289, 290]	A	SM+PF+AF	6M	278	0.86	(0.62, 1.11)	<0.001*	-0.01	(-0.24, 0.23)	0.942



[a] Diagnosis: T2 = type 2 diabetes, A = asthma

[b] Intervention content: SM = self-monitoring of blood glucose, IDS = insulin dose suggestions, AF = other automated feedback, PF = health professional feedback

[c] Measurement end point in months, equivalent, study intervention duration.

[d] Sum of individuals analysed in intervention and control groups.

[e] Standardised mean difference (Cohen's d) with associated 95% confidence interval and [f] exact P value ('*' highlights values significant at the 5% threshold).

Table 4-11 **Observed effects of app-supported interventions on patient-centred outcomes**

Instruments were poorly standardised across studies. Consequently, the table combines conceptually compatible measures and sub-scores from different instruments into six overarching domains: overall quality of life; emotional impact; self-rated function; self-efficacy, engagement with self-care behaviours; attitudes, self-care. The standardised mean difference is used, provide a comparable common measure of effect.

						Baseline versus endpoint, Negative change favours intervention				
						Within-group change App-supported intervention		**Between-group change App-supported intervention versus control**		
Study	**Dx [a]**	**Intervention [b]**	**T [c]**	**n [d]**	**Instrument**	SMD (95% CI) [e]	P Value [f]	SMD (95% CI) [e]	P Value [f]	Forest Plot, SMD (95% CI)
Overall quality of life										
Rossi et al. (2013) [276]	T1	SM+PF+IDS	6M	127	DSQOLS [299]	0.08 (-0.27, 0.43)	0.668	-0.15 (-0.50, 0.20)	0.411	
Ryan et al. (2012) [71, 289, 290]	A	SM+PF+AF	6M	201	mAQLQ [295]	0.66 (0.37, 0.95)	<0.001*	0.01 (-0.27, 0.28)	0.961	
Kirwan et al. (2013) [287]	T1	SM+PF	6M	72	DQOL [300]	0.37 (-0.10, 0.84)	0.119	0.33 (-0.13, 0.80)	0.161	
										-1 0 1
										←Favours control Favours intervention→
Perceived emotional impact of disease										
Rossi et al. (2013) [276]	T1	SM+PF+IDS	6M	127	DSQOLS [299]	0.09 (-0.26, 0.43)	0.645	-0.23 (-0.57, 0.12)	0.207	
Quinn et al. (2011) [264-268]	T2	SM+IDS+AF	12M	79	PHQ-9 [301]	0.12 (-0.46, 0.70)	0.691	-0.23 (-0.72, 0.26)	0.363	
Holmen et al. (2014) [283-286]	T2	SM+AF	12M	79	heiQ [302]	0.01 (-0.44, 0.46)	0.954	-0.15 (-0.59, 0.29)	0.516	
Rossi et al. (2010) [273-275]	T1	DI+SM+PF+IDS	6M	130	SF-36 [303]	0.40 (0.05, 0.74)	0.023*	0.04 (-0.30, 0.39)	0.822	
Charpentier et al. (2011) [277-279]	T1	SM+IDS	6M	116	DHP [304]	-0.05 (-0.42, 0.33)	0.823	0.22 (-0.14, 0.59)	0.239	
Kirwan et al. (2013) [287]	T1	SM+PF	6M	72	DQOL [300]	0.59 (0.12, 1.06)	0.014*	0.54 (0.07, 1.01)	0.024*	
Liu et al. (2011) [291]	A	SM+AF	6M	89	SF-12 [305]	0.25 (-0.17, 0.67)	0.252	0.71 (0.28, 1.14)	0.001*	
										-2 -1 0 1 2
										←Favours control Favours intervention→

						Baseline versus endpoint, Negative change favours intervention				
						Within-group change App-supported intervention		Between-group change App-supported intervention versus control		
Study	**Dx [a]**	**Intervention [b]**	**T [c]**	**n [d]**	**Instrument**	SMD (95% CI) [e]	P Value [f]	SMD (95% CI) [e]	P Value [f]	Forest Plot, SMD (95% CI)
Self-rated function										
Rossi et al. (2010) [273-275]	T1	DI+SM+PF+IDS	6M	130	SF-36 [303]	0.07 (-0.27, 0.41)	0.710	-0.10 (-0.44, 0.25)	0.594	
Quinn et al. (2011) [264-268]	T2	SM+IDS+AF	12M	79	SCPOI	0.18 (-0.40, 0.75)	0.565	0.19 (-0.30, 0.68)	0.450	
Holmen et al. (2014) [283-286]	T2	SM+AF	12M	79	heiQ [302]	-0.08 (-0.53, 0.37)	0.725	0.21 (-0.23, 0.65)	0.364	
Kirwan et al. (2013) [287]	T1	SM+PF	6M	72	DQOL [300]	0.33 (-0.13, 0.80)	0.162	0.33 (-0.14, 0.79)	0.171	
Charpentier et al. (2011) [277-279]	T1	SM+IDS	6M	116	DHP [304]	-0.05 (-0.42, 0.32)	0.800	0.40 (0.03, 0.77)	0.032*	
Liu et al. (2011) [291]	A	SM+AF	6M	89	SF-12 [305]	0.41 (-0.02, 0.84)	0.060	0.57 (0.14, 0.99)	0.009*	
										-1 0 1 ←Favours control Favours intervention→
Self-efficacy										
Ryan et al. (2012) [71, 289, 290]	A	SM+PF+AF	6M	231	KASE-AQ [296]	0.47 (0.21, 0.74)	0.001*	0.13 (-0.12, 0.39)	0.313	
										-1 0 1 ←Favours control Favours intervention→
Engagement with self-care behaviours										
Holmen et al. (2014) [283-286]	T2	SM+AF	12M	79	heiQ [302]	0.05 (-0.40, 0.50)	0.831	0.01 (-0.43, 0.46)	0.956	
Kirwan et al. (2013) [287]	T1	SM+PF	6M	72	SDSCA [306]	0.45 (-0.02, 0.92)	0.058	0.11 (-0.35, 0.58)	0.639	
										-1 0 1 ←Favours control Favours intervention→

						Baseline versus endpoint, Negative change favours intervention				
						Within-group change App-supported intervention		Between-group change App-supported intervention versus control		
Study	**Dx [a]**	**Intervention [b]**	**T [c]**	**n [d]**	**Instrument**	SMD (95% CI) [e]	P Value [f]	SMD (95% CI) [e]	P Value [f]	Forest Plot, SMD (95% CI)
Positive attitudes towards self-care										
Holmen et al. (2014) [283-286]	T2	SM+AF	12M	79	heiQ [302]	-0.08 (-0.53, 0.37)	0.747	-0.12 (-0.56, 0.32)	0.599	
Ryan et al. (2012) [71, 289, 290]	A	SM+PF+AF	6M	240	KASE-AQ [296]	0.21 (-0.04, 0.47)	0.105	0.07 (-0.19, 0.32)	0.618	
Rossi et al. (2013) [276]	T1	SM+PF+IDS	6M	127	DTSQ [307]	0.13 (-0.22, 0.48)	0.490	0.18 (-0.17, 0.53)	0.313	
Rossi et al. (2010) [273-275]	T1	DI+SM+PF+IDS	6M	130	DTSQ [307]	0.77 (0.42, 1.12)	<0.001*	0.35 (0.00, 0.69)	0.049*	
										-1 0 1
										←Favours control Favours intervention→

Abbreviations: ACQ = Asthma Control Questionnaire (ACQ), DHP = Diabetes Health Profile, DQOL = Diabetes Quality of Life Scale, DSQOLS = Diabetes Specific Quality of Life Scale, DTSQ = World Health Organisation Diabetes Treatment Satisfaction Questionnaire, heiQ = Health Education Impact Questionnaire , heiQ = Health Education Impact Questionnaire , KASE-AQ = Knowledge, Attitude and Self-Efficacy Asthma Questionnaire (KASE-AQ) - Self-Efficacy, miniAQLQ = Mini Asthma Quality of Life Questionnaire, PHQ-9 = Patient Health Questionnaire - Depression, SCPOI = Self-Completion Patient Outcome Instrument, SDSCA = Summary of Diabetes Self-Care Activities, SF-12 = Short-Form 12 Questionnaire, SF-36 = Short-Form 36 Questionnaire.

[a] Diagnosis: T1/T2 = type 1/2 diabetes, A = asthma

[b] Intervention content: DI = dietary intervention, SM = self-monitoring of blood glucose, IDS = insulin dose suggestions, AF = other automated feedback, PF = health professional feedback

[c] Measurement end point in months, equivalent, study intervention duration.

[d] Sum of individuals analysed in intervention and control groups.

[e] Standardised mean difference (Cohen's d) with associated 95% confidence interval and [f] exact P value ('*' highlights values significant at the 5% threshold).

No clear differences were seen in studies reporting engagement with self-care behaviours (n=2) or attitudes towards self-care (n=4), although one study, Rossi et al. (2010)[273] found a significant but modest improvement in positive attitudes at six months favouring intervention (SMD 0.35, 95% CI 0.00 to 0.69, P=0.049).

Only three studies in diabetes solicited feedback from patients about perceptions of the app component of the intervention. Charpentier et al. (2011)[277] asked participants if they would want to continue using their blood-glucose logging system after conclusion of the study and found that 67% (n=40/60) agreed. Tsang et al. (2001)[280] surveyed 19 participants and found that 95% (n=18/19) agreed to the statement that their diet-monitoring system for diabetes was easy to use, that just under two thirds (63%, n=12/19) found dietary tracking useful and that the same proportion would consider using the system again. Quinn et al. (2008)[16] reported that at least 91% (n=12/13) of users indicated that they were satisfied with aspects of app-supported management such as receiving feedback via an app, but did not provide detailed statistics.

Safety

For type 1 diabetes, Rossi et al. (2010)[273] and (2013)[276] reported data on the perceived frequency of hyper- and hypoglycaemia collected using the WHO Diabetes Treatment Satisfaction Questionnaire [307]. Rossi et al. (2013) demonstrated a significant reduction in perceived hyperglycaemia (SMD 0.63, 95% CI -0.98 to -0.27, P = 0.001) in intervention groups, not seen in Rossi et al. (2010) (SMD -0.07, 95% CI -0.41 to 0.28, P = 0.710). In both studies, however, there was a non-significant trend towards greater frequency of hypoglycaemia. Rossi et al. (2010) found a SMD in self-rated frequency favouring control of 0.31 (95% CI -0.04 to 0.65, P = 0.083). For Rossi et al. (2013) the SMD was 0.13 (95% CI -0.22 to 0.47, P = 0.490), although the proportion of severe episodes per patient was lower in the intervention group (0.33 vs 2.29). Garg et al. (2008)[288] found a significantly higher proportion of severe hypoglycaemic events in the intervention group (n=26) vs control (n=8, P = 0.040). Four other studies[264, 277, 281, 282] reported no difference in the frequency of hypoglycaemic events but did not provide detailed statistics.

Quinn et al. (2008)[16] examined the proportion of patients with identified medication errors and found a significantly higher rate in those using the app-supported intervention (53.4% intervention vs 0% control, P = 0.002). However, the study authors did not explore whether this reflected greater detection or a higher rate of *de novo* error in the intervention group.

For asthma, Ryan et al. (2012)[71] reported frequency data on the proportions of patients experiencing either acute exacerbations (31%, n=43/140 intervention vs 32%, n=45/141 control) or

requiring steroid courses (20%, n=28/140 intervention vs 21% n=30/141 control) during the 6-month study period (Table 4-9). No difference was seen in either exacerbation frequency (OR 0.95, 95% CI 0.57 to 1.57, P = 0.853) or requirement for steroids (OR 0.93, 955 CI 0.52 to 1.66, P = 0.818). This differed from Liu et al. (2011), where a significant increase in both inhaled (six-month endpoint 709µg/day ±209 SD intervention vs 630µg/day ±264 SD control) and systemic (2.38mg/day ±3.67 SD intervention vs 1.25mg/day ±2.37 SD control) corticosteroid use was seen in intervention participants. However, the study authors argued that this represented appropriate increases in treatment in response to fluctuating asthma symptoms, rather than excessive usage.

Tsang et al. (2001) tracked system performance in their study of diabetes and reported technical issues affecting up to two fifths (37%, n=7/19) of participants as a result of either local device or data transmission problems, although this early study relied on fixed telephony to share data with professionals.

Efficiency

Ryan et al. (2012)[71] performed a cost analysis of their app-supported intervention for asthma and found no significant difference in the mean cost of respiratory care (mean per-participant cost of £246±£226 SD intervention vs £245±£201 SD paper-based control) but an excess cost in providing telemonitoring services of £69 to intervention group participants that contributed to a significant increase in cost overall (mean £315±£226 SD intervention vs £245±£201 SD control, P = 0.006). Combined with a lack of demonstrable impact on measured quality of life (Table 4-11), they concluded that the intervention was not cost-effective.

No other study reported cost-effectiveness outcomes.

Other outcomes

In their pilot study, Quinn et al. (2008) examined physician perceptions of the impact of app-supported diabetes self-care on their ability to manage patients. At three months, responsible physicians (n unknown) considered that app-supported care had increased the amount of data being received from patients (100%, n=13/13 intervention vs 23%, n=3/13 control, P = 0.001) and increased the proportion of patients for which they received data necessary for diabetes management (100%, n=13/13 intervention vs 8%, n=1/13 control, P < 0.001). Overall, professionals judged that self-management skills had improved in a greater proportion of intervention participants compared to control (100%, n=13/13 vs 15%, n=2/13, P < 0.001). The findings of this short-duration study are balanced, however, by results in longer duration studies. Kirwan et al. (2013)[292] observed a gradual decreasing trend in the quantity of data entries logged by diabetes patients per

month from 184.53 (±137.41SD) at the start of the study to 84.84 (±153.47 SD) at six months. At 12 months, Holmen et al. (2014)[283] considered less than a third (31%, n=20/51) of patients to be active users of their diabetes intervention.

4.5.5 *Ongoing studies*

Searches identified thee studies that were either ongoing or had not been reported at the conclusion of the analysis. Sevick et al. (2008)[308] reported on aspects of the design process and patient acceptability of a PDA-based self-monitoring intervention for type 2 diabetes as part of a randomized controlled trial (ENHANCE), however a full study report could not be located. Skrøvseth et al. (2013)[309] published a protocol for a randomized controlled trial self-help diary app incorporating statistics-based automated feedback to patients with type 1 diabetes. Finally, Baron et al. (2015)[310] published preliminary engagement data (but not clinical outcomes) for a mixed-methods randomized controlled trial of a mobile telehealth intervention for patients with type 1 and 2 diabetes.

4.6 Discussion

4.6.1 *Summary of results*

Key findings of the systematic review were:

- Evidence of clinical benefit for patients with diabetes undertaking app-supported self-monitoring reflected in measured improvements in HbA1c, a proxy measure of glycaemic control, but without clear positive impact on quality of life, subjective perceptions of disease or self-care skills. Even modest gains in HbA1c have been shown to be associated with improved outcomes in both type 1 and 2 diabetes [181, 311].
- A limited evidence base of two studies yielding a mixed picture that app-supported self-care for asthma is better than standard methods for supporting self-care involving paper-based diaries. For example, while Ryan et al. (2012)[71] saw significant reductions in unscheduled healthcare utilisation, they saw no significant improvement in any self-rated measure of asthma control or quality of life *compared* to control. However, both app-supported and paper-based strategies were able to drive significant within-group improvements in self-rated symptoms, self-efficacy and perceived quality of life in study participants, suggesting that while app-based care might not be better than standard methods for supporting self-care, it is not clearly worse.

- No clear evidence that app-supported interventions were less safe than usual care for either condition. For diabetes, a nonsignificant trend towards higher rates of hypoglycaemia in intervention groups probably underlined the challenges associated with avoiding excessive reductions in fasting blood glucose when patients are encouraged towards tighter glycaemic control.
- Very limited evidence assessing other relevant outcomes, such as cost-effectiveness, impacts on care delivery or acceptability to patients. The one study incorporating a cost-effectiveness analysis of app-supported self-care and nurse-based feedback for asthma[71] did not demonstrate clinical benefit, and concluded that the intervention as not cost-effective compared to standard self-care support. However, the cost of app-supported care was similar to paper-based care when remote monitoring was excluded. For diabetes, the inclusion of remote monitoring and feedback was not associated with improved outcomes.
- Study designs which commonly adopted a data-driven approach to self-care in which participants recorded parameters about their condition, such as blood glucose, in a longitudinal diary and received support for decision-making through either automated data analysis or professional feedback. Over half (n=7/13) of studies adopted a remote monitoring approach in which submitted data were made available for review by a clinician, blurring the boundary between self-care and telemedicine. Increased costs and a lack of evidence for benefit for glycaemic control associated with remote monitoring observed in this review questions whether the inclusion of remote support is necessary, even if it is technically feasible. No studies examined information-only interventions or other novel forms of self-care support, such as peer networking that could take advantage of the multimedia or network capabilities of the mobile device.

4.6.2 *Integration with other findings*

Relevant literature was introduced at the start of this chapter (section 4.2 above) as part of the justification for this review.

For diabetes, findings of clinical benefit in terms of improved glycaemic control without clear impacts on other biochemical parameters are consistent with existing systematic reviews. Unlike Liang et al.[255], no clear difference in effect was observed in studies targeting patients with type 1 versus type 2 diabetes. Although the direction of improvement, suggesting greater scope for benefit in type 2 diabetes, was the same in both reviews, findings in the current review were of lower magnitude and did not attain significance.

For asthma, mixed findings of benefit in only one of two studies mean that the motivating aim to address the limitation in synthesis of studies of asthma apps cannot satisfactorily be addressed. Since both studies were performed in patients with poor or difficult-to-control asthma, the argument of McLean et al.[168] that technology-supported interventions for asthma are more likely to be beneficial in those with severe asthma cannot be directly challenged.

Although rare, study findings underline the potential for clinically relevant negative effects, such as hypoglycaemia, arising from app-supported self-care. This issue will be revisited in, and formed part of the motivation behind, the exploration of apps offering automated insulin dose recommendations in chapter six.

4.6.3 *Review limitations*

Limitations arising from the conduct and availability of primary studies (highlighted in the previous section) represent the major threat to the validity of inferences that may be drawn from the findings presented above. The short duration of most studies, with only four studies of duration either 12 (n=3) or 13 (n=1) months, precluded exploration of the secondary aim to identify factors promoting sustained app use. Although participant attrition was common, affecting up to two fifths of participants, e.g. in Quinn et al. (2011)[264], no studies attempted to explore factors influencing loss of participants, despite evidence of differential attrition between intervention and control (e.g. in Quinn with completion of 61% intervention vs 90% control or Istepanian et al. (2009)[269] with completion of 67% intervention vs 85% control) with possible implications for acceptability to participants. This is unfortunate, given the lack of data exploring this dimension of quality in relation to app use. Only three studies explored participant attitudes, and all relied on simple closed-question feedback. Sustaining interest in self-monitoring is an important challenge for clinical care (see section 2.4.3) and it is unfortunate that no study explored this issue, given the capability of apps to provide tailored motivational support (section 2.3.4). For example, although many studies included reminders, no study attempted to explore the impact of these nor the differential impact of tailored versus generic messages or differing messaging frequency.

Few studies incorporated a clear account of the design of their interventions and no study reported a theory-informed approach, limiting characterisation of factors likely to maximize app-supported intervention success. In many cases, interpretation was confounded by multi-component designs in which non-app-based patient support strategies, such as professional feedback or customized management plans, were included in the intervention group but not replicated in the control group. The rationale for including these components, which complicate interpretation of self-care support

strategies, should be questioned, particularly since meta-analysis suggested no additional benefit for the inclusion of remote monitoring support in studies of diabetes. In addition, study reports often failed to incorporate clear information about the expected frequency of these components, complicating interpretation of the relative 'dose' received by participants in different studies. In response, an investigation of the determinants of pooled effects, such as aspects of intervention design on HbA1c, was undertaken using exploratory *post hoc* subgroup analyses. While this approach provided estimates of the binary impacts of the presence or absence of certain factors, such as the incorporation of professional feedback, it could not account for interactions between these elements nor potentially confounding characteristics. Future work should explore the potential for meta-regression to explore these interacting elements.

Despite the incorporation of a systematic approach with formal bias and error control strategies, aspects of the review process were also subject to potential limitations. Although the study search spanned a wider range of resources than previous reviews and was not restricted by language, it did not explicitly incorporate non-English language resources. It is possible that there is a literature which was not identified by the search strategy and with findings that challenge those identified above, although review of related systematic reviews suggests that this is unlikely. As noted above, definitive synthesis was not possible for a number of outcomes because of limitations in the quality and numbers of studies reporting these, particularly for asthma. This means that future updates to this review will be necessary as new literature emerges.

4.6.4 *Issues identified for thesis discussion*

Issues arising from the review that will be addressed in the thesis discussion in chapter eight are:

- What the state of evidence means for healthcare professionals interested in integrating apps for self-care into routine practice. In particular, discussion will return to the issue of equivalent versus superiority of clinical outcomes raised by the equivocal findings in asthma studies. Chapter eight will argue that a lack of definitive studies should not act as a uniform barrier to implementation strategies.
- The opportunities for future research arising from gaps identified by this review, such as the lack of pragmatic studies exploring patient or clinical experiences for future intervention studies.

4.7 Chapter summary

Chapter four aimed to assess the impact on quality-related outcomes of app-supported interventions enabling self-care by individuals with asthma and diabetes. Limitations in available literature meant that the review was only partially successful in this aim. Consistent evidence for benefit was observed for app-supported self-care in diabetes, however explanation of the factors influencing this success was constrained by the lack of study-level analysis or intervention descriptions that would permit a higher-level synthesis. Evidence backing app-supported self-care interventions for asthma is limited by the availability of only two randomized studies. Chapter five also examines self-care apps for asthma, but rather than relying on published intervention studies, reports data from an observational analysis of apps available through public marketplaces. Rather than rely on directly-measured outcomes, the study assesses the degree to which published apps conform to clinical standards for content and design as a marker for likely benefit in use.

Chapter five: Quality of mobile medical apps for asthma. Results from serial systematic content assessments

5.1 Chapter introduction

Chapter five will present data from two serial studies of the quality of publicly-available mobile medical apps for asthma. Two factors motivated the decision to undertake a primary evaluation of commercial apps. The first was the limitation observed in available evidence, highlighted in the previous chapter, in particular for asthma. In addition, limited crossover was seen between mobile medical apps evaluated by the research literature and those available for public use, raising the prospect of quality issues not captured by existing interventional research literature. The second reflected recent data about app uptake suggesting scope for real-word impacts should such issues go unexplored. A 2014 cross-disciplinary survey of US healthcare professionals found that up to a third had recommended specific apps to patients[61], while a quarter of app-users in 2013 reported having received such a recommendation[312].

This chapter introduces a systematic approach to assess the content quality of mobile medical apps which contrasts with the outcomes-focussed evaluation from experimental literature reported in chapter four. The cross-sectional method, which relies on observer judgements against transparent criteria, enables *de novo* evaluation of potentially large numbers of apps produced by different publishers where evaluation data may be limited, inaccessible or at high risk of bias, and where the generation of suitable outcomes data would be infeasible on time or resource grounds. A 2013 survey of mobile medical apps supporting management of the most prevalent long-term conditions identified at least 3,500 apps[313], underlining the need for an evaluative approach capable of identifying and grouping issues in a manageable way.

The studies reported here focus on the second sense of 'effectiveness' quality recognised by the Institute of Medicine (IoM), which concerns consistency with established professional knowledge[210]. Where experimental approaches might quantitate impact directly, this stance instead assumes a predictive link between the extent to which the design of a healthcare technology, such as an app, is informed by strategies backed by evidence and the scope for clinical benefit or disbenefit that may be realised in practice. Predictive relationships could theoretically be advanced

to connect each of the IoM quality domains and specific design considerations. However, in practice, scope is constrained both by the availability of appropriate evidence and questions of validity. In particular, the predictive approach assumes a normative relationship which may not hold for aspects of quality with substantial subjective influences, such as acceptability, or those with complex situational determinants, such as equity, cost-effectiveness and timeliness of care. As a result, the focus will be on aspects of clinical effectiveness (in this chapter) and safety (in the next) for which objective standards may be clearly defined.

To gauge adherence to evidence-informed practices influencing effectiveness and safety, standardised criteria were developed. The development process, and the use of clinical guidelines as the major source shaping criteria specification, is introduced and explained below (section 5.3.2 below). As discussed in the methods exposition in chapter three (section 3.4.2.2 above), the method also required strategies for controlling the risk of assessment-related error and bias, and these are also described. The feasibility of a criterion-based method was suggested by an existing extensive literature describing assessment-based approaches for the evaluation of health websites[25] and, at the time the research was first planned, to mobile medical apps for health behaviour change[43], pain management[42] and two studies of diabetes apps[39, 314].

The number of studies applying similar methods to apps for diabetes has subsequently grown[35, 40, 315, 316], and findings from these related assessments are discussed later in the chapter. The discussion concludes with a synthesis of topics relevant to the overall thesis aims and discussion of methodological limitations. Safety is the focus of chapter six, which responds to the scope for potential clinical harms relating to issues identified in mobile medical apps for diabetes, as well as those recognized by contemporary studies[17, 315].

Portions of this chapter have been published under open access license (http://creativecommons.org/licenses/by/4.0) as peer-reviewed journal articles, for which I retain copyright:

- Huckvale K, Car M, Morrison C, Car J. Apps for asthma self-management: a systematic assessment of content and tools. BMC Med. 2012;10(1):144.
- Huckvale K, Morrison C, Ouyang J, Ghaghda A, Car J. The evolution of mobile apps for asthma: an updated systematic assessment of content and tools. BMC Med. 2015;13(1):58.

5.2 Study-specific objectives

The primary objective of the work described in this chapter, which reflects data from two sequential studies, was to assess the extent to which the design of mobile medical apps for asthma intended for use by the general public through approved device marketplaces was consistent with evidence for effectiveness informing accepted clinical practice.

To address the range of app types available, a multi-domain assessment method was developed in which specific features of these apps, for example information content, were assessed separately. These assessment domains are described in section 5.3 below. To capture the concept of 'accepted clinical practice', assessment criteria were substantially based on national and international clinical practice guidelines. The justification behind this approach is also addressed below.

Secondary objectives were:

- To characterise the types and features of mobile medical apps for asthma. A cross-sectional approach was used in which all apps available at a particular point in time were identified and reviewed.
- To explore whether the quality of mobile medical apps for asthma has changed over time. To do this, an initial cross-sectional survey in August 2011[317] was followed, 24 months later, by a second survey in August 2013[318]. The quality characteristics of apps available in 2011 and those newly available in 2013 were then compared.
- To prospectively identify issues affecting the suitability of apps for use by patients, or as tools recommended by healthcare professionals as part of planned care, for example software problems or potential safety concerns. A schema-based approach was used to group identified issues for discussion.

5.3 Methods

5.3.1 *App selection*

App selection was performed using a three-stage process of search, screening and selection, first performed in August 2011 and repeated in August 2013. Mobile medical apps available at each time point were treated as separate cohorts to enable comparative analysis.

The public app stores of the two most widely-used mobile operating systems (Android and iOS, 2013 market share data) were searched using a pre-defined search strategy to identify apps whose title, description or keywords contained any of the terms 'asthma', 'inhaler', 'peak flow', or related word

variants. Searches were performed using the user interface tools provided by the web interface of each app store. Search results including app titles, descriptions, screenshots, cost and, if available, user ratings and download counts, were extracted using an HTML extraction tool (OutWit Hub Pro, version 1.0.2.5, OutWit Technologies, Neuilly, France), de-duplicated and staged for subsequent analysis in a custom database (Microsoft SQL Server 2008, Microsoft Corporation, Redmond, Washington, USA).

After each search, app titles, descriptions and screenshots were screened to eliminate obviously irrelevant content. The remaining apps were then downloaded and reviewed against pre-specified selection criteria (Table 5-1). All apps containing asthma-specific content or tools intended for patient or public use were eligible for inclusion. Apps were included irrespective of payment model (free or paid-for) or device type (smartphone, tablet or both). Apps were excluded if they targeted only healthcare professionals (relying on claims made by the app developers), were unavailable from UK-based app stores, or would not start after at least two attempts on different test devices. No restriction was placed on country of origin, however all included apps supported English as either the default or a user-selectable language option. Apps included in the 2011 analysis which remained available in 2013 were re-reviewed for eligibility if they had been updated.

Table 5-1 **Asthma app selection criteria**

Inclusion criteria
Smartphone or tablet app
Free or paid
Running on Android or iOS platforms
Content or tools addressing one or more aspects of asthma diagnosis, management or support as either the sole function; or in a way that means asthma-related elements can be isolated from the rest of the content
Presenting content in any format
English language
Targeted at patients of any age
Exclusion criteria
Not available through an approved device marketplace
Explicitly disclaimed use for a health-related purpose
Could not be downloaded because of country restrictions that prevented access in the United Kingdom
Could not be used because of technical problems, after two attempts

As part of a bias and error-control strategy, screening and final selection were performed in duplicate. Each app was reviewed by myself and a second reviewer (see section 5.3.8 below), working independently. Screening and selection decisions were recorded on a standard template and then compared. Any discrepant decisions were jointly re-examined in order to reach a final consensus. A third party (Josip Car) was nominated to act as arbiter in the event of irreconcilable disagreement, but in practice this did not occur.

5.3.2 *Assessment criteria development*

Assessment criteria were developed to structure the review of each included app. Prior to the start of the study, an initial scoping search was undertaken to identify features of mobile medical apps for asthma requiring evaluation. This identified two main feature domains: information provision and self-management tools, such as diaries.

Reflecting the overall aim of the study to assess consistency with the state of current knowledge and, in particular, knowledge informing accepted practice, it was decided that clinical asthma management guidelines should be used as the key source informing criteria development examining these two domains. The choice of clinical guidelines as a primary source reflected several considerations.

Clinical guidelines are "systematically developed statements to assist practitioner and patient decisions about appropriate health care for specific clinical circumstances.[319]" They are, therefore, explicitly intended to inform the delivery of specific aspects of healthcare[320]. Guidelines have been identified in quality improvement literature as offering a sound basis for clinical evaluation and audit[321], recognizing that the prescriptive content is often well-suited for conversion into discrete assessment criteria. Initial scoping suggested that asthma guidelines did incorporate content addressing both feature domains amenable to criteria development (although with variable coverage, see section 5.3.3 below). Because guidelines are intended to shape clinical practice, they adopt a pragmatic stance in which research evidence is balanced by practical considerations. This approach offered a desired contrast in perspective to the research-based literature review presented in the previous chapter. Finally, it was anticipated that the standardised processes of comprehensive evidence appraisal and peer review that underpin contemporary guideline development[322] would serve to enhance the potential content validity of any derived criteria.

It is recognized, however, that clinical guidelines may occasionally contain information that is incorrect[320]. To address this risk, a process of triangulation was used such that the final

assessment criteria reflected the consensus position across three independently-produced, English-language guidelines sourced from the UK, the USA and the international Global Initiative for Asthma. This consensus approach also aimed to ensure that there could be no disagreement about whether or not apps developed in different countries should be held to country-specific guidance, since the resultant criteria reflected positions held in common across all settings.

Selected guidelines were those most recently available at the time of study development and represented the three English-language guidelines with the highest composite quality score in a 2013 systematic appraisal[323] using international criteria for guideline evaluation[322] to assess technical quality of defined scope, stakeholder involvement, development rigour, clarity, applicability and editorial independence.

- British Thoracic Society, Scottish Intercollegiate Guidelines Network (2012) British guideline on the management of asthma - a national clinical guideline. May 2008, revised January 2012.
- US National Asthma Education and Prevention Program (2007) Expert panel report 3: guidelines for the diagnosis and management of asthma. Full report 2007.
- Global Initiative for Asthma (2012) Global strategy for asthma management and prevention. Updated 2012.

The final assessment criteria were also reviewed by study collaborators (see section 5.3.8 below) and an independent clinician prior to the start of the study.

5.3.3 *Assessment of asthma information*

Structured self-management education has been demonstrated to improve health outcomes in asthma[110]. Recommended content for asthma self-management education was well-specified and substantially consistent across the three selected clinical practice guidelines. As a result, it was possible to derive detailed criteria examining:

- *The comprehensiveness of information presented by apps*

  This was measured by the extent to which apps addressed topics under eight key self-management domains (Table 5-2) identified by guidance, for example, the appropriate use of an action plan. Operational criteria, detailed in the table, were attached to each of these domains. Apps were assessed as satisfying each domain either wholly, partially, or not at all on the basis of the proportion of criteria addressed in information content.

Table 5-2 **Operational criteria for assessing the comprehensiveness of asthma self-management educational materials**

Domains and criteria were based on UK BTS/SIGN[324], US EPR-3[139] and GINA[140] guidelines.

Domain	Criteria
Basic facts about the nature of the condition	▪ States that asthma is a lung disease characterized by inflammation and narrowing of the airways; ▪ States that the four main symptoms of asthma are cough, wheeze, shortness of breath and chest tightness; ▪ States that asthma cannot be cured (although childhood symptoms may remit) but can be effectively controlled; ▪ States that the cause of asthma is not known.
The nature of treatment: relievers and preventers	▪ States that there are two classes of medication: relievers and preventers; ▪ Explains possible side effects of medication (tachycardia/tremor in B_2 agonists; thrush/cataracts/dysphonia for inhaled steroids; possible additional effects for high dose steroids) ▪ States that early treatment can prevent symptoms from worsening.
Allergen and trigger avoidance	▪ States that recognizing and avoiding personal triggers is an important part of asthma control; ▪ Provides guidance consistent with the primary and secondary prophylaxis components of the BTS/SIGN guidelines in relation to specific triggers.
How to use treatment	▪ States that preventer medication must be used regularly to be effective; ▪ States the importance of good inhaler technique and appropriate use of a spacer device[1] ▪ States the importance of ensuring inhalers are in date and are not empty.
Self-monitoring and assessment skills	▪ States that learning to recognize signs of change in asthma status is an important personal skill; ▪ States that both symptom recognition and peak flow measurements are valid approaches for self-monitoring; ▪ Explains the purpose of a peak flow meter and how to use it; ▪ States the importance of regular physician review.
The role of a written, personalized action plan	▪ States that patients with asthma should have an up to date written action plan; ▪ Explains the purpose of an action plan (to step up and step down treatment, and to seek appropriate

Domain	Criteria
	help in response to changing symptoms and/or peak flow).
Recognizing and responding appropriately to acute exacerbations	▪ Describes signs/symptoms of worsening asthma (increasing wheeze; cough; night time disturbance; breathlessness limiting activity; reliever inhalers not working); ▪ States the importance of changing treatment and/or seeking help promptly. ▪ Steps involved in lay management of acute asthma o Recognizing the signs of an asthma attack o Appropriate rescue inhaler use o Other practical steps, e.g. sitting the patient up o Providing reassurance o When to seek emergency assistance
Personalizing the definition of good asthma control	▪ States that it is reasonable for most people to achieve minimal symptoms and limitation of activities; ▪ Asks patients to reflect on what they would consider as good asthma control; ▪ Advocates discussion with personal health provider to set treatment goals in partnership.

[1] Because of the diversity of different available inhaler types, inhaler technique was addressed separately, see section 5.3.3.

- *Consistency of information with evidence-based strategies for asthma management*

  Consistency was assessed by the extent to which included apps complied with evidence-based recommendations adopted by guidelines when providing specific advice, for example, to advocate the efficacy of smoking cessation in people with asthma in reducing asthma symptoms (in addition to other health benefits). Apps were expected to appropriately communicate uncertainty in association with recommendations where evidence was either lacking, conflicting or unclear. For example, the unclear impact of influenza vaccination on exacerbations questions its routine use as a seasonal intervention for people with asthma[325]. Nine evidence based strategies (detailed in Table 5-3) were addressed by all three guidelines and were used as the basis for assessment of consistency.

In addition, separate assessments were performed for information addressing:

- Lay management of acute asthma, a potentially high-risk management task because of the scope for life-threatening consequences of failures to either control symptoms effectively or seek appropriate specialist help. Apps were assessed for: symptom and sign recognition; appropriate use of rescue inhalers; practical steps such as sitting a patient up; providing reassurance and when to seek emergency assistance.
- Inhaler technique, for which technique problems a common in asthma and where poor technique can substantially impair drug delivery to the lung[151]. This was a post hoc addition to the 2013 assessment in response to the growing number of inhaler technique apps released since 2011. Because inhaler technique was not addressed in detail in clinical guidelines, manufacturer instructions were used to establish criteria examining eight domains, such as appropriate inhaler preparation. These are detailed in Appendix 6.

Since evidence-based approaches were not expected to be compatible with alternative medical traditions, apps presenting exclusively information satisfying the definition of CAM[326] were assessed only for compliance with recommendations for appropriate acute asthma lay management, recognizing the importance of seeking conventional medical help should CAM-based strategies prove ineffective, and were assumed to be noncompliant with other domains. Apps presenting evidence from mixed conventional and alternative traditions were assessed, however.

Apps were assessed regardless of information medium and delivery format. Textual information content was also evaluated for readability using two validated sampling methods which estimate the ease with which content can be understood: the Flesch-Kincaid method (FKGL)[327], a commonly used measure, and the Simple Measure of Gobbledygook (SMOG)[328], which recent evaluations have suggested may be more accurate than FKGL for evaluations of health texts[329]. Both use sentence length and syllable counts to estimate the minimum US school grade level where comprehension of a particular text would be reasonably expected. A minimum of 30 sentences of sample text was extracted from each app for evaluation.

Table 5-3 **Management strategies used to assess consistency of asthma information with evidence-base**

Strategies were extracted from UK BTS/SIGN[324], US EPR-3[139] and GINA[140] guidelines and considered only management strategies discussed by all three sets of guidelines. 'Qualified benefit' was used where factors were identified that should shape the scope of the evidence, such as evidence applicable only to individuals with severe asthma; where a strategy might be considered for reasons other than those directly relating to asthma, as in the case of seasonal influenza vaccination; or where the advice given by the guidelines differed.

Management strategy	Evidence	Guideline positions
Removal of pets from the home	Qualified benefit	[1] "**The reported effects of removal of pets from homes are paradoxical**, with either no benefit for asthma, or a potential for continued high exposure to induce a degree of tolerance." [2] [EPR-3 suggests that animal removal **could be considered** but rates the evidence Grade D, which reflects panel consensus only] [3] "Complete avoidance of pet allergens is impossible […] Although removal of such animals from the home is encouraged, even after permanent removal of the animal it can be many months before allergen levels decrease and **the clinical effectiveness of this and other interventions remains unproven**."
Fungal allergen avoidance and control measures	Qualified benefit	[1] "Although fungal exposure has been strongly associated with hospitalization and increased mortality in asthma, **no controlled trials have addressed the efficacy of reduction of fungal exposure** in relation to control of asthma." [2] "The Expert Panel recommends consideration of measures to control indoor mold […] but **the relative contribution of fungi, house-dust mites or irritants [to asthma symptoms] is not clear**." [3] "Air conditioners and dehumidifiers may be used to reduce humidity to levels less than 50% and to filter large fungal spore. **However, air conditioning and sealing of windows have also been associated with increases** in fungal and house dust mite allergens."

Management strategy	Evidence	Guideline positions
Cockroach avoidance and control measures	Qualified benefit	[1] "Cockroach allergy is not a common problem in the UK and studies of attempts to avoid this allergen elsewhere have **produced conflicting results**." [2] [EPR-3 recommends cockroach control **if the patient is sensitive to cockroaches**] [3] "[Measures for cockroach control] are **only partially effective in removing residual allergens**."
Cessation of active smoking	Beneficial	[1] "**Direct** or passive exposure to cigarette smoke **adversely affects** quality of life, lung function, need for rescue medications for acute episodes of asthma and long term control with inhaled steroids." [2] "[Smoke exposure] is associated with **increased symptoms, decreased lung function, and greater use of health services** among those who have asthma." [3] "Asthma patients who smoke and are not treated with inhaled glucocorticosteroids, have a **greater decline in lung function** than asthmatic patients who do not smoke."
Avoidance of passive smoking	Beneficial	[1] "Direct or **passive** exposure to cigarette smoke **adversely affects** quality of life, lung function, need for rescue medications for acute episodes of asthma and long term control with inhaled steroids." [2] "[Smoke exposure] is associated with **increased symptoms, decreased lung function, and greater use of health services** among those who have asthma." [3] "Secondhand smoke **increases the frequency and severity of symptoms** in children with asthma."

Management strategy	Evidence	Guideline positions
Avoidance of exposure to air pollution	Qualified benefit	[1] "Time-series studies suggest that **air pollution may provoke** acute asthma attacks or aggravate existing chronic asthma although the effects are **very much less than those with infection or allergen exposure**." [2] "Clinicians [should] advise patients to avoid, to the extent possible, exertion or exercise outside when levels of air pollution are high." [3] "Avoidance of unfavorable environmental conditions is **usually unnecessary** for patients whose asthma is controlled."
Immunotherapy for a defined allergen	Beneficial	[1] "Immunotherapy can be considered in patients with asthma where a **clinically significant allergen cannot be avoided**." [2] "Immunotherapy [should] be considered for patients who have persistent asthma if evidence is clear of a **relationship between symptoms and exposure to an allergen** to which the patient is sensitive." [3] "Appropriate immunotherapy requires the **identification and use of a single well-defined clinically relevant allergen**."
Weight reduction in obese patients	Beneficial	[1] "One randomized parallel group study has shown **improved asthma control following weight reduction** in obese patients with asthma." [2] "Obesity has been associated with **asthma persistence and severity** in both children and adults. […W]eight loss in adults resulted in improvement in pulmonary mechanics, improved FEV1, reductions in exacerbations and courses of oral corticosteroids and improved quality of life." [3] "Weight reduction in obese patients with asthma […] has been demonstrated to **improve lung function, symptoms, morbidity and health status**."

Management strategy	Evidence	Guideline positions
Seasonal influenza vaccination	Qualified benefit	[1] "Immunizations should be administered **independent of any considerations related to asthma**." [2] "[We recommend] that **clinicians consider inactivated influenza vaccination for patients who have asthma** […] however the vaccine should **not be given with the expectation that it will reduce either the frequency or severity of asthma** exacerbations during the influenza season." [3] "Patients with moderate to severe asthma **should be advised to receive an influenza vaccination** every year […] **however routine influenza vaccination** of children and adults with asthma **does not appear to protect them from asthma exacerbations or improve asthma control**."

5.3.4 *Assessment of self-management tools*

In contrast to self-management education, specification of the format of other self-management tools was only partially addressed by guidelines. While was not possible to derive detailed systematic criteria for the assessment of self-management tools, specific features were evaluated. Diary apps were assessed for the support offered for both symptom logging and peak flow monitoring in diary apps, since both are recognized as valid methods for self-monitoring. Asthma action plan features were evaluated for support provided for the customized specification of at least 2 steps reflecting symptom or peak-flow based criteria established by a responsible healthcare professional[155].

The performance of calculators and assessment instruments, such as diagnostic questionnaires, was assessed by identifying cited algorithms and validation information and, if possible, comparing generated output to expected values.

For all other apps, a descriptive approach was used to characterise content and functions.

5.3.5 *Other assessment domains*

Reflecting the secondary objective concerning the identification of other relevant issues affecting suitability for routine use in clinical care, all apps were assessed for compliance with a set of content-independent criteria reflecting best-practice for ethical disclosures about ownership and handling of personal information (detailed in Table 5-4). Criteria were derived from existing criteria developed for the evaluation of health information on the internet by the Health on the Net Foundation[330]. Software issues encountered during testing were also logged and analysed using the schema presented in Table 5-5.

Table 5-4 **Ethical disclosure principles for smartphone apps**

Adapted from the Health on The Net Foundation principles for health information on the internet[330] and developed for our earlier review[317].

#	Principle
1	Information must be authoritative: all medical information presented by [and/or calculations performed by an app] must be attributed to an author and his/her training in the field must be mentioned.
2	Purpose [of the app]: A statement clearly declaring that the [app] is not meant to replace the advice of a health professional has to be provided. A brief description of the [app]'s mission, purpose and intended audience is necessary. Another brief description of the organization behind the [app], its mission and its purpose is also necessary.
3	Confidentiality: The [app publisher] must describe its privacy policy regarding how you treat confidential, private or semi-private information such as email addresses and the content of emails received from or sent to [its users]
4	Information must be documented, referenced and dated: All medical content [including calculations and formulae] has to have a specific date of creation and a last modification date.
5	Justification of claims: All information about the benefits or performance of any treatment (medical and/or surgical), commercial product or service are considered as claims. All claims have to be backed up with scientific evidence (medical journals, reports or others).
6	[App] contact details: The [app] must be operational and the information must be accessible and clearly presented. There must be a way to contact the [app publisher], such as a working email address or contact form, for visitors who would like to have more details or support.
7	Funding: [The app publisher] must include a statement declaring its sources of funding.
8	Editorial and advertising policy: Conflicts of interest and external influences which could affect the objectivity of the editorial content must be clearly stated in the disclaimer. All [apps] displaying paying banners have to have an advertising policy. This policy must explain how the [publisher] distinguishes between editorial and advertising content and which advertisements are accepted. Any conflict of interest has to be explained.

Table 5-5 **Categories of software issue considered during assessment**

Categories used to group any software errors, user interface problems of other issue encountered during testing, extending those identified by our original review [317].

Issue type	Description	Example(s)
Data entry validation	▪ Data can be entered that are out-of-range or inappropriate, for example, textual values in a numeric field. ▪ New data can overwrite existing data without warning.	▪ Negative values of peak flow can be entered and are stored. ▪ New entries can overwrite existing data without warning.
Functionality	▪ A function of the app (e.g. calculation, data saving) does not operate as expected.	▪ App miscalculates the score of Asthma Control Test for adult. ▪ App displays an 'unfortunately you did not beat your highest score' message even if score is 100%.
Presentation and user interface (UI)	▪ Content having spelling and layout mistakes. ▪ User interface controls (e.g. textboxes, labels, buttons) are mislabeled, inoperative or inaccessible. ▪ Navigation between different parts of the app does not occur as expected or can lead to the user getting stuck on a particular screen.	▪ Some controls hidden when opened on a lower resolution screen. ▪ Text box for recording peak flow labelled as 'Peek Flow'. ▪ Some user controls not labelled in English.
Crash	▪ App stops responding in a timely way to user input or was closed unexpectedly by the smartphone or tablet operating system.	▪ App crashes when a backup of data entered by the user is attempted.
Network	▪ Problems with online or other data services (e.g. a website that an app downloads data from).	▪ Content does not load as expected. ▪ Synchronization with online service fails.
Other	▪ Any other software issue not described above.	▪ GPS function does not work.

5.3.6 *Data extraction*

Each app was reviewed by myself and at least one other researcher, working independently, who extracted data according to the criteria detailed in the previous section into a structured form for subsequent comparison and review (Appendix 7). Evaluations were combined, after discussion, into a single consolidated data extraction database for final analysis. To ensure consistency between the 2011 and 2013 reviews, a process of calibration was undertaken in which 10 apps that had been reviewed in the 2011 study were re-reviewed and judgements compared.

5.3.7 *Statistical analysis*

Unit of analysis

The unit of analysis presented here is the platform-independent mobile medical app, constituted by grouping apps available on multiple platforms into a single element for reporting and comparison. When multiple versions of an app were available on a given platform, for example 'demo' and 'full' versions, analysis was based on the more fully-featured version, ignoring free and paid status.

This approach reflects a change to that adopted in the initial 2011 analysis (and that reported in the published review[317]), in which no grouping was performed. The rationale for treating each app as a separate unit for analysis in that earlier analysis was the scope for quality variation arising from the need to tailor each platform and feature variant. However, the final data suggested that this was not in general the case. While in 2011, the number of duplicate apps was small (n=13) and sensitivity analysis demonstrated minimal impact when apps were either analysed separately or combined, by 2013, the number of duplicates had grown substantially (to n=77) with consequently greater scope for bias had apps continued to be double-counted.

Descriptive analysis

Descriptive statistics were used to summarize the types, functions, and quality characteristics of apps available in 2011, those released since 2011 (abbreviated to "New 2013" in data tables and legends), and overall ("All 2013").

When reporting comparisons between 2011 and 2013, data are written in chronological order, e.g., for "(X vs. Y)", X are data from 2011 and Y reflect data for apps released since 2011, unless explicitly specified.

Statistical comparisons

Statistical comparisons were performed between apps available in 2011 and those release since, on the basis that newer apps might have different quality characteristics arising from greater experience amongst developers and the influence of discourse in both medical and computer science literature emphasizing the importance of high-quality mobile medical apps. Planned analysis compared the proportion of educational domains completely, partially, or not satisfied, and the proportion of guidance consistent with the evidence base in those available in 2011 and those released since. It also compared the proportion of apps satisfying principles for ethical disclosures of information and the proportion of apps with specific software issues.

Apart from these planned comparisons, a small number of additional tests were conducted to compare differences in the proportion of paid-for apps, apps addressing complementary and alternative medicine, and the incorporation of features such as support details, in-app help, and social sharing features. Exploratory analyses were also performed to assess the feasibility of defining proxy measures, such as user ratings or content-independent criteria, for information content quality. These are marked as *post hoc* comparisons in the results.

All statistical comparisons of contingency-table counts were performed using a two-tailed Fisher's exact test [41], which evaluates the likelihood that the relative proportion in one variable is independent of a second. Unlike Chi-squared tests, Fisher's test is suitable for small sample sizes (<5 in any contingency table numerator or denominator). The Freeman-Halton extension [42] was used to handle two by three cases for information comprehensiveness and (post hoc) content orientation. Pearson's product moment correlation coefficient[331] was used to explore linear relationships between quantitative variables. To control for multiple comparisons, a Holm-Bonferroni [43] sequential adjustment was used to constrain the group-wise error rate at 5%, instead of specifying a fixed significance level for comparisons. All analyses were performed using R (Version 3.1.2, The R Foundation, Vienna, Austria).

5.3.8 *Contributions of other researchers*

To maximise sensitivity and minimize assessment related biases, both app selection and subsequent evaluation relied on judgements made by myself and at least one other reviewer. In the 2011 assessment, I was assisted by Mate Car, a colleague and fellow PhD student. In the 2013 update, second reviews were performed by Jing Ouyang and Aseem Ghaghda, medical students at Imperial College London.

The researchers named above, and supervisors Cecily Morrison and Josip Car, provided critical feedback during research planning, once results had been analysed and compiled, and on the draft manuscripts ultimately submitted for publication, but otherwise the work of study planning, data analysis and manuscript writing was mine alone.

5.3.9 *Governance*

Ethical approval was not required for this study which involved no patients, human tissue or identifiable data.

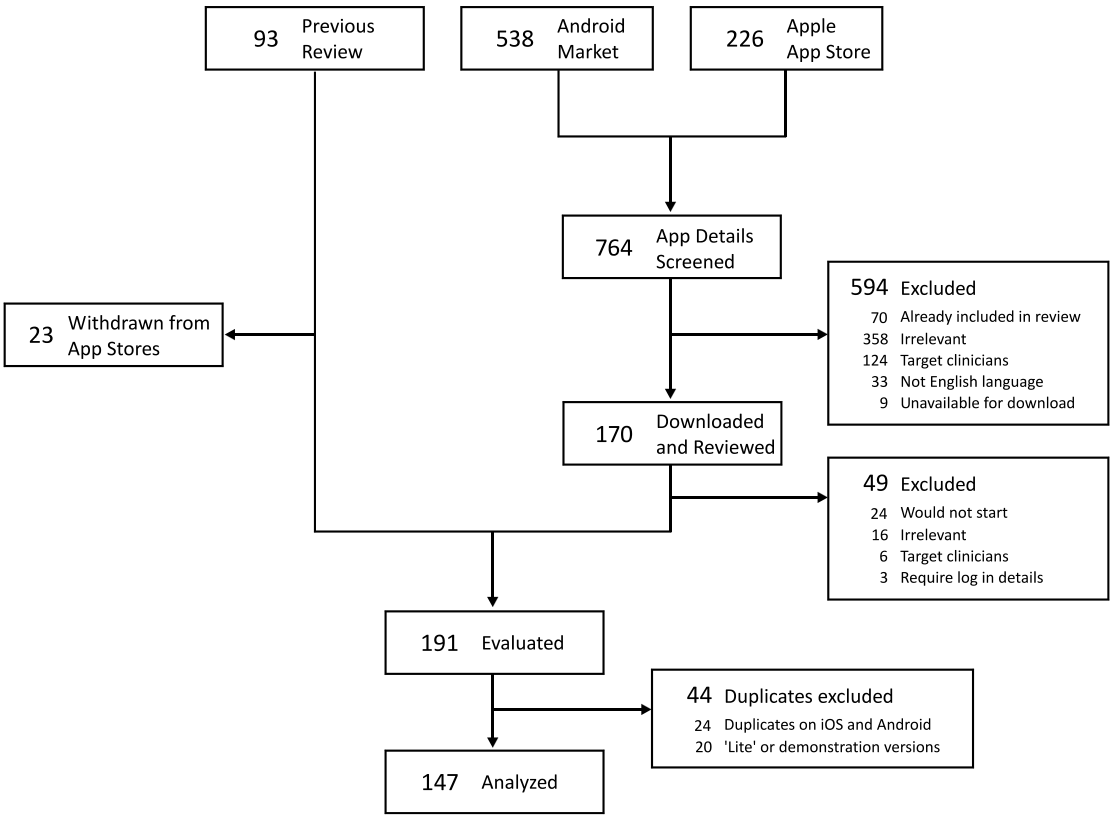


Figure 5-1 **Flowchart of 2013 app selection process**

Flowchart details the process of selecting individual apps. After evaluation of 191 apps, duplicates available on both iOS and Android (n=24) and, when more fully featured versions were available, 'lite' or demonstration versions (n=20) were excluded, leaving 147 unique apps for subsequent analysis.

5.4 Results

5.4.1 *Search results*

Searches performed in July 2011 identified 189 apps (n=101 Android, 8 Apple). After excluding unsuitable apps (n=96), 93 mobile medical apps were selected for evaluation. Second round searches performed in June, July, and August 2013 identified 764 apps (Figure 5-1, n=538 Android, 226 Apple). After excluding unsuitable apps (n=643), 191 apps were selected for evaluation. These included 70 apps identified in 2011 that remained available. Illustrative details of apps excluded at the final review stage in the 2013 round are provided in Appendix 8.

The number of mobile medical apps for asthma more than doubled between 2011 and 2013 (from 93 to 191), dominated by growth in apps available for Android (from 41 to 103, 151% increase, vs. iOS 52 to 88, 69% increase, charted over time in Figure 5-2). Forty-one apps were available on both Android and iOS platforms and a further 36 had multiple versions on a single platform. After removing 24 platform duplicates and 20 demonstration versions where a more fully-featured version was available, 2013 analysis was performed on 147 unique apps. Over a quarter (28%, n=22/78 unique apps) included in the 2011 review had been withdrawn, and a similar proportion (24%, n=19/78) updated, between 2011 and 2013. Withdrawals are included in reported 2011 statistics but not in overall 2013 totals. At the conclusion of analysis in June 2014, a further 20 apps had been withdrawn. These were retained for analysis, but annotated as withdrawn in data tables provided in web resource tinyurl.com/AsthmaFile2 which provides a detailed breakdown of the state of asthma apps in 2013.

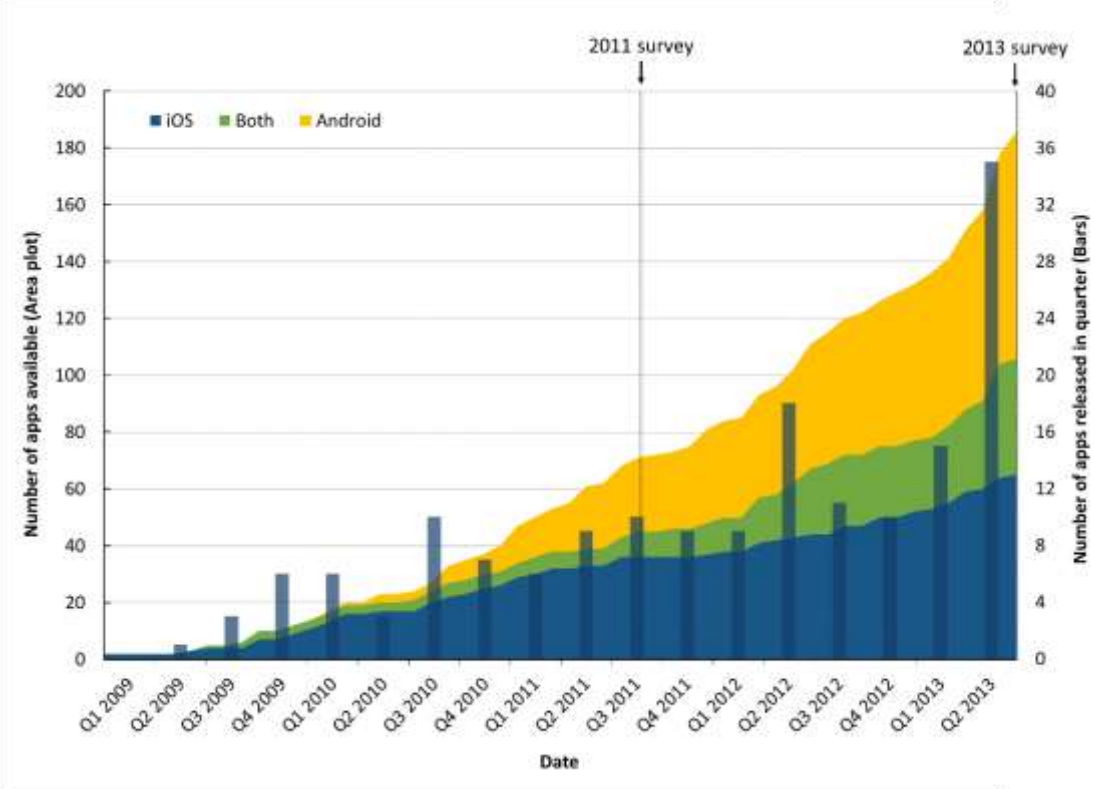


Figure 5-2 **Change over time in numbers of asthma apps available through public app stores**
Plot shows the total number of available apps for asthma against time, based on the original release date, for the period 2009 to mid-2013. Withdrawals are accounted for. Vertical lines indicate the dates of the 2011 and 2013 surveys. Data were not available for 5 apps; therefore, final n=186.

5.4.2 *Basic characteristics of apps*

Table 5-6 summarizes the basic characteristics of included apps.

Just over half of all mobile medical apps for asthma available in 2013 were free (54%, n=80/147). Compared to apps available in 2011, apps released since were significantly more likely to be free (33%, n=26/78 vs. 64%, n=59/92, *P* <0.001, *post hoc*) but also more likely to carry advertising (18%, n=14/78 vs. 34%, n=31/92, *P*=0.024, *post hoc*), although the difference was not significant after sequential adjustment. Between 2011 and 2013 the median cost of paid-for apps decreased from £1.27 GBP to £0.89 (£1.12 overall), reflecting a reduction in the proportion of apps charging more than £1.00 (37%, n=29/78 vs. 22%, n=20/92). The proportion of apps offering in-app upgrades to unlock addition functions remained unchanged at 9% (n=13/147) overall, (8%, n=7/78 vs. 7%, n=6/92, *P*=0.576, *post hoc*). While the US was consistently the major source of apps for asthma at both time points, accounting for almost half of apps with a known country of origin

Table 5-6 **Basic characteristics of included apps**

Characteristic	2011 (n=78) Yes	%	New 2013 (n=92) ¤ Yes	%	All 2013 (n=147) ¤ Yes	%
Platform						
Android only	32	41%	52	57%	73	50%
iOS only	40	51%	28	30%	57	39%
Both	6	8%	12	13%	17	12%
Cost						
Free	26	33%	59	64%	80	54%
Paid-for	52	67%	33	36%	67	46%
Median	£1.27	-	£0.89	-	£1.12	-
Country of origin †						
USA	24	31%	31	34%	52	35%
United Kingdom	5	6%	6	7%	8	5%
India	7	9%	7	8%	8	5%
Australia	3	4%	4	4%	7	5%
Other	10	13%	24	26%	33	22%
Unknown	29	37%	20	22%	39	27%
Content orientation						
Conventional medicine only	56	72%	59	64%	101	69%
CAM only	15	19%	17	18%	26	18%
Mixed	7	9%	16	17%	20	14%
Audience targeting ‡						
Children or young adults	2	3%	7	8%	8	5%
Parents or caregivers	3	4%	15	16%	19	13%
No audience stated	73	94%	73	79%	123	84%
Other features						
Adverts	14	18%	31	34%	39	27%
Social sharing	13	17%	35	38%	61	41%
Cloud storage	3	4%	10	11%	16	11%
Clinical disclaimer	32	41%	37	40%	55	37%
In-app help	14	18%	28	30%	43	29%
Online help	5	6%	6	7%	10	7%

¤ New 2013 = Apps available in 2013 that were not available in 2011; All 2013 = All apps available in 2013, excluding those available in 2011 that were subsequently discontinued.

† Four countries with highest overall number of apps in 2013 shown. Other countries were: Ireland (n=5), Germany (n=4), Switzerland (n=4), Japan (n=3), Romania (n=2), Singapore (n=2), Austria (n=1), France (n=1), Italy (n=1), Norway (n=1), Poland (n=1), Portugal (n=1), Spain (n=1), Sweden (n=1).

‡ Audience targeting was identified by specific claims made in the app title or description or content. We found no cases where apps explicitly indicated they were intended for adult use only. A small number of apps targeted both children and their parent or caregiver (2011 n=0, New 2013 n=3, All 2013 n=3).

available in 2013 (48%, n=52/108), the number of countries represented increased from 13 to 21.

Information provision was the function most commonly offered by nearly three fifths of mobile medical apps for asthma (56%, n=83/147; Table 5-7), followed by self-management tools in almost half (48%, n=70/147). The number of apps combining self-management tools, such as diaries, with any form of information content grew from one (1%) in 2011 to nine (6%) in 2013. As in 2011, small numbers of apps available in 2013 provided functions for assessing asthma symptoms using questionnaires (n=11) or sensors (n=2) or assisting with aspects of therapy (n=6). Over two thirds (69%, n=101/147) of apps available in 2013 presented content oriented towards conventional medical practice, little changed from 2011 (73% n=57/78). Although there was an increase in the proportion of apps released since 2011 incorporating mixed content addressing both conventional and alternative medical traditions, the change in relative frequencies was not significant (*P*=0.268, *post hoc*; Table 5-6).

The majority of available mobile medical apps for asthma (84%, n=123/147) did not target content at a particular group or by condition severity. However, although the overall proportion of new apps indicating that the product was targeted at a particular group remained low (16%, n=24/147), apps released since 2011 were significantly more likely to provide information targeting parents/caregivers (4%, n=3/78 vs. 16%, n=15/92, *P*=0.011, *post hoc*). There was also a non-significant increase in the proportion of apps targeting children (3%, n=2/78 vs. 8%, n=7/92, *P*=0.182, *post hoc*).

5.4.3 *Rating and download data*

Almost three fifths (56%, n=82/147) of app store entries available in 2013 included average user rating data derived from impression-based, voluntary ordinal ranking of between one to five stars (increasing numbers of stars indicating better subjective ratings). Most apps received neutral-positive ratings with a median average app rating of 3.5 and mean 3.5±0.9 SD. Only one in ten apps (10%, n=8/82) had average user ratings of 2 or fewer stars. Apps released since 2011 had higher average user ratings than earlier apps (median 3.5, mean 3.4, n=23 vs median 4.0, mean 3.7, n=49). While most apps received few ratings (median 12, mean 128±728 SD), distribution was positively skewed. The proportion of apps with available rating data almost doubled compared to 2011 (29%, n=23/78).

Download count data were available only for apps for Android (n=69 in 2013), since the iOS app store does not report download data. Because counts available from Android app store entries were supplied as discretised ranges (e.g. 10-50), the mid-range point was used to compute summary

Table 5-7 **Breakdown of app functions**

The table compares the types of functions present in mobile medical apps for asthma available in 2011 and 2013, and provides a breakdown by platform for 2013. 25 apps included in the 2011 assessment were withdrawn and this accounts for the lower overall total in 2013. Some apps contain multiple functions and are counted more than once.

			By date †				**By platform**	
	2011 (n=78)		New 2013 (n=92) ¤		All 2013 (n=147) ¤		All 2013 (n=191)	
Function	n	%	n	%	n	%	Android	iOS
Information	37	47%	60	65%	83	56%	66	44
General information	36	46%	51	55%	74	50%	56	39
First aid	12	15%	18	20%	23	16%	19	14
Inhaler technique guidance	2	(3%)	10	(11%)	12	(8%)	6	13
Other therapeutic instructions	13	17%	10	11%	16	11%	15	9
Self-management tools	36	46%	38	41%	70	48%	42	49
Diaries and trackers	21	27%	18	20%	36	24%	23	26
Pollen status	3	4%	8	9%	12	8%	6	10
Pollution status	3	4%	6	7%	9	6%	2	9
Allergen database	4	5%	3	3%	7	5%	5	4
Forum	0	0%	1	1%	1	1%	1	0
Online pharmacy	0	0%	1	1%	1	1%	1	0
Combined with information	1	1%	8	9%	9	6%	6	7
Assessment tools	9	12%	8	9%	16	11%	10	11
Physiological measurement	2	3%	1	1%	3	2%	0	4
Assessment questionnaires	4	5%	7	8%	11	7%	7	9
Standalone calculators	2	3%	2	2%	4	3%	3	1
Therapeutic tools	2	3%	5	5%	6	4%	1	5

† Apps available on both Android and iOS are counted only once. ¤ New 2013 = Apps available in 2013 that were not available in 2011; All 2013 = All apps available in 2013, excluding those available in 2011 that were subsequently discontinued.

statistics. The median number of downloads per app available in 2013 was 750, but like user rating counts, this was positively skewed (mean 20812±99636 SD). Ten apps (14% of those with counts, n=10/69) had been downloaded at least 10,000 times and two apps – a fitness tracker incorporating peak flow log, and a guide to home remedies based on CAM – at least 100,000 times. Of the remaining eight most popular apps, three provided CAM-based therapeutic tools, one was a pollen alert, and the remainder was sources of first aid (n=2) and allergy information (n=2). Approximately a fifth (21%, n=15/69) of apps had been downloaded fewer than 50 times. Summing reported counts yielded a conservative estimate of at least 1.4 million Android-based downloads of asthma-related apps by 2013, more than three times the number of downloads estimated in 2011 (421962 from n=26).

5.4.4 *Information apps*

The number of mobile medical apps offering information about asthma increased from 37 in 2011 to 83 by 2013, with 60 new apps and 14 withdrawals. Most information apps available in 2013 incorporated general information about asthma (89%, n=74/83), although a growing proportion of apps (23%, n=18/78 vs. 34%, n=31/92, *P*=0.174, *post hoc*) also incorporated specific instructions about the management of acute asthma, inhaler technique, and other aspects of self-management (discussed further in section 5.4.6 below.) Apps used a range of media to communicate information including text (64%, n=53/83), video and animation (10%, n=8/83), or by combining different media types (27%, n=22/83). A significantly greater proportion of apps released since 2011 used a medium other than text to communicate information (11%, n=4/37 vs. 42%, n=25/60, *P*=0.001, *post hoc*). A new development in 2013 was the use of gameplay (n=3) to provide interactive education in three products targeted at children and teenagers. Full details of information-containing apps are provided in web resource tinyurl.com/AsthmaFile2 : Table AF8.

Although increasing in number, the proportion of products presenting information based exclusively around conventional medical practices was unchanged (51%, n=19/37 vs. 50%, n=30/60). Just over a fifth of all apps available in 2013 (23%, n=19/83) combined alternative and conventional information and the remainder (28%, n=23/83) presented information based on alternative medical principles alone. Consequently, there were 59 apps (vs. 23 in 2011) incorporating conventional medical information for which it was possible to assess coverage of self-management education topics and consistency with guideline recommendations.

Comprehensiveness

Over two thirds (83%, n=49/59) of all mobile medical apps available in 2013 provided at least some details about basic aspects of asthma pathophysiology (Table 5-8). However, only just over half provided information about basic principles of medical management (53%, n=31/59), and fewer addressed key self-management skills, including allergen and trigger avoidance (44%, n=26/59), self-monitoring skills (39%, n=23/59), or how to use treatment appropriately (39%, n=23/59). Less than a third of apps addressed how to recognize the signs of deterioration (31%, n=18/59), the importance of personalized treatment and goal setting (31%, n=18/59), and the role of an action plan (22%, n=13/59). There was no significant difference in the proportion of mobile medical apps released since 2011 addressing domains other than basic facts (27%, n=6/22 vs. 20%, n=9/45, *P*=0.542), nor in the proportion of apps addressing each domain considered individually (*P* values shown in Table 3). While the overall number of products addressing three or more educational domains, at least partially, grew from 14 to 31 between 2011 and 2013, new apps were not more likely to address multiple domains (64%, n=14/22 vs. 51% n=23/45, *P*=0.435). In the same period, the number of products addressing all eight domains at least partially grew from two to five (with one withdrawal). No product in either 2011 or 2013 provided complete coverage of all eight domains by satisfying all criteria.

No consistent differences were seen in the proportion of mobile medical apps addressing any information domain either partially or wholly when partitioned by either payment model or platform, and no *post hoc* comparison achieved significance (Appendix 9). Exploratory analyses of the number of domains addressed either partially or wholly demonstrated negligible evidence for correlation (r=0.14, 95% CI -0.26 to 0.49) with app-store derived user ratings (n=27/59, median rating 4, range 1.5-5, median count of ratings per app =9) and weak negative correlation (r=-0.27, 95% CI -0.56 to 0.08) with download counts available for Android apps (n=33/59, median download count 100, range 1-50000).

Table 5-8 **Comprehensiveness of overage of asthma self-management education topics by information apps**

The table compares the proportion of mobile medical apps containing asthma self-management education information that address guideline-recommended topics either partially or wholly between 2011 and 2013. Apps focusing solely on CAM were excluded.

	2011 (n=23)				New 2013 (n=44) ¤					All 2013 (n=59) ¤			
Educational topic	No	Partially	Wholly	% †	No	Partially	Wholly	%	P value ‡	No	Partially	Wholly	%
Basic facts about the nature of the condition	2	15	6	91%	9	26	9	80%	0.510	10	37	12	83%
Allergen and trigger avoidance	9	12	2	61%	25	19	0	43%	0.094	33	24	2	44%
The nature of treatment: relievers and preventers	11	7	5	52%	22	18	4	50%	0.333	28	25	6	53%
Recognizing and responding appropriately to acute exacerbations	14	7	2	39%	30	9	5	32%	0.728	41	12	6	31%
How to use treatment	16	6	1	30%	27	17	0	39%	0.259	36	22	1	39%
Self-monitoring and assessment skills	16	6	1	30%	27	16	1	39%	0.632	36	20	3	39%
The role of a written, personalized action plan	18	2	3	22%	34	5	5	23%	1.000	46	6	7	22%
Personalizing the definition of good asthma control	17	5	1	26%	29	15	0	34%	0.244	41	18	0	31%

† The proportion of information apps that wholly or partially address a given educational topic.

‡ Two-tailed probability obtained from the Freeman-Halton extension to Fisher's exact test of the comparison of topic coverage in apps available in 2011 and those released subsequently. After applying a Holm-Bonferroni correction to control the family-wise error rate at less than or equal to 5%, no comparisons achieved significance.

¤ New 2013 = Apps available in 2013 that were not available in 2011; All 2013 = All apps available in 2013, excluding those available in 2011 that were subsequently discontinued.

Table 5-9 **Consistency of information apps with evidence-based recommendations**

The table compares the proportion of apps containing particular management advice that was consistent with evidence-based recommendations between 2011 and 2013. The expected advice is shown in parentheses. We use the term 'qualified benefit' when additional factors such as personal sensitivity to particular allergens or aspects of personal choice are relevant concerns and unconditional recommendations are therefore inappropriate. Apps focusing solely on CAM were excluded. Statistical comparison between apps in 2011 and new apps in 2013 was performed but is not shown because all comparisons, performed using Fisher's exact, yielded an exact probability of 1.0.

	2011			**New 2013 ¤**			**All 2013 ¤**		
Statement	n †	Consistent	% ‡	n	Consistent	%	n	Consistent	%
Removal of pets from the home (Qualified benefit)	3	1	33%	7	1	14%	8	1	13%
Fungal allergen avoidance and control measures (Qualified benefit)	8	0	0%	9	0	0%	13	0	0%
Cockroach avoidance and control measures (Qualified benefit)	6	0	0%	4	0	0%	7	0	0%
Cessation of active smoking (Beneficial)	7	7	100%	14	14	100%	19	19	100%
Avoidance of passive smoking (Beneficial)	8	8	100%	15	15	100%	21	21	100%
Avoidance of exposure to air pollution (Qualified benefit)	8	1	13%	14	1	7%	17	2	12%
Immunotherapy in atopic asthma (Beneficial)	1	1	100%	4	4	100%	5	5	100%
Weight reduction in obese patients (Beneficial)	3	3	100%	4	4	100%	7	7	100%
Seasonal influenza vaccination (Qualified benefit) **	4	1	25%	8	2	25%	10	2	20%

† The number of apps that took a stance on a given topic, for example by stating that a given action is definitely effective in controlling asthma symptoms.

‡ The proportion of apps whose stance is consistent with the evidence base.

¤ New 2013 = Apps available in 2013 that were not available in 2011; All 2013 = All apps available in 2013, excluding those available in 2011 that were subsequently discontinued.

* Seasonal influenza vaccination is routinely offered to asthmatic patients, however it is unclear if vaccination reduces the severity or frequency of flu-related asthma exacerbations[325].

Consistency with evidence base

Thirty-six mobile medical apps (vs. 14 in 2011) were evaluated for consistency of recommendations against nine evidence-based topics (Table 5-9) because they contained content addressing at least one topic. Smoking cessation and passive smoking avoidance were the topics most commonly addressed by apps (by n=19 and 21, respectively) and, as in 2011, were correctly recommended as beneficial by all apps. All apps addressing immunotherapy (n=5) and weight reduction (n=7) correctly advocated their use in specific patient populations. However, apps were also likely to recommend actions for which there is unclear evidence of benefit, such as mould (n=12/12) and cockroach (n=7/7) avoidance measures, removal of pets (n=7/8), and avoidance of air pollution (n=15/17). Most apps covering seasonal influenza vaccination recommended it (n=8/10) without acknowledging the uncertain impact on asthma [44].

Compared to 2011, there were no significant differences in the proportion of apps released since that presented advice consistent with the evidence base, either when considering each statement individually (exact *P* values computed from proportions shown in Table 4 were all 1.0) or when comparing the proportion of apps containing no statements contradicting evidence (36%, n=5/14 vs. 43%, n=12/28, *P*=0.747). No differences were seen in the proportions of apps consistent with evidence when partitioned either by payment model or platform (Appendix 10). Because of the polarization of consistency data, it was not possible to explore correlation with user-ratings or download counts.

A new finding in 2013 concerned a small number of mobile medical apps (n=6) containing advice emphasizing the possible harmful effects of conventional medicine and, in two cases, promoting a commercial product, for example a homeopathic remedy. Previously, apps containing mixed content had tended to emphasize the right to choose between medical approaches rather than denying accepted medical practice.

Readability

Sixty-two apps (vs 16 in 2011) contained at least 30 sentences of textual content on which readability analysis could be performed. The mean overall US grade level of apps available in 2013 was 9.98±2.26 SD (median 9.52), estimated by FKGL, and 9.12±1.70 SD (median 8.80), estimated by SMOG, requiring comprehension levels equivalent to those expected in UK school year 10 (ages 14 or higher). There were no significant differences in reading levels between apps published in 2011 (n=16, FKGL mean 10.50±1.97 SD) and those published since (n=45, 9.92±2.39 SD, P=0.387 *post hoc)* or by payment model (free vs paid, FKGL mean 9.98±2.41 SD, n=34 vs 9.98±2.07SD, n=28). Apps for adults (n=58) had a higher mean FKGL (10.04±2.29 SD) than the small number (n=4) targeting

children (9.09±1.55 SD) but the difference was not significant (P=0.4191 *post hoc*). However, there was evidence of lower required comprehension levels, equivalent to approximately a grade level difference, in apps for iOS (n=15, mean FKGL 8.86±1.74 SD) compared to those available for Android (n=38, 10.31±2.48 SD, P=0.044 *post hoc*), despite similar use of presentation formats and a greater proportion of iOS-only apps addressing conventional medical content (76%, n=19/25 vs 33%, n=15/45).

5.4.5 *Self-management tools*

Diaries

Thirty-six mobile medical apps available in 2013 (24%, vs. 27% in 2011) were diaries for recording asthma symptoms (n=27), peak flow measurements (n=24), and medication (n=24, detailed in web resource tinyurl.com/AsthmaFile2 : Table AF9). Six apps allowed a user to document an action plan. Six incorporated inhaler trackers, including two where this was the sole function, designed to alert a user when a metered dose inhaler or other medication was running low. One app connected to an electronic inhaler to automatically log doses. Two thirds of diaries (67%, n=24/36) offered a mechanism to summarize either recorded symptoms (n=4), peak flow (n=11), or both (n=9) in chart form. Over half (55% n=11/20) of apps charting peak flow used predicted (n=6), personal best (n=7), or manually entered (n=3) thresholds, either alone or in combination, to classify charted data to aid interpretation, for example, as 'green', 'yellow', and 'red' zones. Nine apps provided alerts based on changing input values. Seven provided specific advice, either by excerpting relevant parts of a user supplied-action plan (n=3/6 apps with action plan support) or displaying standardized text (n=4). Ten allowed reminders to be set to take peak flow measurements (n=9) or medication (n=3), and for scheduled appointments (n=2) or vaccinations (n=1). Compared to 2011, there were increases in the proportion of apps synchronizing and storing data online (10%, n=2/21 vs. 44%, n=8/18, *P*=0.025, *post hoc*) but not those offering a mechanism for sharing data with clinicians (62%, n=13/21 vs. 61%, n=11/18, *P*=1.000, *post hoc*), for example, email or file export.

Other tools

Nineteen apps (compared to 6 in 2011, Table 5-8) provided status information about pollen (n=10), air pollution (n=7), or both (n=2; web resource tinyurl.com/AsthmaFile2 : Table AF10). Most (n=12) provided coverage of locations in the US. Only one product, which relied on used-supplied data, offered global coverage. Seven apps (vs. 4 in 2011) offered databases of chemical additives to allow patients to identify potential triggers in food and cosmetic ingredients. One app combined an electronic version of an action plan with links to information about asthma. Another product

connected to a forum where users could view topics about asthma management and post their own questions. A third app offered UK patients the ability to purchase asthma medication online.

Diagnostic and assessment tools

Fifteen mobile medical apps (vs. 6 in 2011) contained diagnostic or assessment functions. Ten products offered questionnaires for asthma diagnosis (n=4) or assessment (n=6; web resource tinyurl.com/AsthmaFile2 : Table AF11). Two apps used the validated Asthma Control Test under license and one app reused a questionnaire developed by the University of Maryland. One app assigned a numeric score based on Global Initiative for Asthma criteria for asthma control. However, while these criteria exist[332], no validated approach could be identified in which criteria were assigned numeric scores to yield an aggregate sum. The remaining apps either did not provide a citation or validation information or the information provided was insufficient to verify the basis for assessment.

Nine products available in 2013 provided predicted peak flow calculators as either the main function (n=3) or integrated into a diary to provide reference values for chart generation (n=6). No calculator app provided a clear citation, but the underlying formula was deduced for two apps. Issues first identified in 2011 resulting in incorrect calculation output for two apps where the formula was deduced were unresolved. One app would silently forget the gender of the patient and subsequently provide male predicted values if the device was physically rotated to change from a portrait to landscape screen display. The other had a systematic error where female predicted values were returned for individuals five inches shorter in height than those entered. Only one app acknowledged the use of different peak flow measurement scales by allowing the user to pick which type of meter they used.

Three products used the device microphone to attempt to quantify lung volume (n=1) and analyse breath sounds (n=2), but were either not validated or experimental products that had not yet received regulatory approval.

5.4.6 *Therapeutic instructions and tools*

Management of acute asthma

Of the 23 mobile medical apps incorporating advice about the management of acute asthma, approximately half (52%, n=12/23) provided a clear description of the signs of acute asthma and gave practical advice such as sitting a patient up (48%, n=11/23) and offering reassurance (52%, n=12/23). Three fifths (61%, n=14/23) provided appropriate instructions about when to seek further help. While almost two thirds (65%, n=15/23) recommended the use of a rescue inhaler, less than a

third (30%, n=7/23) provided specific dose and timing instructions and only four apps (17%) provided instructions appropriate for children in addition to adults. Overall, four apps (17%) addressed all five components (web resource tinyurl.com/AsthmaFile2 : Table AF12). The proportion of apps released since 2011 that made treatment recommendations based on alternative medical practices did not change significantly (76%, n=13/17 vs. 56%, n=14/25, *P*=0.207, *post hoc*), and almost three fifths of apps available in 2013 (58%, n=19/33), and 39% (n=9/23) of those intended to manage acute asthma, recommended procedures unsupported by evidence, for example, the use of a hot water bottle to warm the chest, cider vinegar administered orally, or fasting for the duration of an attack.

Inhaler technique

Forty-one mobile medical apps (28% of n=147) contained specific instructions for the use of inhalers (8%, n=12/147), first aid for acute exacerbations (16%, n=23/147), or other approaches to the management of asthma such as the use of herbal remedies (11%, n=16/147, breakdown in web resource tinyurl.com/AsthmaFile2 : Table AF12). After pressurized metered dose inhalers (pMDI), either alone (100%, n=12/12) or with spacer devices (92%, n=11/12), the devices most commonly addressed by inhaler technique guidance were Accuhalers (58%, n=7/12) and Turbohalers (50%, n=6/12), although a range of additional devices were also covered (web resource tinyurl.com/AsthmaFile2 : Table AF12). Apps used text (33%, n=4/12), video (25%, n=3/12), animation (8%, n=1/12), or a combination (33%, n=4/12) to provide guidance. *Post hoc* evaluation (criteria in web resource tinyurl.com/AsthmaFile2 : Table AF6) examined the proportion of apps providing complete and correct information about inhaler preparation (67%, n=8/12), positioning in the mouth (67%, n=8/12), and the sequence of inhalation and actuation (50%, n=6/12). While a quarter (25%, n=3/12) addressed all three domains, the majority of apps omitted or misstated at least one step necessary for effective delivery of drugs to the lungs [45,46] for at least one of the inhalers discussed. The most common error (in 25%, n=4/12) was the failure to explain how inspiration should start before, and continue after, actuation of a pMDI. A variable proportion of apps addressed other aspects of inhaler use such as holding the breath after inhalation (83%, n=10/12), timing of a second dose (58%, n=7/12), and mouth rinsing to reduce the risk of candidiasis with inhaled steroids (50%, n=6/12). While five apps (42%) provided information about identifying empty Turbohalers or Accuhalers, no app addressed dose-tracking using pMDI. The two apps (17%) that covered inhaler care both provided incorrect information about spacer cleaning that risked static build-up interfering with subsequent doses.

Other tools

A small number of products available in 2013 (n=6 vs. 2 in 2011) were tools intended to have a therapeutic effect. Three apps provided training in aspects of Buteyko breathing, which may have a future role in asthma management [47]. The remaining three were based on alternative medical principles using hypnosis, mantra, and motivational messages.

5.4.7 *Content-independent assessment*

Results of assessment for compliance with ethical disclosures about authorship and data protection are summarized in Table 5-10 (based on criteria detailed in Table 5-4). Perhaps reflecting the increase in mobile medical apps syncing data to a cloud service (4%, n=3/78 vs. 11%, n=10/92, *P*=0.145, *post hoc*) or offer social sharing (17%, n=13/78 vs. 38%, n=35/92, *P*=0.002, *post hoc*), apps released since 2011 were significantly more likely to have a privacy policy (9%, n=7/78 vs. 36%, n=33/92, *P* <0.001). New apps were also significantly more likely to provide contact details (41%, n=32/78 vs. 64%, n=59/92, *P*=0.003). While no apps in 2011 had an editorial or advertising policy, five new apps did.

In general, apps provided limited information about the information sources used for the advice they contained. The proportion of mobile medical apps providing any kind of content attribution was unchanged (36%, n=21/78 vs. 33%, n=26/92, *P*=0.856). While a higher proportion of apps with authorship information addressed three or more educational domains at least partially (67%, n=16/24 vs 42%, n=15/36) the difference was not significant after adjustment (P=0.067 *post hoc*) and no difference was found when comparing the proportion of apps addressing domains other than basic facts (21%, n=5/24 vs 19%, n=7/36, P=1.000 *post hoc*). A similar pattern was seen in apps providing contact details versus those without (Appendix 11) but no consistent relationship was seen between information content comprehensiveness and the presence of information versioning, present in only a minority of apps (n=4), or any other content independent assessment domain.

Almost three fifths of information-containing apps (57%, n=47/83) available in 2013 repackaged content available freely online from resources such as Wikipedia, a small increase from 2011 (54%, n=19/35). The majority (77%, n=36/47) of these apps did so without referencing the original content sources. Overall, 35% (n=29/83) were ‘junk’ apps that reused, without attribution, information of generally low quality that was freely available online in a paid-for or advert-supported format.

Table 5-10 **Summary of ethical disclosures and software issues**

The table compares the proportion of mobile medical apps satisfying best practices for content attribution and ethical disclosures (detailed in Table AF4), and those with software issues identified during testing (detailed with examples in Table AF5), between 2011 and 2013.

	2011 (n=78)		New 2013 (n=92) ¤			All 2013 (n=147) ¤	
Quality domain	Yes	%†	Yes	%	P value‡	Yes	%
Ethical disclosures							
Attribution of authorship §	21	36%	26	33%	0.856	40	33%
Purpose clearly stated	69	88%	88	96%	0.090	141	96%
Privacy policy available	7	9%	33	36%	<0.001*	44	30%
Information versioning	1	1%	3	3%	0.626	4	3%
Contact details provided	32	41%	59	64%	0.003*	90	61%
Funding model clear	21	27%	30	33%	0.502	49	33%
Editorial/advertising policy	0	0%	5	5%	0.063	5	3%
Software issues							
Data entry validation issues **	9	33%	8	32%	1.000	16	33%
Functionality issues	13	17%	9	10%	0.252	15	10%
User interface issues	25	32%	34	37%	0.522	45	31%
Crashes	8	10%	8	9%	0.796	13	9%
Network issues	3	4%	20	22%	<0.001*	25	17%
Other issues	10	13%	18	20%	0.301	28	19%

† The proportion of information apps that satisfy a particular domain. Unless otherwise stated, the denominator is the total number of apps shown in the relevant heading.

‡ Two-tailed probability obtained from Fisher's exact test of the comparison of topic coverage in apps available in 2011 and those available since 2013. After applying a Holm-Bonferroni correction to control the family-wise error rate within each domain at less than or equal to 5%, three comparisons were significant. There are indicated with asterisks (*).

§ Denominator for proportions reflects only apps with attributable content, e.g. written information, measurement scales, pollen/pollution data. (Attribution of the software itself lies with the developers whose details are always released). Denominators: 2011 n=59, New 2013 n=80, 2013 n=120.

¤ New 2013 = Apps available in 2013 that were not available in 2011; All 2013 = All apps available in 2013, excluding those available in 2011 that were subsequently discontinued.

** Data entry validation concerns steps taken to prevent out-of-range or inappropriate data being stored in an app, for example, textual values allowed in a numeric field. As a result, the denominator reflects only apps permitting data entry, e.g. calculators, diaries. Denominators: 2011 n=27, New 2013 n=25, 2013 n=49.

5.4.8 *Software issues*

Software issues encountered during the test process were captured and summarized in Table 5-10. (using criteria detailed in Table 5-5). Compared to 2011, there was no change in the proportion of new apps lacking appropriate data entry validation to prevent, for example, textual data being entered in numeric data fields (33%, n=9/27 vs. 32%, n=8/25, *P*=1.000). The proportion of apps with problems with the user interface, such as mislabelled data fields (32%, n=25/78 vs. 37%, n=34/92, *P*=0.522), or core functionality, such as the correct operation of a calculator (17%, n=13/78 vs. 10%, n=9/92, *P*=0.252), was also unchanged. However, there was a significant increase in apps released since 2011 experiencing network problems when trying to access online content or services (4%, n=3/78 vs. 22%, n=20/92, *P* <0.001). Crashes affected about one in ten apps during testing, unchanged from 2011 (9%, n=13/147 overall).

5.4.9 *Research links*

Eight mobile medical apps (5%, n=8/147) self-identified as being linked to some form of research programme. Five were diaries, two provided air quality information and the seventh incorporated an asthma symptom questionnaire. Published literature was identified only for the questionnaire app, m.Carat for iOS and Android, where a pilot usability study involving 8 patients was used to inform user interface design changes[333]. No clinical trials were identified.

5.5 Discussion

5.5.1 *Summary of results*

Key findings of the assessments of mobile medical apps for asthma were:

- Evidence for limited compliance with best-practice recommendations for the design of education content and supportive tools. This was most clearly demonstrated for self-management educational information, accounting for over half of apps and for which detailed criteria could be specified. However, gaps were also identified in content targeting inhaler technique and assistive tools such as diaries. For example, only a fifth (20%, n=6/35) of diaries incorporated support for an asthma action plan.
- No evidence that apps produced since 2011 were more likely to be consistent with evidence. Combined with availability of CAM-based apps offering therapeutic interventions or instructions which appear to be popular but have no basis in evidence, the findings raise the prospect of substantial app use from which little or no clinical benefit can be expected.

- Limited availability of features enabling communication, other than sharing of static 'snapshots' of data as files or email, with either clinicians or peers. Only a minority of apps available in 2013 (6%, n=9/147) combined information with tools enabling skills to be put into practice, although this proportion had increased compared to apps available in 2011.
- Identification of apps posing potential clinical safety risks, arising either from the failure to provide appropriate contingent advice for the management of acute asthma or relating to failures in the implementation of diagnostic and calculator algorithms which might lead to delayed or inappropriate treatment decisions. For example, a peak flow calculator that underestimates predicted lung capacity might inappropriately delay medication escalation if action plan step-up criteria were to be derived from the calculation.
- Evidence for unattributed content re-use linked to commercial products as part of a proposed class of 'junk apps' whose purpose appears to be to generate sales rather than support asthma management, for example by promoting commercial products or incorporating pay-per-click advertising and reusing material originally produced by online content farms [334].
- Apparently high rates of app withdrawal, updates and new app releases. Unexpected removal of existing apps poses a potential challenge to clinical services based around the availability of particular products, while updates create a recurring requirement for quality appraisal and testing with concomitant workload impacts. The emergence of new features, such as the use of online data storage, raises the prospect of evaluation strategies that will need to adapt quickly to changing risks, such as information governance.

5.5.2 *Integration with existing research*

A range of studies have used observational methods to characterise and evaluate apps targeting specific health issues, including diabetes. An overview of these studies is presented here. Studies were either identified incidentally during a multi-database literature search performed for the systematic review described in Chapter four (search strategy detailed in Appendix 2), from a recent systematic review[335], or through snowball searches of related literature.

Observational assessments of mobile medical apps for asthma

One additional study was identified incorporating mobile medical apps for asthma, but this focused on numbers of available apps and did not evaluate content. An April 2013 survey of apps addressing the most prevalent health conditions identified by the WHO identified 107 iOS and Android apps for

asthma[313]. The results presented here (n=191) suggest that this was an underestimate, perhaps arising from a search strategy that examined only apps returned by a search for the term asthma, rather than additional related terms or word variants.

Observational assessments of mobile medical apps for diabetes

Unlike asthma, there have been multiple studies of commercially-available mobile medical apps for diabetes. Serial assessments of apps for diabetes have demonstrated rapid growth, paralleling those seen in apps for asthma. A study of iOS apps found 60 in July 2009, growing to 260 by February 2011[39]. A subsequent study in April 2013 identified 630 apps intended for patient use, of which 263 ran on iOS, 260 on Android and 107 on both platforms[316], although these figures be an underestimate[313].

Descriptive characterisations of mobile medical apps for diabetes identify a number of differences compared to apps for asthma, suggesting a dominant focus on self-monitoring activities in contrast to the information provision features of asthma apps[40, 315, 316]. In a comprehensive assessment of 656 diabetes apps undertaken in April 2013[316]:

- A third (35%, n=226/656) of apps for diabetes incorporated educational information. This is substantially lower than asthma, where almost three fifths of apps were a source of asthma information.
- Over half (53%, n=348/656) of apps provided a diary or logging function and substantially higher than the quarter of apps for asthma providing a diary function, and addressing a broader range of data types, such as blood glucose, insulin dose, carbohydrate intake, weight and physical activity[40]. While the proportion of apps providing some kind of decision support (17%, n=58/348) was similar to that seen in asthma (19%, n=7/36), a greater proportion of diabetes apps incorporated mechanisms for sharing data with a clinician (58%, n=204/348 vs 40%, n=13/36). Just over a fifth (22%, n=75/348) of diabetes diaries incorporated a medication reminder, compared to fewer than one in ten of asthma diaries (8%, n=3/36). Similar to the limited support for wireless peak flow meters found for asthma apps, only a small number of apps supported functionality for data transfer from a Bluetooth glucose meter.
- Similar to the condition-specific functions provided in certain apps for asthma, such as pollution alerts, targeted apps for diabetes incorporated functions such as food databases and dietary advice (15%, n=95/656).

A high prevalence of logging apps, but concomitantly lower rates of educational content, was also found in 2001 multi-platform survey of diabetes apps[39]. A separate analysis by Eng et al.[40] of a random sample of 100 iOS apps also identified similar categories, although the estimated proportions varied. This study identified a discrete category of insulin dose calculators (8%, n=8/100) not reported in the Arnhold review.

Only two studies were identified in which the content of mobile medical apps for diabetes were evaluated using evidence-based clinical criteria and both examined feature comprehensiveness. Chomutare et al.[39] used diabetes clinical guidelines to identify six desirable app features that might enable coherent effective self-management: self-monitoring (of glucose, insulin, weight, physical activity, diet and blood pressure); education; reminders; social media integration; disease-related data-sharing and synchronization with a personal health record. The study identified a lack of structured educational materials, incorporated in only a fifth (20%, n=27/101), and tailored in only a small number of apps (n=7), but did not otherwise interrogate content accuracy or coverage. An associated lack of integration between tools and educational content echoes findings for asthma (6%, n=9/147). The authors propose that this as a potential barrier to app use for diabetic individuals not using insulin, who may not appreciate the value of self-monitoring without suitable, personalized educational and motivational support. In a 2014 review of 54 Spanish-language apps for iOS, Aguayo et al.[336] examined the extent to which diabetes self-management education topics and skills referenced in app store descriptions were present in downloaded apps, finding that almost 80% claimed to support content that was not available. However, it was unclear if this reflected inaccuracy of descriptions, a lack of Spanish-language translations within apps, or both. No study of diabetes apps has included a systematic evaluation of the evidence-based consistency of individual components, such as self-management education. The feasibility of this option was considered during study development but ultimately discounted (explanation in section 5.5.3 below).

A small number of studies attempted to evaluate the usability of mobile medical apps for diabetes using either laboratory evaluations or expert judgement. In a laboratory study, Rao et al. [314] asked 22 adults with either type 1 or 2 diabetes to complete a series of structured tasks using three 2009 iOS self-monitoring apps for diabetes and measured time-to-task-completion and self-rated ease of use and perceived feature usefulness. Although younger participants were, on average, up to 82% faster than users aged 44 or older, time-to-task completion, using the app subjectively rated as easiest to use, did not vary by gender, prior exposure to smartphone technology or educational status. In a subsequent 2011 study of 8 apps for iOS (n=4) and Android (n=4), Garcia et al. used a

keystroke analysis to identify specific opportunities for improving data-entry task efficiency, including providing user interface elements, such as keyboards, optimised to underlying data type and finding a balance between user customization capabilities and 'option overload' [41]. Patient participants in Rao consistently identified ease-of-use, which was negatively correlated with task-completion time, as 'very important'. Individuals reported value in features directly associated with data entry such as wireless transfer from a blood glucose meter ahead of considerations such as price, user interface design or data summary and sharing capabilities. However, it was unclear if participants were blinded to time-keeping necessitated by the study design, which may have influenced perceptions, and the study did not examine attitudes reflecting longer-term use.

Demidowitch et al.[35] presented the results of researcher usability evaluation of 42 diabetes self-management apps available for Android in April 2011. Two researchers applied a study-specific instrument to score ease-of-use, interface design, customisation capability, data entry, retrieval and sharing and data use in charts and graphics for six function types, including blood glucose tracking and insulin calculation. Each function type was rated separately using an ordinal scale from 1-5 (scoring 0 if not present in an app), averaged across researchers, and then combined. The mean average function-specific score was 3.0 ± 0.9SD, while the mean sum, reflecting the composite of function coverage and usability score, was 11.3 ± 5.9SD out of 30.0. Fewer than one in ten apps (n=4/42) generated a composite usability score of greater than 20 indicating comprehensive feature coverage and good subjective usability. Although the study was performed with clinical specialist input, no detail was provided about validation of the measurement approach and, while mean usability scores were moderately correlated with app-store based user ratings (Pearson's r = 0.57), no association was seen with composite scores, or between study scores and cost or download counts. As a result, while highlighting the scope for variation in aspects of design best-practice, the relevance of these to patients was less clear.

The potential limitations of these studies in either defining suitable criteria for expert judgement that robustly proxy user perceptions or in adequately capturing user attitudes from time-limited laboratory-based evaluations were the main reasons why an equivalent evaluation was not performed in apps for asthma. Instead, a qualitative approach was used to gather detailed information about factors shaping patterns of use in apps for asthma and diabetes. The results of this separate study are presented in chapter seven.

Echoing deficits in asthma attack guidance and diagnostic algorithms identified in apps for asthma, a few studies of diabetes apps have recognised scope for harms arising from errors in app design or function. Arnhold et al. used a custom schema to rate the usability of a sample of 66 apps (drawn

from the larger assessment described above) on a 5-point Likert scale[316]. While modal usability scores were comparable with Demidowitch et al. and inversely correlated with the number of supported functions, a number of issues were identified. These included poor fault tolerance, conceptually equivalent to software errors identified in apps for asthma, and a lack of appropriate cues identifying interactive features in user interfaces. Separately, Eng et el. linked software failure in diabetes apps to the risk of adverse clinical events, observing that none of 8 insulin dose calculator apps reviewed had undergone FDA approval, but did not interrogate the behaviour of these apps in detail[40]. Garcia et al. noted the potential negative impact of unrecoverable errors on user experience, but did not connect these to a risk of clinical harms arising from slips or lapses caused by task disruption[41]. However, they did identify scope for privacy compromise arising from the failure to secure personal information during data transmission.

Arnhold also uncovered variable compliance with features intended to make content accessible to users with specific impairments which appeared to segregate by operating system. Thus while 86% (n=25/29) of iOS apps supported text-to-speech screen reading (compared to 68%, n=19/28 of Android apps), no iOS provided effective large type support (versus 40%, n=11/27 of Android apps). The content focus of the asthma review provides a complementary perspective by highlighting the high required levels of reading comprehension implied by the measured complexity of written content.

Assessments of mobile medical apps for other conditions

Few studies appear to have systematically evaluated mobile medical apps for long-term conditions other than diabetes. Pandey et al.[337] evaluated compliance with evidence in 46 iOS apps providing information about cancer targeted at patients and the public. While half (50%, n=23/46) provided general information about cancer, and over a quarter (28%, n=13/46) provided targeted patient support tools, fewer than a third (32%, n=15/46) incorporated only scientifically valid information, significantly less than apps targeted at healthcare professionals. Like asthma, management tools, in particular, were highlighted as being poorly supported by evidence. In a separate 2013 assessment, Bender et al.[33] found no app for which a published evaluation was available from a set of 269 iOS, Android, Blackberry and Symbian cancer apps. The study identified missed opportunities for assisted self-monitoring, communication with care givers and peer support. In contrast to this expert-based approach, at least one study has attempted to use patient data to qualify judgements about feature coverage.

In an evaluation of 45 free mobile medical apps for patients with Parkinson's disease for iOS, Divakaruni et al. [338] found that less than half incorporated features identified as important

through a patient survey. Although most apps supported multiple, customisable drug entry, only a third (33%) supported a mechanism to print and share medication history, despite this being prioritised by patients.

Rather than evaluate content directly, some studies have examined content attribution and evidence of appropriate clinical input during app design. The potential for limited clinical input was first highlighted in a survey of 111 pain management apps performed in 2010[42], in which 86% of app developers reported no involvement of any healthcare professional. For apps without a clinical developer, 95% did not provide any details about content sources, although content attribution, where present, appeared to be reputable. In a separate study, O'Neill and Brady[339] examined professional involvement in the development of 29 mobile medical apps for colorectal disease available in 2012, and identified only four apps where input had been sought. Connor et al.[340] also assessed professional involvement in the development of apps for hernia, but additionally examined compliance with evidence and the presence of commercial content. Of seven identified apps, only two satisfied all three domains, however the criteria used to judge each domain were not clear specified. No study examined the reliability of content authorship or other proxies as a predictor of formally evaluated content quality or safety.

Mobile medical apps promoting health behaviour change, such as smoking cessation, have been the subject of a number of evaluations. Updating an earlier review[3], Abroms et al.[44] scored 98 smoking cessation apps for iOS (n=47) and Android (n=51) for adherence to US clinical guidelines for treating tobacco use, using a custom rating scale. Apps achieved a mean score of 12.9 out of 42[44], representing low overall adherence and, in particular, deficits in recommending effective treatments such as nicotine replacement, counselling or 'quitline' services[3]. Azar et al.[341] evaluated 23 apps for weight management available in 2012, and identified low rates of integration of behavioural theory-based strategies in features such as diet tracking and recipe planning. A similar result was demonstrated by Middelweerd et al.[342] who examined 64 apps intended to promote physical activity on iOS (n=41) and Android (n=23) and found that apps incorporated a mean of 5 out of 23 possible behaviour change techniques. Limited implementation of behaviour change strategies was identified as cross-cutting issue in a review of over 3300 health and fitness apps which encompassed those targeting emotional, mental and sexual health needs in addition to those focussed on healthy eating, exercise and physical health[343]. In a 2012 review of apps addressing the prevention and risk management for sexually transmitted infections (STI) , fewer than one in ten apps (9%, n=6/69) addressed five evidence-based content areas for HIV and STI prevention, such as testing and appropriate use of condoms.

Mobile medical app assessment methods research

Recently, a number of studies have attempted to standardise approaches to mobile medical app quality assessment. While motivated by factors similar to this study, such as evidence for app uptake by patients with anticipated scope for benefit and harm, and the desire to enable informed app selections by patients and clinicians, these studies instead propose universal criteria for assessment. The underlying aim appears to be to increase the reach of appraisal by removing, or reducing, the need for domain-specific criteria that require specialist technical knowledge to define and are potentially time consuming to apply.

Accessibility to non-technical or clinical-specialist audiences was a key factor in the design of the mobile app rating scale (MARS), a 23-question instrument addressing four quality domains of engagement, functionality, aesthetics, information credibility [344]. The tool incorporates a combination of subjective and objective closed-choice questions, from which domain-specific and average overall quality scores may be derived. A separate section captures subjective perceptions of usage intentions which may qualify interpretation of quality scores. Internal consistency and inter-rater reliability have been demonstrated for the assessment of well-being apps, but no data were found examining performance in the evaluation of apps for long-term conditions.

While quality scores enable comparisons and correlational analyses, they also abstract details that may be important for interpretation. Other authors have proposed strategies that involve a standardised descriptive approach intended to inform context-specific judgements about app suitability rather than generating a single quality score with a fixed interpretation. Cummings et al. identified a set of nine 'areas of concern' for consideration by end users and interested parties[69]. These were partitioned into 'data issues' concerning storage security, privacy, questions of data ownership, governing jurisdictions and third party access rights, and 'software issues' including accessibility, clinical effectiveness, credibility, information quality, information quality and intended usage. Separately, Albrecht proposed 'AppSynopsis'[345, 346], a seven-domain instrument detailing metadata about the developer of each app, its intended purpose, functionality and usability, data addressing validity, and information governance-related issues of data collection, protection and transmission. Albrecht suggests that data addressing these domains could be published as a structured disclosure accompanying the release of apps to enable users and clinicians to judge suitability and trustworthiness.

A similar approach was proposed by Lewis, who suggested that content-independent criteria produced by the Health on the Net Foundation for the review of internet health information (also used as part of this review) could be repurposed as the basis of a self-certification approach involving

open disclosures of authorship, financial and ethical issues[347]. Reliance on developer disclosures, also required for AppSynopsis[346], raises questions about the extent to which developers would be prepared to engage with such programmes. Notably, it contrasts with the user-led approach of MARS which, in theory, creates no such requirement. However, data collected during the development of AppSynopsis[345] found that limitations in publicly-available information presented a barrier to user judgements about privacy-related, suggesting that, for some domains at least, developer disclosures or expert evaluations may be necessary.

Common to these assessment methods is recognition of the importance of effectiveness and clinical accuracy, with a specific on information content, which overlaps with the scope of this review. However, while a desire for simplified, accessible assessments is understandable, it is currently unclear whether content-independent criteria can efficiently proxy domain-specific assessments. In this review, no clear relationship was found between criteria such as disclosure of authorship or information versioning and information content quality. Nor did other accessible potential proxies for quality, such as user ratings, appear to predict content comprehensiveness. In addition, the finding of a possible inverse relationship between download counts and content scores highlights the possibility that factors other than content quality substantially influence patient app use. This possibility, and quality factors identified in the assessment methods described above that were not examined in the asthma review, such as perceptions of usability, will be the subject of chapter seven. However, they are also the result of *post hoc* exploratory work, reflecting the fact that the asthma assessment was not specifically designed to explore predictive relationships between quality domains. Future work must address this question more directly before firm conclusions may be drawn.

5.5.3 *Study limitations*

The study design incorporated a strategies intended to maximise the sensitivity of app identification and control bias and error arising from the assessment process, including the use of pre-specified assessment criteria and statistical comparisons. By examining two time points, and analysing mobile medical apps available at each separately, it aimed to address the possibility that quality issues first identified in 2011 might be transient rather than representative of persistent phenomena with clinical relevance. Nevertheless, the design had a number of limitations.

The study did not incorporate non English-language apps, nor, in 2013, those available for platforms other than iOS and Android. The 2011 study also examined Blackberry and Windows Phone, but these were not included in the final analysis because of limited and declining market share. The

possibility exists, although the limited 2011 data do not support this, that these apps might have different content and quality characteristics not identified in this systematic assessment.

Nor is it possible to infer trends from data based only two time points and a high identified rate of turnover amongst published apps. The emergence of apps using online data storage and multimedia content may not be indicative of longer-term or sustained changes in apps. Specific quality issues affecting particular apps may change as new features are introduced. Nevertheless, is seems unlikely that broad categories of quality issue, such as poor information content quality or potential safety issues arising from aspects of interactive tool design, will disappear as relevant considerations for the designers of mobile medical apps or those involved in evaluating their quality. A finding of low overall compliance with evidence-based guidelines has relevance as a factor informing *contemporary* discussion about the use of apps in routine care and related considerations, such as issues of scope in current efforts designed to assist consumers in choosing suitable apps.

Assessment was also constrained by the extent to which specific topics were specified and consistent in clinical guidance. As discussed (section 5.3.2 above), triangulation across guidelines was used to try to ensure both assessment validity and evaluation relevant to current accepted practice. The approach aimed also to address potential concerns about the appropriateness of country-specific guidance being applied to mobile medical apps developed in other settings by adopting locale-independent standards for assessment. For asthma, this was substantially enabled by homogeneity in the core management approaches advocated by international guidance. However, not all components of self-management were specified in detail and in particular, there was variable detail about the design of self-management tools. For example, while evidence addressed aspects of action plan design[155], no detailed guidance was available about design factors influencing the effectiveness of self-monitoring diaries. It is possible that assessment design based on *de novo* synthesis of primary studies, or secondary syntheses, may have yielded more comprehensive criteria, although BTS/SIG and GINA guidelines were newly updated at the time of study design. This approach to criteria development would also have tended to undermine the claim to be representative of accepted best-practice in which research findings are calibrated against pragmatic concerns and feasibility.

A lack of consistency and detailed specification of both self-management education and tool design was a major factor influencing a decision not to incorporate apps for diabetes in this assessment (or as a separate study). The difficulty of establishing a consensus basis for diabetes app assessment is underlined by the fact that, amongst at least seven systematic studies of diabetes apps, none have attempted to perform content assessment beyond identifying the presence or absence of high-level

self-management features, such as glucose monitoring. Together these two limitations – of coverage in asthma guidelines of specific tool types described in the previous paragraph, and of consistency across diabetes guidelines – highlight scope for primary research focussing on the mechanics of self-management, whether supported by technology or otherwise, to address gaps in knowledge and resolve uncertainties giving rise to inconsistent guideline advice.

5.5.4 *Synthesis of issues for thesis discussion*

Issues identified in this chapter that will be developed further in the thesis-level synthesis and discussion presented in chapter eight are:

- Findings of limited compliance with evidence-based recommendations which question the likely effectiveness of commercially available mobile medical apps for asthma and diabetes. Chapter eight will examine the potential roles for developers, app stores and regulators in addressing this identified gap and deal with specific issues, such as the emergence of 'junk' apps. Discussion will consider whether contributions from app assessment methods research (see section 5.5.2.4 above), such as proposals for structured disclosures of validation processes, have a role to play in future quality assurance.
- Potential translation challenges arising from the gap between the supported self-care focus of research literature (described in chapter four) and the limited communication and data sharing facilities afforded by publicly-available mobile medical apps.
- Practical implications for clinical practitioners interested in integrating apps into routine practice arising from high observed prevalence of quality issues, app turnover and feature evolution. Chapter eight will explore issues of capacity (to detect quality issues), resources (to support patients and ensure assessments are up-to-date) and governance (to provide protections against unexpected app withdrawals) for clinical programs that use publicly-available apps.

5.6 Chapter summary

Chapter five examined the quality of commercially available mobile medical apps for asthma, reporting data from serial assessments of apps for asthma. A variable degree of consistency with evidence for effectiveness informing clinical practice guidelines was demonstrated most clearly in apps providing information about asthma, but also identified in tools offering diagnostic and therapeutic functions. No evidence was found that quality had improved over time. The findings

raise the prospect of large numbers of apps with limited potential for clinical benefit. The findings are consistent with gaps in inclusion of guideline-recommended features in apps for diabetes, although no study for diabetes has applied the kind of detailed assessment approach described here.

The study also aimed to prospectively identify issues affecting the suitability of mobile medical apps for use by patients. The following chapters develop two issues identified as part of this discussion. Chapter six focuses on app safety, presenting the results of an empirical investigation of dose-calculation apps for diabetes. Motivation for this study was, in part, a response to the recognition of potential safety issues affecting the performance of predicted peak flow calculators. Issues identified during asthma app evaluation informed the development of the error taxonomy used in this subsequent assessment. Chapter seven responds to the need to examine the perspectives of mobile medical app users in interpreting issues of quality by reporting the results of a qualitative study of experiences from patients already using apps for either asthma or diabetes.

Chapter six: Safety of dose calculator apps for diabetes. A systematic content assessment

6.1 Chapter introduction

While chapter five focussed on the anticipated effectiveness of publicly-available mobile medical apps for self-care, this chapter examines the possibility that self-care apps available for public use might pose a safety risk. Continuing the systematic assessment approach introduced in the previous chapter, it presents the results of a detailed review of insulin dose calculator apps. The rationale for a safety focus has been described earlier (section 2.6.2 above) but is recapitulated and expanded below to explain the specific choice of insulin dose calculators as a test case. Like chapter five, the work seeks to provide an observational perspective involving real world apps (Thesis Objective 2) that offers a contrast with findings from intervention studies of apps (Thesis Objective 1).

A focus on safety is justified, in general, by its inclusion as a top-level quality domain . However, there are a number of specific factors that additionally motivated its examination in relation to mobile medical apps for self-care. The first arises from the flexibility of apps to incorporate functions with substantial potential clinical risk. Examples include diagnostic functions, where missed or incorrect diagnoses may delay treatment or lead to inappropriate therapy, and apps offering therapeutic functions or advice that, in addition to questions of effectiveness, may carry potential harms. This scope is formally recognized in recent in guidance produced by European[233] and US regulators[22], which uses a risk-based approach to require that apps offering such functions undergo approvals equivalent to those applied to physical medical devices. Little is known, however, about the extent to which mobile medical app developers are aware of, and are proactively complying with, these requirements. Despite mobile medical apps numbering at least 13,500, by 2014 the US Food and Drug Administration had granted formal clearances to only 100[348].The growing numbers of apps and the breadth of potential functions coupled with feature evolution of the kind identified in the assessment of asthma apps, highlights potential challenges of both scope and scale for regulatory oversight.

Related to issues of scope was a second observation concerning the unclear, and potentially variable, capacity of patient users to identify and mitigate safety risks in health technologies compared to professional users. Design strategies to assist users in avoiding errors arising from the use of

information technology, such as validation of data entry, are advocated in computer systems intended for expert use[6], but may be even more important in those intended for non-professional users whose clinical knowledge and skills – and consequent ability to recognize and respond appropriately to failures – cannot be guaranteed. A changed risk profile may also arise from differences in the ways mobile medical apps are developed compared to traditional medical software. For example, while in the UK software systems used by professionals in primary care are produced by a limited number of established companies, the barrier to entry to app development is low and, based on information collected during the asthma review, populated by globally-distributed companies which vary in size and focus. Questions have been posed about the extent to which mobile medical app development routinely incorporates clinical expertise[42], the differing quality incentives that might shape developer behaviour compared to clinical practitioners[349], and the extent to which quality control methods are standardised[350] and routinely applied[346]. All have potential impacts on app safety, and recommend empirical investigation.

Third was recent evidence identifying defects in clinical mobile medical apps offering both diagnostic and therapeutic functions. The review of mobile medical apps for asthma described in chapter five identified failures in predicted peak flow calculators, asthma attack advice and apps advocating CAM-based techniques. Variable sensitivity and specificity was highlighted in a separate study of four mobile medical apps offering diagnostic screening for melanoma using analysis of camera images[17]. Tested with 188 reference images of known histology-based diagnosis, the positive predictive value – the likelihood of a melanoma diagnosis flagged by the app being correct – was never greater than even (range 33.3 to 42.1%). Conversely, the negative predictive value ranged from 65.4 to 97% highlighting the possibility of false reassurances arising from false negatives. These findings, while striking, must nevertheless be viewed in terms of the limited number of apps reviewed. In a larger study of 111 mobile medical apps, a risk of adverse effects, including unnecessary distress relating, arising from the use of therapeutic products with no scientific basis leading to poor symptom control was also identified in a review of apps for pain management[42]. In addition to research findings, there have been isolated examples of app withdrawals on safety grounds. In 2012, Sanofi Aventis, a pharmaceutical company, temporarily recalled its diabetes app after errors were identified in insulin dose calculation[348]. In 2013, a medical calculator developed by another drugs company, Pfizer, was withdrawn after calculation errors were identified[19]. In the US, the Federal Trade Commission, although not specifically charged with a healthcare regulatory role, has also acted to eliminate apps making therapeutic claims with no basis in evidence[18].

Although these data are interesting, they are limited. Safety issues were an incidental finding in the review of asthma apps rather than a planned objective. The evaluative approach, based on identification of comparator data against which to evaluate the performance of tools such as calculators, was developed as a reactive strategy to app functions identified in the original 2011 review rather than being base on a formal schema of the kind used to evaluate content consistency with evidence. In addition, the danger of inferences based on small numbers of apps or events, such as app withdrawals, that rely on developer issue recognition or regulator intervention was highlighted by a 2014 assessment of consistency of medical calculator app output against a stated formula found errors in only 1.4% of test cases[351]. At the time of research planning, no study was identified which had aimed to provide a systematic exploration of safety issue in relation to a long-term condition, and this – together with those factors described above – motivated the study described in this chapter. It was anticipated that a census-based approach, similar to that used to evaluate asthma apps, might effectively address these concerns by exhaustively evaluating multiple apps according to planned criteria.

The decision to focus evaluation on a specific class of mobile medical apps, insulin dose calculators, reflected a balance between feasibility, relevance to self-care (for diabetes) and scope to contribute to the broader discussion about patient app safety. The breadth of potential app functions for which questions of safety exist recommended a targeted approach on pragmatic grounds if assessment were not to become intractable. The specific choice of diabetes calculators was informed by several factors. Tailored insulin therapy is a core component of self-management for type 1 and, increasingly, type 2 diabetes as a result of data indicating clinical benefits arising from strict glycaemic control. Methods for calculating insulin dose are taught as part of self-management education programs[352]. However, it is recognized that manual calculation may be challenging for individuals with varying levels of functional numeracy and literacy[353]. Automated calculators intended to assist with dose estimation already exist, both as standalone devices or integrated into pumps for patients on subcutaneous infusion therapy and appear to be popular with patients[354]. In addition to potential relevance to clinical educators, and patient users, insulin dose calculation carries a well-defined risk of actual clinical harm. Potential negative outcomes associated with insulin dosing error include symptomatic hypoglycaemia (in overdose) and inadequate glycaemic control (arising from systematic under—dosing)[355]. Scope for harms arising from insulin self-administration errors has been highlighted by recent findings of increasing rates of referrals to poison centres in the US[73, 199]. Connecting to the broader issue of safety regulation, dose calculation is recognized as a moderate risk application for which regulatory oversight is required. However, at the time of study development, limited data were available about the extent to which

this was occurring in practice. Systematic assessment provided an opportunity to examine this question, with potential relevance for discussions about the capacity of regulators to effectively police mobile medical apps.

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Huckvale K, Adomaviciute S, Prieto JT, Leow M, Car J: Smartphone apps for calculating insulin dose: a systematic assessment. BMC Med 2015, 23(1).

6.2 Study-specific objectives

The primary objective of the study was to systematically assess the safety of insulin dose calculators incorporated into mobile medical apps intended for patient use in controlling the risk of either accidental and systematic errors leading to clinically inappropriate dose recommendations.

Accidental errors of input were defined, based on the error taxonomy developed by Reason[228], as those arising from user interaction with the app and categorised as:

- Slips during data entry leading to incorrect values being used for calculation;
- Lapses leading to required data being accidentally omitted; and
- Mistakes of understanding about the form or types of data required to perform calculation correctly.

It was expected that safe apps should adopt, wherever feasible, strategies for controlling the risk of accidental error. A criterion-based approach (described in section 6.3.2 below) was used to assess the extent to define and measure inclusion of such strategies.

Systematic errors of output were defined as those reproducibly arising from failures in the calculation process irrespective of user behaviour, including the failure to correctly implement a defined clinical algorithm. Systematic errors were assessed a combination of criterion-based evaluation and exhaustive testing of generated outputs against simulated data.

Secondary objectives were:

- To systematically characterise the algorithmic basis for calculation adopted by insulin dose calculators, as well as ancillary features, such as data logging.
- To quantify the proportion of apps having undergone either FDA or UK MHRA approval.

- To describe the context and processes involved in the development of dose calculator apps through engagement with app developers.

6.3 Methods

6.3.1 *App selection*

The UK versions of online app marketplaces for the two most widely used smartphone operating systems were searched in August 2013 using the individual terms ‘insulin’, ‘glucose’, ‘bolus’ and the combination of ‘diabetes’ with any of ‘dose’, ‘calculator’ or ‘algorithm’ (or related word variants and abbreviations, such as ‘DM’).

Obviously irrelevant apps were eliminated by reviewing app store descriptions and screenshots to identify apps that were either unrelated to diabetes self-management or for which no calculator could be present, for example, diabetes eBooks. The remaining mobile medical apps were downloaded and evaluated using pre-specified inclusion and exclusion criteria. Each stage of search and selection was performed by myself and at least one researcher (see section 6.3.5 below), working independently. Consensus was reached by pooling independent decisions and resolving any discrepancies through group discussion involving all search investigators in which discrepant apps were re-reviewed against selection criteria. An independent arbiter (Josip Car) was nominated in the event that resolution was not possible, but in practice this was not needed.

Mobile medical apps were eligible for inclusion if they were in the English language and contained a tool for performing a mathematical operation on one or more patient- and context-specific numeric parameters to suggest a dose of rapid or short-acting insulin. Apps were not restricted by cost, country of origin, target platform, download count, or intended audience (Table 6-1). Consistent with the approach taken by medical regulators [28], calculators explicitly disclaiming medical use for self-management or treatment were not excluded, since the only valid use of a product advertised as a drug dose calculator is for medical purposes. Apps meeting the inclusion criteria were excluded only if technical issues prevented them from being downloaded or run on test devices. Duplicate apps running on the same platform were excluded. However, apps available on both iOS and Android were retained to assess consistency between the operating systems.

App stores were rechecked in October 2014 to see if included apps remained available for download or had been updated during the study period. Updated apps were re-evaluated.

Table 6-1 **Diabetes app selection criteria**

Inclusion criteria
Smartphone or tablet app
Containing a rapid-acting insulin dose calculator, a tool to perform a mathematical operation on one or more patient- and context-specific numeric parameters
English language
Targeted at patients of any age or clinicians, or both*
Free and paid apps
Exclusion criteria
Not available through Android or iOS device marketplaces
Could not be downloaded because of country restrictions that prevented access in the United Kingdom
Could not be used because of technical problems, after two attempts
Sliding scales, lookup tables or other standard instruments that do not involve mathematical transformation of patient-supplied inputs

6.3.2 *Assessment criteria development*

Assessment criteria were developed to address the two issue domains relating to the control of the risk of accidental user error during data input, and systematic error arising from poor calculation performance (described in section 6.2 above) This partitioning was explicitly intended to differentiate issues for which users and educating professionals might be able to adopt mitigating strategies, such as double-checking data entry to identify accidental error, and those arising from software failures over which a user would have no control, respectively.

Criteria development was informed by experience gathered during the assessment of asthma apps[317] and through related work[13, 228, 356, 357]. It was refined by discussion with colleagues (section 6.3.5 below), including a clinical endocrinologist.

The schema and operational criteria used for assessment are detailed in Table 6-2. Accidental error control examined the inclusion of strategies designed to validate data during input, flag missing values, provide unambiguous cues about the nature and form of expected data and ensure data could be entered with in valid formats. Systematic errors were classified according to those arising from violations of basic clinical principles, inconsistency between app-based calculation and its stated formula and state problems reflecting disconnection between inputs and displayed outputs arising for any reason. Software errors unrelated to calculation performance, such as crashes, were also captured during assessment.

Table 6-2 **Schema and operational criteria used for app issue identification**

Issue type	Criteria	
Accidental error control		
Numeric validation lacking	1a	No upper bound placed on input values
	1b	Negative input values accepted
	1c	Textual input values accepted
Calculation despite missing inputs	2a	Calculation proceeds when data are missing
Ambiguous terminology	3a	Ambiguous, confusing or contradictory terminology
	3b	Ratio factors labelled incorrectly
Data entry issues	4a	Limited precision prevents recording of at least 1 decimal place for measurements requiring such precision, e.g. mmol/L for blood glucose.
	4b	Problems entering or saving data in the correct input fields
Systematic calculation errors		
Clinical model violation †	5a	Calculation using impossible inputs, e.g. zero-valued blood glucose
	5b	Increasing correction bolus in response to falling blood glucose
	5c	Meal bolus not offset by negative correction bolus (blood glucose below target blood glucose)
Formula inconsistency	6a	App does not conform to stated formula, for any reason
Input-output mismatch	7a	Output is not updated reliably if inputs are changed (Automatic calculators)
	7b	Output is not updated reliably when calculation button is pressed (Manual calculators)
Other software errors	8a	Any other software issue, e.g. crash, not described above

† There are many contextual factors which might affect the suitability of calculation, for example the effect of pregnancy on insulin resistance. Here, we considered only those factors that apply to all patients. The possible impact of contextual factors is addressed in the discussion.

6.3.3 *Assessment and data extraction*

Mobile medical apps were assessed using a standardized method to examine each component of the calculation process (Box 6-1). Expected inputs and outputs, supported unit systems, terminology, and any supplementary app features were characterized by inspection. Simulated data were used to define behaviour in response to missing and extreme input values.

Box 6-1 **Details captured during app assessment**

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1. Basic app details
    - Platform
    - Cost
    - Version
    - Description and release notes
2. Developer information including contact details
3. Download statistics (only available for Google Play)
4. Input parameters
    - Supported unit systems for glucose and carbohydrate (all other parameters derive from these base measures)
    - Labels used to describe inputs
    - Numeric ranges and precision accepted by app
    - Optional or mandatory status for calculation
    - Methods for entering data
    - Additional configuration options, for example parameters that may be customized by time of day
5. Output parameters
    - Labels used to describe outputs
    - Numeric ranges and precision of generated outputs
6. Calculation process
    - Process for triggering calculation
    - Impact on calculation of omitting specific parameters
    - Impact on calculation of providing zero-valued parameters
    - Warnings or other messages generated by app
    - Formula used by app, if identified
    - Results of exhaustive testing (see Supplementary Methods S3), if performed

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7. Details of contact with developer
    - Motivation for developing software
8. Other software features
    - Related self-management features, e.g. glucose diary
    - Support contacts
    - Clinical disclaimer
        - Value of seeking professional advice prior to use
        - Role for personal judgment in interpreting results
        - Disclaims all medical uses
    - Third-party accreditation
    - Paid-for enhancements
9. Other software issues identified during testing
10. Audit trail for testing process

Where the formula used for calculation was not displayed in the app or in associated documentation, the developer was contacted to request details. For those apps where a formula was ultimately identified, performance was assessed using a set of test cases generated by permutation of the range of possible values for each input parameter. The procedure for generating test cases is described in Appendix 12. A software tool was created to automate the process of test case generation based on the identified characteristics of the app and the underlying algorithm.

Where present, clinical disclaimer text was extracted and coded to identify statements advocating discussion with a healthcare professional prior to calculator use and the role of personal judgment in interpreting generated results. App developers were also asked to provide basic information about the motivation for app development and to clarify the extent of clinical involvement, if any, during development or testing. The US FDA Establishment Registration and Device Listing[358] and UK MHRA Public Access[359] databases were searched to identify registration of either apps or developers.

All apps were assessed by myself and a second reviewer, working independently. While also intended to minimize the risk of bias, comparison of these independent reviews served mainly to identify accidental errors or omissions during assessment. We planned for a third investigator to provide arbitration in the event that differences could not be resolved by discussion, but in practice

this was not required, and the small number of scoring differences were resolved by rechecking the affected apps.

6.3.4 *Statistical analysis*

Descriptive statistics were used to summarize the characteristics of included apps and prevalence of identified issues. The unit of analysis was the individual app and issues identified within apps were aggregated for analysis such that multiple issues occurring within an issue domain were counted only once.

It was hypothesized that the prevalence of identified issues might vary both by platform and the payment model (free or paid), because all apps (not just mobile medical apps) for iOS are subject to a quality control process prior to release whereas Android has no such requirement, and because developers of paid-for apps may invest more in quality assurance. Fisher's exact test was used to calculate the two-tailed probability of an association between issue prevalence and platform or distribution model. A significance level of 0.05 was pre-specified. Statistics were computed with R (Version 3.0.0, The R Foundation, Vienna, Austria).

6.3.5 *Contribution of other researchers*

Similar to the assessment of mobile medical apps for asthma (section 5.3.8 above), selection and testing of calculators was performed by myself and at least one other researcher, working independently to control the risk of error and bias. Two second reviewers were involved in this process: Samanta Adomaviciute, then a colleague and Research Assistant, and José Tomás Prieto, a visiting PhD student.

SA and JTP reviewed the draft study plan. Endocrinologist Dr Melvin Leow reviewed and provided expert feedback on the assessment criteria used in the study. Together with supervisor Josip Car, all provided interim feedback on the compiled interim results and then reviewed the draft manuscript. Otherwise the work of study planning, data analysis and manuscript writing was mine alone.

6.3.6 *Governance*

Ethical approval was not required for this study which involved no patients, human tissue or identifiable data.

6.4 Results

6.4.1 *Search results*

Forty-six mobile medical apps (21 Android, 25 iOS) were selected for inclusion into the study (Figure 6-1). Of these, nine were available on both platforms but evaluated separately. Details of excluded apps are provided in Appendix 13.

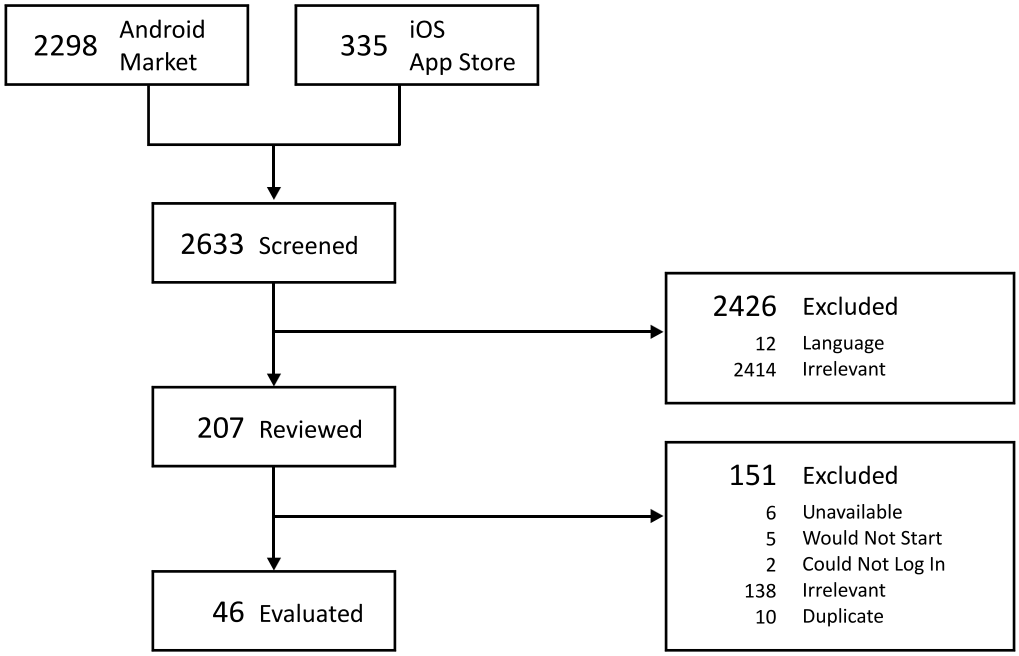


Figure 6-1 **Flowchart of app selection process**

6.4.2 *Characteristics of dose calculators*

Approximately two-fifths (37%, n=17/46) of apps were standalone calculators (Table 6-3, detailed in Appendix 14). Most (59%, n=27/46), however, combined a calculator with a diary for recording blood glucose measurements. Over half of apps (59%, n=27/46) included a clinical disclaimer. Most disclaimers emphasized the importance of discussing use of a calculator with a physician (n=12/27) and using judgment before accepting any dose recommendation (n=10/27). A small number (n=4/27) explicitly stated that the app should not be used for treatment or other medical purposes. However, because these apps were clearly advertised as dose calculators they were retained for analysis. One iOS app was associated with an evidence-based diabetes self-management education program [30,31] and another, available for both iOS and Android, had been developed by healthcare

professionals [32]. Download counts were available for Android, but not iOS. While not necessarily reflecting the number of active users, they allow a conservative aggregate estimate of at least 105,000 global downloads of the calculators included in the study by October 2014. While the majority of Android calculators had relatively low download counts (median 1000), three apps had been downloaded at least 20,000 times each.

All apps performed a basic meal bolus calculation, designed to work out the amount of insulin required to offset counted carbohydrate intake that was extended in most cases (83%, n=38/46) with an adjustment for current blood glucose measurements (details in Appendix 15). All apps accepted inputs entered manually by the user. Eight apps provided a food database for quantifying carbohydrate intake. One (Glucose Meter for Android [33]) supported automatic transfer of blood glucose measurements from a Bluetooth-enabled meter. Apps extended the basic calculation by incorporating additional adjustments for exercise levels (n=10), measured ketones (n=2), and lipids (n=1). Two-fifths of apps (39%, n=18/46) allowed calculations to be tailored by specific events (for example, mealtimes, n=12), time of day (n=6), or both (n=1). No apps performed adjustments for basal insulin regimes or, for type 2 diabetic patients, combined oral and injected therapy.

The formula used to suggest an insulin dose was listed in a third (n=14/46) of apps and obtained on request for a further seven. Formulae were broadly consistent across apps. Meal boluses were generated by dividing carbohydrate intake by a user-supplied, personal carbohydrate factor; the number of grams of carbohydrate required to offset the reduction in blood glucose caused by one unit of rapid-acting insulin. Correction boluses were derived similarly, by dividing the difference between current and target blood glucose values by an insulin sensitivity factor; the expected reduction in blood glucose in response to 1 unit of insulin for an individual. Some apps used the inverse form of carbohydrate (n=9) and insulin sensitivity (n=2) factors, performing a multiplication operation to calculate meal and correction boluses instead. Postprandial adjustments of correction boluses were supported in a fifth (22%, n=10/46) of apps that either attempted to model residual insulin activity (n=5) or supported post-meal custom factors (n=5). One app provided a warning that two-hour postprandial corrections should be adjusted to reflect the pharmacokinetics of a recent mealtime dose. Most (76%, n=35/46), however, relied on the user to know that an adjustment would be required for insulin-on-board to avoid a risk of overdose.

Table 6-3 **Characteristics of included dose calculator apps**

Characteristic	Number by platform (%) Android (n=21)	iOS (n=25)
App type		
Standalone calculator	6 (29%)	11 (44%)
Diary with integrated calculator	14 (67%)	13 (52%)
Other*	1 (5%)	1 (4%)
Region of origin		
Europe	11 (52%)	12 (48%)
North America	6 (29%)	8 (32%)
Asia and Australasia	4 (19%)	5 (20%)
Cost		
Free	9 (43%)	10 (40%)
Paid for	12 (57%)	15 (60%)
Releases**		
Updated during study period	5 (24%)	12 (48%)
Updated in 12 months prior	13 (62%)	16 (64%)
Still available at close of study	20 (95%)	22 (88%)
Self-management features		
Food database	3 (14%)	5 (20%)
Data sharing	11 (52%)	8 (32%)
Reminders	3 (14%)	3 (12%)
Other features		
Clinical disclaimer	11 (52%)	16 (64%)
Accreditation	1 (5%)	2 (7%)
In-app help	12 (57%)	13 (52%)
Support contact	10 (48%)	16 (64%)

* One app available for both Android and iOS contained information about insulin pump therapy but included a dose calculator as an additional feature. Many pumps themselves contain dose calculators, potentially rendering a separate calculator redundant.

** Study period was August 2013 to October 2014.

6.4.3 *Development context*

Half (50%, n=23/46) of developers did not respond to requests for information, contact details were not found for three, and two refused to provide information on grounds of commercial confidence.

Over a third of responding developers (37%, n=7/19) reported a personal motivation, for example as a diabetic patient or an affected family member. In over two fifths of cases (42%, n=8/19), development principles were reported as being based on procedures taught by clinicians. Four apps reported using principles adapted from DAFNE, a diabetes self-management education programme.

Substantive clinical input in the development process was reported by only a quarter of apps (26%, n=5/19). One developer reported that their app (Insulin Bolus Calculator for Android) was

undergoing clinical trials, but no related records could be found in trial registry databases or citation databases. Author responses were unclear, and follow-up requests for information did not provide clarifying detail, in three cases.

A search of US FDA and the UK MHRA databases identified no mobile medical apps with associated device or manufacturer registrations.

6.4.4 *Control of accidental error*

All Android apps (n=21) and most (92%, n=23/25) iOS apps had issues with data input that might increase the risk of an incorrect value being used for calculation (Table 6-4). The majority (n=21/21 and n=21/25 of Android and iOS apps, respectively) did not apply validation to all numeric inputs. Measured blood glucose was the most likely to have some form of validation. 24% (n=11/46) of apps either flagged extreme values with a written message (n=7) or using colour (n=4), but only one refused to complete calculation. Two-fifths (40%, n=10/25) of iOS and two-thirds (67%, n=14/21) of Android apps placed no range limits on any input. A small number of apps (n=1 and n=4 of Android and iOS, respectively) allowed textual input in numeric fields. Four apps for iOS applied validation to all numeric inputs. Three-fifths (59%, n=27/46) of all apps allowed calculation to proceed when one or more values was missing. A small number of apps had data entry issues, such as mmol/L glucose measurements constrained to be whole integer values, that meant that data were either not preserved correctly (n=2) or could not be entered with appropriate precision (n=4).

Just under half (48%, n=22/46) of apps used ambiguous terminology to label and describe inputs. Non-specific terms such as “correction factor” were common but used inconsistently, describing both insulin sensitivity and carbohydrate factors in different apps. In addition, there appeared to be a geographical basis for certain calculation conventions. Apps originating from the USA (n=13) expected meal boluses to be calculated using a carbohydrate factor, while most apps from Germany (n=5/6) required the inverse form of the factor. Poor documentation meant that the expected form would be invisible to users in half (50%, n=23/46) of apps. In a small number of cases (n=3), labelling was frankly incorrect. For example, one app used the phrase “Insulin units to decrease blood glucose by 1 mmol/L” to describe insulin sensitivity factor.

Table 6-4 **Frequency of identified issues, grouped by platform and cost**

Input issues affect the entry of data and increase the risk that calculation will proceed without correct parameters. Output issues affect interpretation of the calculated value. They create a risk of incorrect dose recommendation even when all input parameters have been supplied correctly. While input issues may be amenable to corrective action taken by a user, for example by double-checking data entry, output issues may only be effectively addressed through changes to the software.

		Frequency by platform (%)			Frequency by cost (%)		
Issue category and type	**All apps (n=46)**	**Android (n=21)**	**iOS (n=25)**	**P value***	**Free (n=21)**	**Paid (n=25)**	**P value***
Accidental error controls	44 (96%)	21 (100%)	23 (92%)	0.493	20 (95%)	24 (96%)	1.000
Numeric validation lacking	42 (91%)	21 (100%)	21 (84%)		20 (95%)	22 (88%)	
No validation of any input	24 (52%)	14 (67%)	10 (40%)		12 (57%)	12 (48%)	
Some validation	18 (39%)	7 (33%)	11 (44%)		8 (38%)	10 (40%)	
Calculation despite missing inputs	27 (59%)	14 (67%)	13 (52%)		10 (48%)	17 (68%)	
Ambiguous terminology	22 (48%)	8 (38%)	14 (56%)		8 (38%)	14 (56%)	
Data entry issues	6 (13%)	3 (14%)	3 (12%)		4 (19%)	2 (8%)	
Precision issues	4 (9%)	1 (4%)	3 (14%)		4 (19%)	0 (0%)	
Data not stored correctly	2 (4%)	2 (8%)	0 (0%)		0 (0%)	2 (8%)	
Systematic calculation errors	31 (67%)	17 (81%)	14 (56%)	0.115	14 (67%)	17 (68%)	1.000
Clinical model violation	22 (48%)	13 (62%)	9 (36%)		10 (48%)	12 (48%)	
Formula inconsistency †	3 (14%)	1 (11%)	2 (17%)		0 (0%)	3 (23%)	
Input-output mismatch	17 (37%)	9 (43%)	8 (32%)		8 (38%)	9 (36%)	
Automatic calculator	3 (7%)	2 (10%)	1 (4%)		0 (0%)	3 (12%)	
Manual calculator	14 (30%)	7 (33%)	7 (28%)		8 (38%)	6 (24%)	
Other software errors	11 (24%)	8 (38%)	3 (12%)	-	4 (19%)	7 (28%)	-

* Two-tailed p value for the comparisons between Android and iOS and Free and Paid apps respectively, calculated using Fisher's exact test.

† The denominator used for calculating percentages for this issue was the number of apps for which a formula was identified (n=21, Android 9, iOS 12, Free 8, Paid 13)

6.4.5 *Systematic calculation errors*

When no missing or out-of-range input values were present, the majority of apps with a known formula (86%, n=18/21) calculated a result consistent with expectations during systematic testing (Table 6-4). Only three apps deviated from their stated formulae. Two introduced an undocumented conversion of glucose values expressed in mmol/L into mg/d, an unnecessary step because a patient using SI base units for glucose would almost certainly not have adjustment factors expressed using conventional US units. A third app silently discounted any negative correction bolus, contradicting the stated formula and creating a risk of over-estimating insulin requirements.

Formula concordance did not guarantee, however, that apps would produce correct output under all circumstances. Over two-thirds (67%, n=31/46) of all apps, including 19 of those with known formulae, carried the risk of displaying an incorrect or inappropriate result despite inputs being configured correctly. Two apps set limits on the maximum insulin dose that would be prescribed, and two used colouring to highlight doses exceeding 20 units, but most apps placed no limits on the calculated insulin dose. Three-fifths (62%, n=13/21) of Android and two-fifths (36%, n=9/25) of iOS apps violated basic clinical assumptions, for example, treating a missing glucose measurement as a real valued number of zero for calculation (n=13) or failing to reduce a recommended meal bolus when blood glucose was below target values (n=6). Of the 27 apps that performed calculation automatically whenever inputs were changed, three did not always update their output in response to changing inputs. Three-quarters (74%, n=14/19) of the remaining apps that required a manual button press to perform calculation did not clear the calculated output when inputs were changed.

6.4.6 *Other software errors*

Crashes unrelated to calculation were identified in approximately a quarter (24%, n=11/46) apps. A fifth of apps (20%, n=9/46) had textual errors of grammar or spelling.

6.4.7 *Statistical comparisons*

Challenging pre-specified hypotheses, there was no significant difference in the frequency of input or output issues grouped either by platform type or distribution model, although there was a tendency towards a greater proportion of output issues, and clinical model violations in particular, in apps for Android.

Only one app, for iOS, was issue-free according to the assessment criteria. A second iOS app had no identified issues, but did not complete systematic output testing because the developer did not respond to requests for details of the formula. If input validation issues were ignored, a further five apps were otherwise issue-free. While comparison of each of the nine app pairs available on both

iOS and Android found no differences in expected inputs, formulae, and outputs, inconsistencies were found during quality assessment. In four cases, Android apps performed no numeric validation, while the iOS version either validated some (n=3) or all (n=1) fields. In two cases, the iOS version accepted textual values where the Android version did not. In one case, an Android app lacked explanatory text present in the iOS version that prevented misinterpretation of an ambiguously labelled input. A further two Android apps either displayed incorrect behaviour when handling missing values (n=1) or did not permit data entry with appropriate precision (n=1).

6.4.8 *October 2014 update*

At the conclusion of the nine-month review process, 89% (n=41/46) remained available in app stores. 18 (44%) had been updated, and one known issue (a data entry bug involving values being stored incorrectly) was resolved.

6.5 Discussion

6.5.1 *Summary of results*

Key findings from this assessment of 46 insulin dose calculator mobile medical apps were:

- Less than a third (30%, n=14/46) of apps provided information within the app explaining the basis for insulin dose calculation. Algorithms were provided for a further 7 apps on request to the developer. Most calculators extended a simple meal bolus calculation – designed to work out the amount of insulin to take in response to planned carbohydrate intake – with an adjustment for current blood glucose levels. A small number incorporated additional elements like insulin on board or exercise. The findings add weigh to proposals for mandated disclosures by developers to make validation information routinely available[346] (see section 5.5.2.4 above), since systematic testing is hindered when formula details are unknown.

- Encouragingly, 85% (n=18/21) of apps where a formula was definitively identified generated dose recommendations consistent with their formulae when the inputs were within possible ranges. However, over two thirds (67%, n=31/46) nevertheless contained systematic errors creating a risk of clinically inappropriate dose recommendations arising from errors of underlying clinical assumptions and state violations, such as failing to update calculation reliably when inputs were changed. Errors did not affect every calculation, but were reproducibly detected under circumstances of typical use. One app, downloaded at least 10,000 times, recommended an increasing insulin dose in response to falling blood

glucose. The results suggest that evaluations of calculator safety that rely simply on concordance with a known formula[351] are likely to miss important issues.

- In addition to systematic error risk, most apps (96%, n=44/96) do not provide adequate protection against accidental errors. The reasons that might prompt use of a calculator might also make it hard for patients to detect errors during use. Patients with limited numeracy may lack an intuitive basis with which to 'sense check' unusual results[76]. The social contexts in which a calculator might be used, such as mealtimes, may mean people attend less to the process of calculation and scrutinizing the output. Numeric validation that placed acceptable constraint ranges on data inputs was consistently present in only four apps (16%, n=4/46). Many apps accepted impossible inputs (e.g. a blood glucose of 0mmol/L) without warning.
- One app was issue-free according to assessment criteria: RapidCalc v1.4.1 for iOS, suggesting that it is technically feasible to design dose calculators that protect against accidental and systematic error.
- Being paid-for did not appear to make an app less likely to contain errors. No other indicators were identified that could act as a reliable proxy for calculation fidelity. The result overlaps with questions about the availability of efficient quality proxies for questionnaire-based methods of app quality assessment raised by the review of asthma apps.
- Over a third of calculator development (37%, n=7/19 developers responding to queries) appeared to be accounted for by personal motivations, responding to self-management needs or those of a family member. Clinical input was clearly demonstrated in only a quarter of apps (26%, n=4/19). Nevertheless, developers appear to understand that their products carry a clinical risk: three fifths carry a clinical disclaimer and many require the user to agree to the disclaimer terms before being able to use the app. The findings appear to confirm questions about development context and quality control, raised in the introduction to this chapter (section 6.1 above), and suggest value in diligence-type activities as part of app quality evaluation.
- Again linking to broader discussions about whether regulator action will provide an effective guarantee of quality for mobile medical apps, there was no evidence of regulator involvement in the development of any app, despite US guidance having been available for at least a year at the time of final review and dose calculators falling clearly into scope for review as class 2 medical devices[22].

- Terminology used by apps when describing carbohydrate and glucose inputs was unstandardized and varied by country of origin. These differences, which were not always apparent without mathematical analysis of calculation behaviour, included examples of the same term being used for different parameters and ratio adjustment factors being incorrectly labelled. Notably, there was a localisation element: apps from the USA universally used a carbohydrate:insulin ratio which was inverted in apps from Germany. In both cases, the consequence for a user not appreciating this difference was a potentially large *over*-estimation of the insulin dose required to offset carbohydrate intake. The findings highlight the importance of standardisation efforts targeted both at clinical management and oversight of mobile medical apps[350].

6.5.2 *Study limitations*

The study used a systematic approach to app evaluation that aimed to evaluate all mobile medical apps available at a particular point in time using a standardised assessment involving multiple raters to control the risk of bias and error. Trade-offs implicit in the decision to restrict scope to a single class of apps were discussed in the introduction. However, the study was also subject to a number of additional limitations:

- Although an update review was performed that confirmed that identified issues had persisted in existing apps, unlike the asthma review, this assessment reviewed only a single time point. As a result, it was not possible to explore whether safety issues have evolved over time.
- Although including mobile medical apps irrespective of country of origin, the study was restricted to English-language apps available through UK app stores. It is possible that some app sales were restricted by jurisdiction (which may be a valid approach on safety grounds, based on the localisation-related issues identified). It is also possible that apps available in languages other than English are affected by different quality issues, although this seems unlikely.
- The decision to perform a detailed assessment within a single class of apps, rather than the broad-based assessment, such as the one used to examine quality in apps for asthma described in chapter five, represents a compromise between rigour and available resources. Potential benefits of an in-depth assessment were highlighted by the identification of classes of issue not flagged by a previous examination of calculator apps which focussed on formula consistency alone[351]. However, in focussing on a single class

of apps, the study relied on assumptions that the development context of dose-calculator apps was sufficiently similar to other types of apps for diabetes and asthma such that findings here can provide a 'signal' to broader issues. However, medical calculators may require greater technical sophistication than, for example, diary or information apps.

The identification of potential safety issues does not imply that those issues are necessarily realised in practice. Part of the reason for partition issues into (modifiable) accidental errors and systematic issues was to recognize that there are some problems for which users may develop effective compensation strategies. Some systematic errors, although produced by scenarios typical of routine use, might not be experienced by all users if, for example, they rely on particular customization options. As a result, there is an opportunity for surveillance type activities to complement these findings to understand what issues are realised in practice. The kind of risk anticipation adopted by this study nevertheless provides a sound basis for identifying defects and underpins methods such as failure modes and effects analysis commonly used to expose and remedy latent failures in complex systems.

6.5.3 *Synthesis of issues for thesis discussion*

Issues identified in this chapter that will be developed further in the thesis-level synthesis and discussion include:

- Concrete identification of safety risks arising from mobile medical apps for self-care of diabetes not managed by developers, app stores or regulators. Chapter eight will discuss the requirement for, and feasibility of, response strategies involving each of these groups. These will be balanced against other potential challenges, such as rapid growth and high observed rates of app turnover identified in chapter five requiring risk management approaches that can scale and adapt.
- Related to this, the requirement for further and ongoing work to assess real-world safety impacts arising from the use of apps (and related technologies), recognizing that technical evolution will result in a risk profile that changes over time.
- Identification of a development context for mobile medical apps where risk management approaches and clinical involvement may not be prioritised, with implications for broader assumptions about the quality and safety of mobile medical apps.
- The potential to mitigate aspects of avoidable error arising from a lack of controls implemented in apps. Chapter eight will consider the role for patient education and clinical support in controlling potential risks, including those arising from safety risks

identified in this chapter and questions of effectiveness prompted during review of apps for asthma. Feasibility will be discussed in light of the requirement for suitable levels of functional health literacy and numeracy; the availability of simple techniques to validate app performance and results presented in the next chapter, which explores the experiences and capabilities of individuals currently using apps to manage their asthma or diabetes.

6.6 Chapter summary

Chapter six focussed on the question of whether mobile medical apps for self-care present a credible safety risk for potential users. It used the example of insulin dose calculators to perform an in-depth assessment of potential risks and act as a signal as to the potential for harms arising from app use. A risk of clinically inappropriate dose recommendations arising from circumstances typical of routine use was identified in most apps. Risks reflected both systematic errors in dose calculation and inadequate protections against accidental error. No calculator had undergone either FDA or UK MHRA regulatory review and clinical input into app design appeared to be limited, although developers appear to recognize that their products may pose a clinical risk.

Chapter seven: How and why do patients use mobile medical apps for self-care? A qualitative interview study

7.1 Chapter introduction

Chapter seven reports findings from the final project contributing to my thesis: a qualitative interview study exploring the ways in which adults with asthma and diabetes use mobile medical apps as part of their repertoire of self-care. The motivation for this final study was informed by issues identified over the course of the PhD recommending a specific focus on patient perspectives. While these issues have already been highlighted in previous chapter discussions, they are repeated here for convenience:

- Mixed findings of clinical benefit arising from clinical trials suggest that the design of effective app-supported interventions is non-trivial (chapter four). However, the relative lack of published, developed accounts of patient behaviour and perspectives linked to complex trial-based interventions frustrates insight into factors that affect intervention effectiveness, such as acceptability and compliance. Although *de novo* intervention design was beyond the scope of this thesis, thorough exploration of experiences amongst existing app users (operating outside the context of clinical studies) represented a viable alternative strategy to develop insight into these factors. Although not in relation to apps, a similar strategy has previously been used when examining the role of technology in health[360].
- The interpretation of quality issues affecting mobile medical apps for asthma (chapter five) and safety concerns in diabetes dose calculators (chapter six) may be qualified by insights into:
    - The way patients choose apps (for example, by possibly prioritising 'trusted' sources of apps);
    - The types of app and app functions) that are used in practice; and
    - The extent to which individuals adopt self-care behaviours that mitigate against harms arising from low quality apps.

Although these issues might be explored in a number of ways, a qualitative study adopting an exploratory approach was considered to be the most appropriate strategy given the early state of research in this area. Trade-offs implicit in this approach are discussed later (section 7.5.3 below).

The chapter adopts the same format used in preceding sections to present the study objectives, methods and results and concludes with a discussion focussing on the relationship of the findings to existing research, limitations and issues that will contribute to the thesis synthesis in the next chapter.

This study has not yet been published in a peer-reviewed journal, however data were presented at a workshop at CHI, the largest human-computer interface conference, and findings informed a published response to a viewpoint paper exploring the potential for mobile health:

Huckvale K, Morrison C: How people use smartphone apps to manage long term conditions**.** In: CHI 2014. Toronto, Canada; 2014.

Huckvale K, Car J: Implementation of mobile health tools. JAMA 2014, 311(14):1447-1448.

7.2 Study-specific objectives

The primary objective of this qualitative interview study was to generate a rich account of why adults with asthma, type 1 or type 2 diabetes decide to use an app to manage their condition, how people use such apps, and why they continue to use them over time. A particular focus was on how features of mobile medical app design or function play a role in decision-making processes and self-care behaviour.

Secondary objectives were:

- To explore the processes that people report using when first choosing an app, for example, screening candidate apps using online reviews, in order to better understand how the 'packaging' of a mobile medical app might influence the likelihood of its adoption.
- To explore the types of general asthma-related and, separately, diabetes-related needs expressed by people who are using an app to manage these respective conditions and how they would like apps to address these needs.

7.3 Methods

7.3.1 *Method selection*

The study involved a framework analysis[246] of qualitative data collected through in-depth, contextual interviews[361] with adults with asthma or diabetes using one or more mobile medical apps as part of the self-care of their condition.

Although originally developed for use in applied policy research, the framework method (hereafter 'framework') for the analysis of qualitative data has gained acceptance in health settings[246]. Framework is a coding-based, interpretative method incorporating seven prescribed steps which involve an iterative process of abstraction from qualitative data sources, such as interview transcripts[247]. The process involves annotating, or 'coding', phenomena of interest within typically textual data; combining codes into higher-level groupings to yield an analytical framework and the reapplication of this framework to the data to generate a comparison matrix which enables exploration between and across data sources. Framework has been recommended when research objectives can be well defined[247] (as here) and when analytical transparency is valued[362]. The ability to combine deductive and inductive strategies contrasts with chiefly inductive approaches such as grounded theory[363]. Analytical transparency is enabled by the systematic approach which emphasises maintaining clear links between interpretation and original participant accounts throughout the research process. Methodological consistency distinguishes framework from other qualitative research techniques, such as thematic analysis[364], where there is considerable latitude to tailor methods. My choice of framework was motivated by the potential for bias arising from my existing experience with mHealth, and that suggesting that app-features influence app selection and patterns of use *at all* is akin to an *a priori* (albeit possibly uncontroversial) hypothesis. In acknowledging this risk of bias, specific attention was paid to reflexivity in the preparation and execution of the study (see also section 7.5.4 below).

Contextual interviewing is a method for generating data for qualitative analysis which extends the traditional researcher-participant interview paradigm by incorporating an element of behavioural modelling in which an individual is observed as they step through routine tasks or behaviour, such as using a self-care app[361]. In a contextual interview, the interviewer uses observed behaviour as the basis for probe questions that aim to generate a richer or 'contextual' characterisation of behaviour than that possible through discussion alone. The method seeks to address the difficulty that some individuals experience in explaining motivations in the abstract by using modelling to provide appropriate cues to past experience and reflections, as well as facilitating discussion with

an interviewer. A link to actual (rather than described or reasoned) behaviour may also act to enhance the validity of interpretation by reducing reliance on subjective accounts of behaviour. Finally, contextual interviewing offers a source of non-verbal data that can be observed and analysed by the interviewer to complement textual transcripts of discussion.

7.3.2 *Participants*

Selection criteria

Eligible participants were adults, aged 18 or older ordinarily resident in England, Wales or Scotland with a clinician-confirmed diagnosis of asthma or diabetes who were, at the time of recruitment, using one or more mobile medical apps on a personal smartphone or tablet device to manage their condition (Table 7-1). The decision not to include those under 18 in the analysis reflected both ethical concerns about consent and the extent to which children could give reliable detailed contextual accounts of their behaviour. Participants were excluded only if they were unable to speak English or if they were a vulnerable adult unable to give informed consent to participate in the study (a requirement for study ethical approval).

Table 7-1 **Participant selection criteria**

Inclusion criteria
Aged over 18 resident in England, Wales or Scotland
Clinician-confirmed diagnosis of asthma, type 1 or type 2 diabetes (or both asthma and diabetes)
User of a personal smartphone or tablet and with a history of having installed one or more mobile medical apps in the past
Currently (at the time of recruitment) using one or more tablet or smartphone apps for their asthma
Exclusion criteria
Non-English speaker
Vulnerable adults (Department of Health, 2000)

Recruitment methods

A variety of strategies were used to promote the study to potential participants. The primary route for study advertising was via social media (Facebook and Twitter). A dedicated study Facebook page was created and, with permission, adverts were placed in the Facebook feeds of Asthma UK and Imperial College London Faculty of Medicine (template adverts in Appendix 16) and in the Twitter feed of Imperial College London. Paid-for advertising was used to place in-feed Facebook adverts for targeted user groups including those expressing interest in asthma, diabetes or related subjects.

Details of the study were also included in email newsletters sent to patients with Asthma by both Asthma UK and Allergy UK and in newsletters directed towards students by Imperial College London. Permission was also sought from Diabetes UK to advertise via their support forum, but they did not respond within the study period. Recruited participants were also invited to recommend the study to any acquaintance who they thought would be interested in the study. Because app use is not yet routinely embedded in clinical practice, the study was not advertised through the NHS.

Adverts directed interested individuals to a study-specific website containing information about the purpose of the study, details of what participation would involve and ethical information, such as the right to withdraw at any time. These details were also made available to download in a printable format (Appendix 17), allowing individuals to review study information at leisure.

Because the main objective was to understand the range of possible ways in which people with asthma or diabetes use apps for self-care, the study adopted a purposive sampling approach, which aimed to maximise the diversity of participants. The study specifically aimed to incorporate:

- Older people, because the clinical need for self-management support extends across the lifespan.
- People with varying degree of educational level, because it was unclear how accessible apps might be to those with varying levels of health-specific literacy
- People with varying degrees of condition severity and/or progression, because of the possibility that the perceived costs and benefits of using an app might be influenced by this and to better understand how apps might fit into differing levels of intensity of medical support. In the case of asthma, this meant finding people with differing levels of symptom control. For diabetes, this involved trying to find people with varying levels of glucose control and secondary complications, e.g. foot, eye or neurological problems.
- People from a range of ethnic and cultural backgrounds, because social aspects of the acceptability of technologies and the visibility of a condition like asthma or diabetes might affect how and why people might use an app.

To try to achieve this, a screening survey was used to collect profiling information about potential participants. Individuals accessing the study website who, after reading participant information, expressed interest in taking part were directed to an anonymous online survey (question schedule in Appendix 19). The survey first checked eligibility to participate in the study. Filter questions based on the study selection criteria (section 7.3.2.1 above) were used to identify ineligible participants, who were thanked for their interest but prevented from supplying further details. For eligible

participants, the survey continued by collecting profiling information including age, gender and ethnic background, condition severity, highest level of education, follow-up contact details and consent to contact. The original intention was that this process would enable a pool of potential participants to be identified, from whom a maximally diverse sample could be chosen. (The possibility that not all people expressing interest would be interviewed was explained in participant information materials.) However, in practice, it proved challenging to identify sufficient individuals. The approach was adapted, therefore, so that profiling information was used to re-target social media advertising, for example to stop advertising to individuals with asthma once a certain number had been recruited. The study aimed to interview between 15 and 20 people (ultimately 14 individuals were recruited).

7.3.3 *Interview procedures*

Initial contact was made with selected participants by telephone (or email, if expressed as a preference). The purpose of the first discussion was to confirm eligibility and maintained interest in the study after an obligatory cool-off period of at least 48 hours; check that the participant had understood what taking part would involve and answer any questions; and arrange a time and place for face-to-face interview. To try to make the process convenient, participants were given free choice as to the time and location for each interview. In practice, participants all elected to follow the study recommendation of meeting in a public place, such as a coffee shop. The possibility of being overheard in these settings was always highlighted to participants before finalising the choice and seeking study consent. Participants were also offered the chance to have a trusted friend or relative present, however no individual did this. Participant travel costs were covered and a small token of thanks was offered for participation (either a £10 iTunes Voucher or Google Play Gift Card).

Each interview lasted between 60 and 90 minutes and was organised using a topic guide to provide consistency between participants (Box 7-1). The topic guide incorporated an initial set of structured questions designed to open the interview, help establish discussion and rapport and build a picture of the participant's wider experience of health and long-term disease. After this, the interview switched to a contextual mode, in which participants were asked to demonstrate their app(s) while responding to questions posed by the interviewer. All discussions were digitally audio-recorded and brief written observations were also made during the interview process to assist recall about app use when reviewing recordings.

Box 7-1 **Interview topic guide**

1. Housekeeping
    - At the start:
        - Give participant opportunity to read information sheet and ask any questions
        - Sign consent forms (one for participant, one for us). Must tick all boxes and sign.
        - Recap purpose of study, explain purpose of interview and set ground rules for confidentiality, limits of discussion.
    - At the end:
        - Talk about follow-up at 4-6 months and preferred method for this (email, phone)
        - Give participant questionnaires in prepaid envelope and explain reason (as a way of filling in detail/checking understanding of disease severity and impact on life)
        - Thank participant and offer £10 gift token – obtain email address to send and record preference for either iTunes or Google Play.
2. For participants with asthma
    - State of asthma control, triggers, contact with health services
        - Initial diagnosis
        - When was asthma last out of control and what happened
    - Routine of asthma control – strategies and behaviours
        - Medication use
        - Sources of skills/training/knowledge
    - Beliefs and attitudes about asthma and the future with asthma
    - Main aims for asthma control
3. For participants with diabetes
    - State of diabetic control, experience of complications and contact with health services
        - Initial diagnosis
        - Any diabetic events or complications
    - Routine of diabetes control – strategies and behaviours
        - Medication use and self-management experience
        - Sources of skills/training/knowledge
    - Believes about diabetes and future with diabetes
    - Main aims for diabetes control
4. For all participants
    - Family and work situation and how disease fits into relationships
    - How smartphone is used on a day-to-day basis
    - Events leading up to decision to use an app

- Self-management repertoire and life routines *before* using an app, did it change and how?
- Process of choosing app, why not other apps?
- How app is used (contextual interview technique) as part of routine and any other occasions (e.g. during an asthma attack), attitude towards reminders
- How collected data are used, particularly numerate data and notes
- How app use has changed over time, including features that are used/not used, and other apps that may have been discontinued, and why
- Interactions with clinicians and any role for app within this
- Recognising that participants may have specific critical commentary that they want to get 'off their chest', any criticisms/suggestions for improvement in their chosen app

At the end of each interview, participants were asked to complete four short validated questionnaires assessing disease control and quality of life, learning style and health literacy.

- Asthma Control Questionnaire[298] or Diabetes Symptom Measure[365]
- Asthma Quality of Life Questionnaire[366] or Diabetes Quality of Life Brief Clinical Inventory[367]
- Functional health literacy[368]

These questionnaires were used to validate narrative observations about asthma severity and impacts and assist interpretation of how participants approached the process of selecting and using their app(s).

Interviews were conducted in three phases:

- An initial pilot was conducted to test the contextual interviewing approach and confirm the scope and suitability of the proposed the topic guide for interview with a single participant. The transcript and recordings were reviewed and discussed with a supervising colleague with substantial qualitative interview experience (see section 7.3.6 below). This process suggested that the interviews could go ahead as planned.
- A further four interviews were then conducted and subject to a preliminary analysis (see section 7.3.4 below). This created an opportunity for refinements to either interview or recruitment procedures, however in practice this was not required.
- A final 9 interviews were then conducted. Analysis continued throughout this phase.

Participants were also followed up at least six months after the initial interview by either telephone or email to establish whether they were still using an app and to ascertain any other changes in their condition status. Details of this follow-up were captured in note form and incorporated in analysis.

7.3.4 *Data analysis methods*

Data analysis followed the seven-step framework approach described by Gale[247]:

1. Verbatim transcription of the entire audio-recorded dialogue for each interview. These transcriptions, together with written observations, completed questionnaires and follow-up interview notes were used as the source materials for subsequent analysis.
2. Familiarization with the content of each interview. This involved reading and reading transcriptions, re-listening to audio interviews. A summary vignette was created for each participant to facilitate recall and discussion during analysis.
3. Preliminary coding, reading each transcript line by line to identify content relevant to the questions of how and why people use apps for self-care. Although dedicated qualitative software was considered (and piloted), coding was ultimately performed in Microsoft Word because of the flexibility this afforded for iterative recoding. As described in the previous section (7.3.3 above), this was conducted initially using four interviews and only subsequently expanded to include all interviews once a provisional coding taxonomy had emerged.
4. Development of a (provisional) analytical framework, grouping identified codes into higher-level themes. Themes included in this analytical framework as summarized in Table 7-2.
5. Recoding of data using analytical framework.
6. Excerpting of transcript data into a tabular matrix, enabling comparison within and across individual participants. This summarisation step contributed to further refinements of understanding.
7. Interpretation of the data leading to study outputs. The nature of outputs, and extent to which these move beyond the analytical framework and descriptive account of participant experience is left open ended in framework[247]. For this study, a discursive account is provided of participant experiences, but this is structured within a revised analytical framework which further refined concepts recognized in the first version, for example to develop the idea of ‘fit’ and the moderating role of emotions beyond fear. This revised framework is summarized in **Error! Reference source not found.**.

In addition to the main framework analysis, I also maintained a reflexive journal exploring my own responses to the research process. Prior to the start of the study I used this journal to record initial ideas about what the study might conceivably encounter in the hope that making these explicit would reduce the risk of unintentional bias. I also used the journal to keep brief notes about the experience of the study process and issues encountered during interviews and, in particular, to reflect on the success of particular interview strategies.

Table 7-2 **Initial analytic framework created during analysis**

The table shows themes identified during coding and the domains within which these were conceptually grouped.

Domain	Theme
User-ascribed purposes	Managing a clinical relationship
	Coping day-to-day
	Taking decisions 'right now'
	Sense-making with numbers
	Unthinking: habit and routine
	Not using an app
Moderators	Fear as a motivator
	Fear as a barrier
	Environmental stability
	Personal disposition
	Existing self-management repertoire
Triggers	Internal versus external
	Immediate versus proximate
Sustaining use	Legitimacy
	Being a visibly good patient
	Generating a sense of control
	Ascribing disease causation
	Better than alternatives

7.3.5 *Ethical issues*

The study plan and all research materials, including website content and online advertising, were reviewed and approved by the Imperial College Research Ethics Committee (ICREC Approval 13/3/9, Appendix 20). All participants gave initial electronic consent allowing their profiling data to be

processed and for them to be contacted by me. Full written informed consent was then obtained prior to the start of each interview (form in Appendix 18). Participants were given the option to withdraw from the study at any stage up until the transcription and primary analysis of their data, allowing a 14-day grace period after each interview for withdrawal. In practice, no participant withdrew from the study.

Medical information discussed during the studies was recognized as being personal but considered unlikely to be of a nature that would either be distressing or embarrassing to participants. At the start of each interview, it was clearly explained that participants could stop the process at any time and that there was no expectation that they should talk about issues that were distressing to them. In practice, a small number of participants disclosed information about aspects of their care experience that they had found dissatisfactory (section 7.4.2.3 below), but no participant expressed distress. No participant disclosed information of a nature requiring confidentiality to be breached, however study plans incorporated contingencies for this eventuality.

The study followed Imperial College policies and the law to ensure that participant data were kept confidential. Study indemnity was provided by Imperial College London (Appendix 21).

7.3.6 *Contribution of other researchers*

Thirteen out of the 14 interviews were performed by myself, and one interview was performed by Cecily Morrison, an experienced qualitative researcher supervising the work, in order to assist her critical oversight of my analytical process (as a novice qualitative researcher). Cecily and Josip Car also reviewed the initial study plan. Otherwise the work of study planning, seeking ethics approval, transcription, analysis and write up was my own. The study originally planned to contract out transcription to a third party service, but ultimately I transcribed manuscripts to assist my familiarization with the data.

7.4 Results

Results are presented in three sections. A brief introduction summarizes participant characteristics. The account continues with a description which lays out the ways in which mobile medical apps were used; focussing on the ‘how’ part of the study primary objective to explore how and why people use apps for self-care. The third section addresses the ‘why’ aspects; exploring broader contextual factors influencing app use.

7.4.1 *Characteristics of participants*

Fourteen adults participated in the study with ages ranging from 19 to 60 (mean 36.6±10.6SD years). Despite attempts to target social media advertising to balance recruitment, over half of participants ultimately agreeing to participate in the study were female (n=9 female vs 5 male) and all except one British Asian male self-identified as White British. All participants scored highly on short-form functional test of health literacy with measured scores ranging from 34-36 (mean 35.6±0.7SD) out of a maximum possible 36.

Nine individuals had asthma, three had type 1 diabetes and two had type 2 diabetes. Asthma Control Questionnaire scores ranged from 1 to 3.8 (score range 0-6, where 6 represents very poor asthma control) indicative of a spread of mild and moderately severe asthma (mean 2.3±1.3SD), while quality of life scores ranged from 3.2 to 5.8, mean 4.9±1.3SD (score range 1-7 where 7 represents optimal condition-specific quality of life). Diabetes Symptom Measure scores ranged from 0.6 to 1.7 indicative of good to fair disease control, mean 1.1±0.4SD (score range 0-4, where 0 represents no diabetes-related symptoms), but self-rated diabetes-related quality of life was more equivocal, ranging from 2 to 3.5, mean 2.7±0.6SD (score range 1-5 where higher scores represent worse subjective perceptions of quality of life).

Most participants (n=11/14) used iOS-based devices. Six used only iPhones, one only iPad and three used both interchangeably. The remaining three participants used Android devices.

7.4.2 *Ways in which mobile medical apps were used*

Overview

With few exceptions, apps were used to support specific tasks involved in the day-to-day business of living with a long-term condition. The most common activity involved recording data, almost always manually entered, into a chronological log:

> *"I normally get up, check my peak flow, stick it in my app. So that's this morning: 370 this morning. So… I had 4 puffs of salbutamol, so I put that in, and then checked in 20 minutes later, so 450… And sometimes if I've not bothered with my peak flow, I will log symptoms instead... And here it's got my triggers in, so if something sets me off I'll record it. So if perfume set me off and I have a low peak flow you can go in and find it. What you can actually do is email my peak flow chart to my consultant. I have done on occasions. And also, to drop me into the abnormal range I have to be pretty wrecked. I can actually track along with fairly rubbish peak flows for quite a while and function quite well. But having the numbers means I can't avoid the problem." (Sarah, 36, asthma)*

> *"[Interviewer: Tell me about how your app fits into your day? Participant:] Wake up. Kettle on. Get my cereal. Milks gotta be ice cold. Get my tablets, take my tablets. App. Phones there, gotta have my phone with me. Open it, record my glucose: pre breakfast sugar. As quick as possible. Yes, so: press add, keyboard comes up, it's got a point as well. Because quite a few apps don't have the decimal point. You've gotta add 7-4-0, and that might not click with some people… Do my day. Come home. More tablets. Injection. Phone with me. Take my injection it's a quick one, record my blood sugar, done! Because… what you're effectively wanting to do is be able to say: What are my numbers? What are my numbers?" (David, 46, type 2 diabetes)*

For asthma this typically consisted of peak flow measurements, with the occasional inclusion of symptoms and medication. For diabetes, all participants recorded blood glucose, and the few individuals performing rapid acting dose titration also recorded insulin doses and carbohydrate. Data logs could fulfil both shorter- and longer-tem functions. For diabetes titration, short-term record keeping solved the problem of having to track the amount of administered insulin necessary to make subsequent dose adjustments safely, sometimes performed several times throughout each day:

> *"So, here… [Indicating diary data] I've annotated the course of the day. So things have… Yeah, so I improved things within a fifteen-minute time frame. Absolutely fine. And then… what I'll do tonight is I'll lower my insulin by half a unit." (Charlotte, 33, type 1 diabetes)*

For asthma, there was occasionally a need for sequential data, for example to be able to remember what medication had been taken during the night. Many, however, used logs collected over a few days to assess the state of their condition, albeit with the same intention of making concrete decisions about treatment, for example, to judge whether to modify an oral steroid dose:

> *"[Interviewer: Do you ever look at the log values yourself? Participant:] Yes, Yes. [Interviewer: What kinds of things do you do?] It depends. If it's been a few days of things dropping, it tends to be a useful cue to ring the GP to ask if I can start my course of pred[nisolone]… It's useful especially when I'm tired, because I do have a tendency when I'm tired to feel like I'm struggling to breathe." (Tania, 19, asthma)*

It was not unusual for apps to offer multiple views on log data including chronological summaries presented in list, tabular and graphical form (Figure 7-1). Uses for each chart type partitioned in general between short-term decision making about treatment, particularly for diabetes, where lists were prioritised (Figure 7-1a) and longer-term reflection using summary charts (Figure 7-1b) and graphs (Figure 7-1c). This was not always the case, however, particularly if line graphs could be zoomed to different time resolutions. For example, Charlotte demonstrated how she would use a charted summary reduced to focus on the past 24 hours thereby viewing only the data necessary for insulin dose calculation. A few participants with asthma, but not diabetes, relied on other

features, such as symptom severity, or made judgements not dependent on measurements, such as whether a morning inhaler dose would last until they were ready to leave for work, to make immediate decisions:

> *"I used to take a reliever in the morning as standard, but then they said: 'Try and take the long acting beta agonist in the Symbicort.' So I try and judge the day by how long that lasts. If I'm on my way to the tube and I find I'm reaching for the inhaler I think 'Oh crap.' " (Danielle, 33, asthma)*

As a result, recording was considerably more variable, in terms of frequency and content, than for diabetes. Several people with stable asthma and one or two taking only long-acting insulin had no specific short-term use for their log data. These individuals kept records either to share with their clinicians or, rarely, solely for personal reflection.

Regardless of the uses for data *once logged*, it was striking how participants who were successfully using an app (in the sense that they showed us more or less complete records extending over periods of months) had a routine, immediate requirement for the data items that were subsequently entered into an app. For example, while serial peak flow measurements might be used to determine overall trends from time-to-time, most individuals described how they would use individual readings to make immediate decisions, for example to adjust medication for that day:

> *"Get up… have cup of coffee… use peak flow meter whilst standing up… get a much better peak flow standing up than sitting down, psychologically very important first thing in the morning… Use the inhaler, take the pill… um, and then, if I've … you know depending on atmospherics, what the peak flow has said, consider using more of the inhaler during the day, during, you know, particularly during the commute just before I leave the flat. And, throughout the day." (Alisha, 30, asthma)*

> *"At the moment I do one [blood glucose measurement] in the morning, one in the evening when I get home between 4 and 5 o'clock. That's brilliant, because that means I'm going to eat within the hour so I can take my fast acting injection." (David, 46, type 2 diabetes)*

These routines of decision-making almost always pre-dated the use of an app and were sometimes described as "rules" which an individual had either been explicitly taught, commonly for diabetes, or, for asthma, had discovered themselves:

> *"And you can identify, once you've got a few months' worth, where the trigger points are. And from that you've got a clear "So this happened, you do this." I very much like a clear "If this happens, you know, if this has happened you need to do that." I like sets of rules, it makes it a lot easier to cope with." (Alisha, 30, asthma)*

It was notable that almost no people with asthma had been given structured rules by a clinician despite individuals themselves considering that they might benefit from an action plan:

> *"Well you think 'I should have one'. 'I should know what to do to manage my own symptoms and control myself, and know what to do to manage myself.' And no, my GP didn't offer it to me, my consultant didn't offer it to me… The… you know, nobody has. I did ask! But… my plan is in my head." (Peter, 43, asthma)*

> *"It's something I asked for. They don't seem to do action plans as a matter of course which is a bit odd." (Kate, 26, asthma)*

Many participants also used apps to set reminders for medications, to take measurements and, less commonly, to order new medications. For people with diabetes, the consequences of a missed dose could be a sustained upset, even if the situation had previously been stable:

> *"Short acting you just fix it a few hours later. Long acting you can like screw up two days if you miss one shot." (Charlotte, 33, type 1 diabetes)*

For asthma, in contrast, people generally indicated their greater latitude to vary timings, although a few participants had particularly complex regimes. The reasons for using reminders in asthma were more commonly linked to recognized forgetfulness, reducing the need to attend to complex medication regimes amongst other demands, or, occasionally, as a form of self-regulation. For example, Emily (27, type 1 diabetes) described how she would sometimes miss blood glucose measurements by choice and how she had decided to try to use reminders as a way to make sure they got done.

a) List-style summary



b) Tabular summary



c) Graphical summary

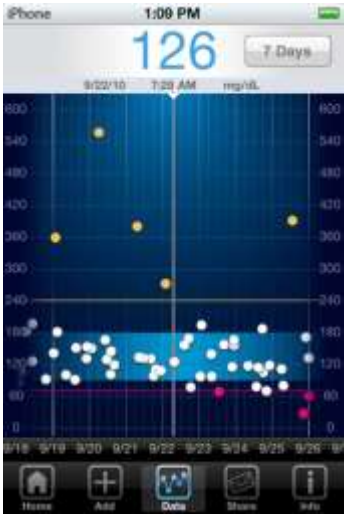


Figure 7-1 **Examples of data summary views in mobile medical apps for asthma and diabetes**

Some people, particularly those with asthma who had frequent contact with clinicians or emergency services, used app functions to compile portable lists of information about medications and medical history:

> *"So I have one on my phone that just does my meds. It lists all of them. It won't do my PRN because you have to pay for that. That came about because I go to so many outpatient appointments and so many urgent admissions I want to be able just to: 'Ugh, that's my drugs.'" (Tania, 19, asthma)*

This meant that information could be relayed accurately and quickly. While frustration with repeated explanations could be a motivator in both conditions, for asthma lists addressed the very practical issue of communication with a breathing impairment.

Several participants described specific information needs for which they used an app. Those with diabetes who were carbohydrate counting had found databases of foodstuffs that simplified the process of working out an appropriate insulin dose:

> *"The way I calculate carbs is… So one thing I've used in this app that's actually really cool is… 'Scan Barcode', I use that where you take a picture of the front [of a food packet] and then the barcode and then they will enter, like the company… within 24 hours will create an entry with the nutrition information." (Charlotte, 33, type 1 diabetes)*

A few individuals with asthma for whom pollen or cold weather was a recognized symptom trigger had downloaded forecasting apps, and used the notifications these generated to plan their days. One or two participants described specialized resources that they would only need to use occasionally, for example Tania (19, asthma), who used a drug interaction checker when purchasing over-the-counter medication to make sure that it was compatible with the Uniphylline she was taking:

> *"There are some meds that really concern me. I feel stress about my Uniphylline. It's such an easy overdose. And it's such a nasty overdose. And it has neurotoxic side effects… Over the counter medications I check for interactions. So I use an app and online interaction checkers." (Tania, 19, asthma)*

Participants did not, however, use mobile medical apps containing more general information about asthma or diabetes, relying on other sources, such as the internet, instead. No participant used apps with the intention of accessing social functions such as forums or social networking, even though several of the younger individuals did communicate with other people with their condition online. These findings highlighted the way that individuals would combine different tools to achieve their

goals, rather than relying on – or expecting – an app to satisfy all their needs. Nor did the introduction of an app necessarily mean displacing existing established routines for self-care:

> *"I keep my peak flow on the whiteboard, and I've got my preventer inhalers on my whiteboard as well. So it's all there. So when I go in, like at the moment, when it's not one hundred percent, I'll do my peak flow then I'll take my inhalers." (Shane, 38, asthma)*

Dealing with data

Uses for chronological log data were a recurring theme in many participant accounts. Data were sometimes collected for the purpose of supporting interactions with clinicians, in some cases substituting for paper diary-based collections that play an important role in established diabetes care and, to a lesser extent, the care of asthma. These use are described further in the following section (7.4.2.3 below). More surprising was the way that some individuals used data themselves, building on basic self-management skills that had usually been taught in the past and, occasionally, data analysis skills used in professional lives, to structure uses that ranged from practical decision-making to more reflective activities incorporating beliefs and hopes about their condition.

Between immediate treatment decisions and undirected reflections about overall control, it was not uncommon for people to describe treatment-directed activities that incorporated a reflective component. In some cases, this arose from a simple requirement to consider patterns independent of day-to-day variation, for example where people were stepping up or down longer-term components of treatment such as steroids:

> *"I use peak flow monitoring as a way of tracking, because it's… …I can kid myself that I'm doing fine and I don't need to take the oral steroids… And it's all part of the past, but having three days of data saying 'no, your peak flow is down 15%' just gives me a boot to say 'Okay, do something about this.'" (Alisha, 30, asthma)*

This sometimes required sophisticated skills to differentiate temporal trends in data, for example, separating the recent increase in variability in the simulated example shown below from the overall longer-term trend towards improved asthma control. Summaries were sometimes automatically annotated according to treatment thresholds (Figure 7-2a). For asthma, these typically reflected a percentage proportion of usual or best peak flow, commonly 80% and 50% values used in routine practice, while for diabetes thresholds were based on blood glucose values defining normal ranges. Although apps sometimes relied on individuals to configure these parameters, no-one indicated that they had struggled to understand or set the ranges. Most apps also incorporated interpretive annotations, such as "well/worse/critical" or "out of control/well controlled" that were automatically generated, sometimes according to less transparent criteria. Of all the activities

relating to data interpretation, automatic annotations generated the strongest reactions. Classifications felt to be "unfair", "a bit daft", or sometimes "plain wrong," were spontaneously pointed out when walking through apps with participants:

> *"I find this [symptom rating data entry UI] rather prescriptive. I often find it easier to tick one of these [night time symptom options] instead, but then it complains if your peak flow is below a certain amount. So then you tick one of these options, but then the app goes 'Uh oh!' [by generating a dialog box warning] It doesn't match up. It should be able to tick anything, but you know, why can't you tick 'Waking at night due to asthma' if your symptoms are severe?" (Peter, 43, asthma)*

This finding provided a key insight into the emotions that data could sometimes generate. The important role for emotions in app use is discussed further below (section 7.4.3.6 below), but a specific example is illustrative here. One asthma app sometimes generated incongruous labels by attempt to extrapolate a peak-flow-based condition label from symptom-only data, which the result that condition state reported by the app could appear to change dramatically in a short space of time (Figure 7-2b). The importance of such labels was suggested by the way that all three past or current users of this app highlighted this issue without prompting. Nor did it appear to relate to impacts on decision-making which was sometimes based on thresholds but which always pre-dated the introduction of an app. One explanation was simply frustration with something visibly prominent that was incorrect:

> *"It was a terrible nag. And it kept on coming up with my asthma might not be well controlled. I don't need my iPad to nag me and come up with totally obvious messages." (Danielle, 33, asthma, who ultimately switched apps)*

However, as in Emily's account, the use of language such as "nag" and "punish" hinted at the possibility that individuals might also want to control exposure to negative messages not simply because they were "totally obvious," but also because they carried emotive weight. One way to achieve this was simply to reframe labels in a way that meant they couldn't apply:

> *"Psychologically it doesn't worry me that it's in red all the time – because they would be such narrow bands it would look ridiculous, and it would go green, yellow, red, green, yellow, red. And the morning would be red and the night time might be green, so I've just left them as they are. The numbers are more important to me than the colours. The colours might look pretty, but yeah…" (Peter, 43, asthma)*

While Peter's asthma was poor, inspection of his charts suggested that it was not as variable as his account might indicate. It was striking how one of the consequences of his decision not to set an appropriate peak flow threshold was that it minimized the apparent variability of his asthma.

a) Automatically categorisation of data based on predicted peak flow thresholds determining 'well', 'worse' and 'critical' asthma state.

b) Incompatible automatic classification in the same app arising from inappropriate mapping of symptom data onto projected peak flow 'well/worse/critical' schema.



Figure 7-2 **Examples of automated data annotation functions in apps for asthma**

Several participants asserted that it was useful to be able to combine data to try to explain, and potentially learn from, condition upsets, such as factors leading up to an unexpected hypoglycaemic episode in those with diabetes. For example, Emily (27, type 1 diabetes) explained how she and her GP would work through app-logged data to explain the cause of such episodes:

> *"And another good thing, you'll create a report in PDF. And you can email it to yourself. And I've got a really good GP and I can print it out and give them to her. She'll literally go through [the data] and say: 'Okay, exercise here… you've had a hypo… you've eaten too many carbs to compensate for your hypo.' She will literally go through and look at it all with me… Having it all together is really helpful for figuring out what's going on." (Emily, 27, type 1 diabetes)*

This process required both the ability to relate different data, such as glucose, insulin dose, exercise and diet, within an explanatory model of causation, and logging incorporating those relevant types. It often proved hard to pin down concrete examples of where this had happened without clinical support. For example, Navinder (45, type 2 diabetes) stated that he used the data himself to improve his diabetes, and described how free text annotation of emotions in his diary had been useful for him to pin down stress as a cause of his poor diabetic control. However, it was difficult to see how his record, which was kept only intermittently, could have been used to reliably exclude other

possible causes. Nor had he discussed his data in detail with his GP. Instead, it was sometimes apparent that people could use such data to reinforce existing attributions about causes or levels of control, although there was no clear indication that this had had negative consequences. Only a couple of individuals described specific attempts, independent of a clinician, to relate different data in a more investigative mode:

> *"So if you're trying to troubleshoot what went wrong the day before, like nobody's memory is that fantastic that this six grams is what I took at this time yesterday. I think that you have an internal schema of what the right to do thing is. But… what you're looking to the app for is… moderating behaviours. Because having that internal schema doesn't necessarily translate into the right decisions." (Charlotte, 33, type 1 diabetes)*

Sometimes, technical barriers may have played a role in limiting data exploration. For example, Danielle (33, asthma) who had experimented with graphing her data in different ways, described how, to record exposure to incense as a particular personal trigger she had had to get inventive:

> *"I created it by using strong scent and wood smoke, which I thought was rather clever." (Danielle, 33, asthma)*

But, she explained, she had also kept it as a specific reminder to discuss with her clinician. The importance of this kind of concrete purpose motivating action was also implied by accounts from people who had found it hard to sustain logging of additional data over time. For example, Alisha (30, asthma) explained how she had started with good intentions to log symptoms as well as peak flow but that "sort of tailed off," and during probing it became clear that there was no particular need for that information as part of her day-to-day management.

Overall, while the *possibility* of integrating different data sources appeared to be appealing, and while activities oriented towards generating feelings of greater "control" or "comfort" were common (discussed further below), there was little in the way of concrete evidence that this was a motivating factor in its own right. Rather, individuals sometimes and sporadically took advantage of data they had collected for the concrete self-care purposes described above, such as treatment decisions, to achieve a secondary purpose, such as some form of reflection on their overall condition.

Managing relationships with professionals

Participant accounts included many examples of apps being introduced into consultations with general practitioners and hospital consultants, and these uses typically centred on patient-collected data. In several cases, log data were expected as part of a usual review process. No participant

reported reluctance on the part of professionals to use app data instead of paper records, or to handle personal devices to inspect those data. Many, but not all, reported positive experiences:

> *"My GP absolutely loves it. He asks to see it, now. He says, 'Show me your app.' And he looks through it all." (Peter, 43, asthma, who started using an app on his own initiative and only later showed it to his GP.)*

Some professionals, however, were not interested in log data, however it was collected, and the use of an app did not change that. For example, Kate explained how her consultant had stated explicitly there was no value in routine peak flow measurements, effectively – in her view – admonishing her for the app diary she had started to keep.

A few participants explained how the additional data had contributed positively to discussions involving their clinician. For diabetes, log data provided an opportunity to replay events like hypos with a doctor and talk about strategies for avoiding future recurrences. While there were benefits to having reliable logs, additional contextual annotations supported by apps, such as concurrent activities and carbohydrate intake recorded alongside blood glucose measurements, could be helpful in recalling and explaining events:

> *"My GP will literally go through it and say: 'Okay, exercise here: you've had a hypo, you've eaten too many carbs to compensate for your hypo.' She will literally go through and look at it all with me." (Emily, 27, type 1 diabetes, who had asked her GP for help improving her diabetic control.)*

For some people, however, data played a more nuanced role, as in Tania's account of logging medication to avoid a label of non-compliance "at her age". A theme of "not being believed" was conveyed in a few accounts with evident frustration. For example, Danielle explained how it was only after maintaining a peak flow log over several months was she able to convince her consultant that she could indeed achieve higher peak flow values and that her symptoms were not simply anxiety-related:

> *"My consultant finally decided, after lots of flip flopping, which drives me mad, that I have difficult asthma… And one of the reasons that happened was because I took these really detailed peak flow measurements. And it helps to have it when you're better and not so good. And that's a mistake I made previously, was only recording it was when it's bad, and then they had nothing to go on. And they'd look at and say, 'What's wrong with that?' And now you have the good, and they'll say: 'Oh, actually that is a lot better, you're right.'" (Danielle, 33, asthma)*

Negotiation of clinical relationships did not always rely on data. Kurt (30, type 1 diabetes), explained how he felt that his educational background meant that his clinicians did not take him seriously. He described a situation where he had identified an opportunity to participate in a clinical trial but was dismissed out of hand by his consultant. His account conveyed a combination of frustration and isolation in feeling that he had no-one he could rely on to look after him. Like Peter, his app use was exhaustive with an emphasis on "perfect" logging of his condition, reflecting his sense of isolated responsibility for self-management but also a means to prove to his clinicians that he was a good patient worthy of their attention. While no other individual had had such a polarised experience, narratives about being a "good" or a "bad" patient were not unusual:

> *"I like sitting in front of my consultant and saying I've done everything you asked, now it's up to you to sort this out. I have done exactly what you asked me to." (Tania, 19, asthma)*

> *"I'm doing as I'm told. My nurse is going to monitor me. She wants to see me. She wants to sit down and see me and see my bloods. So I need an MOT. Every person needs a stick up their ass. And this person is my stick." (David, 46, type 2 diabetes)*

7.4.3 *Why use an app? – Factors shaping the use of mobile medical apps*

Context: cues-to-action and needs

A substantial proportion of each interview was spent exploring the reasons why people chose to use, and keep using, an app when a variety of alternative methods were available. For example, paper-based diaries are commonly used in the clinical care of both conditions, particularly after first diagnosis or hospitalization, and many people had personal experience of using these. While the reasons involved were often layered, with specifics that differed between individuals, participant accounts almost always incorporated two key themes. The first was some kind of need, as perceived by an individual, to make a change in the way that they approached their condition (a cue-to-action). The second concerned the ability for apps to slot into the routines of life.

Triggers could arise in a number of ways. For asthma, many accounts involved an unexpected deterioration in the state of the condition; a "crisis" involving emergency medical and a period of convalescence or, sometimes, ongoing investigations because of sustained instability in asthma control. The common consequence of these unexpected changes was that medical and self-management activities suddenly became a priority. Sarah (36, asthma) offered a typical account:

> *"I've had very mild exercise induced asthma from being a teenager. Didn't generally bother me that much, until this time last year I had a really sudden, terrible acute onset asthma attack at work. Was off work for 8 weeks… was on steroids… was to and from the GP and ended up back in hospital." "I went to my GP and said, 'I have no idea what's going on,' and she said, 'Go away with a peak flow meter and let's see.'" "And it was me thinking there's got to be a good, some way of doing this… there must be an app for this. I've got lots of things on my smartphone, and apps for work." (Sarah, 36, asthma)*

For diabetes, the nature of the "crisis", if present, was quite different and always consisted of a change in the perception of the consequences of sustained poor control, often instigated by a healthcare professional:

> *"But last year my nurse changed. And… She sat me down and she said, 'See these figures? I don't like them. I'm not having them. It's going to change. And that needle thing, you're going to do twice a day.' I'm like: 'Okay!' So I had a bollocking. So I do it now once or twice a day." "And you get a little book, and it's: time, levels, reading, what you had to eat before or afterwards. But doing all that at 5 or 6 in the morning? Hmmmm! Henceforth the apps." (David, 46, type 2 diabetes)*

It was noteworthy how, of the few individuals who reported they had *not* found an app for which they had been able to sustain routine use, only one had a recent experience that could be properly characterized as a crisis. Emotional factors could also sometimes play a role in the decision not to use an app despite a concrete medical need, and these are discussed separately in a subsequent section (7.4.3.6 below)

The concept of 'fit'

While professionals sometimes, as in Sarah's case, suggested an initial concrete course of action, it was also common for individuals to decide themselves what activities they were going to undertake in response to changes in their condition. Some, such as peak flow diaries, were informed by skills learned when first diagnosed, often as children. Others were devised in response to specific perceived challenges, for example initiating medication logging because "at my age, they [clinicians] love to go down the non-compliance route as a way of explaining poor control" (Tania, 19, asthma) Even when a professional gave a concrete recommendation about a particular activity, such as monitoring, the decision to use an app, specifically, was almost always made by individuals without clinical input and there were only one or two cases where a clinician had suggested using an app. Sometimes this meant abandoning a tool that had been recently provided, such as a paper booklet:

> *"And you get a little book, and it's time, levels, reading, what you had either way. Before or afterwards. But I'm a driver for a living. Doing that at 5 or 6 in the morning? Hmmmm! Henceforth the apps! I think this [the app] is so much easier, because whenever you need to use it… there they are." (David, 46, type 2 diabetes)*

David's stated reason – simplifying recording data at an inconvenient time – was typical of the sort of answers to direct questions about what cued a search for an app. However, this is a partial account of what could make an app "fit" for an individual, not least because some uses – and limitations – were only discovered once an app had started to be used.

Analysis suggested three distinct senses in which a mobile medical app could be good fit:

- Task fit, judged by the ability to complete one or more particular self-care related tasks;
- Social fit, weighing the consequences for aspects of management of illness involving other people, including clinicians;
- Illness fit, a sense of compatibility with the demands made by, and priority afforded to, a condition at a particular time.

Task fit – the process of choosing a mobile medical app

Anticipation of task fit was dominant in directly articulated accounts of the reasons behind looking for an app, perhaps because, more so than other judgements, it could be grounded in specific criteria relating to activities such as monitoring and medication taking. Participant accounts of the circumstances surrounding the process of selecting app(s) highlighted a number of distinct strategies. Section 7.4.3.1 above, highlighted the way that contextual factors could act as a 'trigger' leading to a search for a suitable app with a view to performing one or more specific self-management tasks. However, only a small number of individuals articulated some kind of systematic strategy for app selection. For example, Charlotte (33, type 1 diabetes) combined internet searches to identify trusted sources of app reviews with her own testing of shortlisted apps:

> *"I approach being a diabetic with an extremely engineering mind-set… And I out to optimise whatsoever I can. So my goal was trying to combine my diabetes management with exercise and a food journal all in one. It's specific. It's not about convenience… So this particular one is probably the sixth or seventh app that I've actually used… I went to the app store, I went back to the three or four diabetes websites that I trust and started reading reviews. So most apps will let you download a trial, and I'll like run through the basics like, trying to enter a blood glucose reading. You know, I tried, I'll try most of them out pretty fairly I think. And, you know, I don't try everything out, I go from reviews." (Charlotte, 33, type 1 diabetes)*

A small number of participants also discussed potential choices with peers or through online forums. Most, however, relied on less formal judgements where there was no explicit articulation of criteria when picking an app and searching only in the primary app store available on their device. Once consequence of this was participants had widely differing perceptions of the availability of suitable apps, depending on where and how they performed their search. One or two participants insisted that there were only a minimal number of apps performing their chosen function, such as peak flow logging, despite the findings of the review of asthma apps described in chapter five (see e.g. Table 5-7) indicating that this was not the case on either Android or iOS.

Having a limited or unstructured search strategy did not mean that participants did not then actively evaluate the mobile medical apps they downloaded, however. Probing identified evaluative processes involving more or less implicit judgements, rooted either in taught-self management skills or, to a lesser degree, involving an element of comparison with paper-based equivalent tools, such as diaries. Individuals often talked positively in terms of the "speed", "convenience" or "ease" of task completion. Regardless of whether these were experienced in practice, it appeared that sometimes anticipated benefits – perhaps informed by experience using other apps or stories from others – could be a sufficient reason to start using an app. For others, probing suggested that language emphasizing convenience reflected instead perceptions of social and emotional impacts, discussed further below. When queried about the reasons for not using reviews or user-ratings to inform their judgements, these participants identified a number of contributing factors. While a few questioned the quality of available review information; most emphasised the ease afforded by app stores to download, try and then delete unsuitable apps. A few participants also identified cost as influencing factor. For these individuals, the ability to download free trials was an important factor:

> *"I know a lot of the apps you can get have a free version. And then a version that you have to pay for. So I'd download the free version and then if I didn't like it I wouldn't upgrade to the full version. I don't mind having to pay for apps. If I don't like the free version I'm not going to pay. If I'm going to delete it in a few days." (Kate, 26, asthma)*

One shared consequence of a lack of clearly articulated decision criteria was that, although a small number of participants simply chose the first viable option, it was not uncommon for individuals to then move through several selections in a short period before alighting on a final choice:

> *"I've tried loads. I downloaded and played with them. Didn't read reviews. I'd like it all to be on one app. A lot of them don't really do many things. AsthmaTrack was too much information. And too much effort. Lots of surplus stuff. The AsthmaSense medication log reminders, whatever, is the most glitchy part. So I started using [a separate app] on my phone instead." (Tania, 19, asthma)*

This selection process did not mean that users were necessarily, or even often, satisfied with their current choices, however. Participants were often able to enumerate negative aspects of their experiences, typically in the form of detailed technical specifics, for example, the inability to set reminders within precise parameters, or concerning phenomena which disrupted task performance, such as app crashes, which were common. However, as long as the core aspects of a task could be performed, it appeared many users were happy to tolerate suboptimal (in their view) app performance. While a few participant accounts suggested that they had found the app search process challenging, the reasons behind this apparent inertia appeared to involve more than costs associated with search effort, learning to use a new app or the loss of accumulated data. For example, mobile platform changes meant that several participants had to switch apps but none expressed any particular frustration at having to switch. In relation to task fit, it appeared that, as long as desired self-management tasks could be performed satisfactorily, participants often had little interest in further optimizing their experience.

Illness fit

The idea of illness fit arose initially from the central role for a changed clinical context in triggering the initial search for a mobile medical app. However, in addition to this situated component, there was also a dynamic element: as needs changed, so could the requirement for apps. There was no sense in which apps enjoyed a particularly privileged position compared to other strategies for self-management. For example, Kurt (30, type 1 diabetes) had been a fastidious app user, logging all aspects of his diabetes. However, at follow-up, he explained that he had stopped completely as soon as he was able to start using a continuous subcutaneous insulin pump and glucose sensor system. Despite lacking some features that had seemed genuinely valuable to him, such as detailed summary information, the pump system offered automated measurement, dose adjustment and the prospect of better glucose control. These were not only features that an app could not match, they fundamentally altered the work of self-management in day-to-day life because testing and injecting tasks no longer demanded regular attention.

More often, however, there was a nuanced interaction between changes in condition state and the perceived value of using a mobile medical app over time which ultimately resulted in changing patterns of use. While some people appeared to derive intrinsic pleasure from explicitly optimizing their approach which allowed them to “feel flash” (Navinder, 45, type 2 diabetes), “know I’m doing whatever it takes” (Peter, 43, asthma), or “achieve a sense of total comfort” (Charlotte, 33, type 1 diabetes), they were unusual. More often, monitoring was characterized as a burden and a necessity. As a result, app use could be sensitive to improvements in the underlying condition.

At follow-up, several people reported how, as their asthma had continued to improve, they had reduced the frequency with which they were logging data. Unlike asthma, where improvements could reflect changes intrinsic to the underlying condition, better control in diabetes could only reflect success in behavioural regulation and self-management activities. Calibration was evident even in those who were ostensibly positive, such as Charlotte (33, type 1 diabetes), who confessed that for all that she liked knowing she was in control, self-management via manual titration of injected insulin was always going to be, in her view, "not quite good enough." A strategy of occasionally altering parts of her self-management routine, including changing apps, helped, but she still switched to an automated insulin pump system as soon as one was available.

Social fit

Notions of social fit almost always incorporated the role of healthcare professionals in advocating self-monitoring, their response to the use of a mobile medical app and the purposes for which an individual might choose to introduce their app into clinical discussions. Because of the importance of these dynamics for the use of apps in clinical care, these are discussed separately below. Clinical interaction, however, not the only way in which people communicated the idea of social fit in shaping the acceptability of an app. Reminders were perhaps the simplest example of a strategy designed to ensure that aspects of self-management were performed in social contexts where there were other demands for attention. Managing the risk of forgetfulness was common but not the only reason. Individuals with diabetes who had to test and inject throughout the day all reported how they no longer attempted to conceal testing in social situations. Nevertheless, it was clear that this had not always been an easy process: "I used to go and hide in the bathroom" (Charlotte, 33, type 1 diabetes). If the process could be streamlined to reduce social exposure, then people were certainly willing to do this, and some had found that using an app could save vital seconds:

> *"I'll test my sugars in front of my friends. But they don't really get it." "Because [this new phone] is so quick, it's just like… it's just so easy, it's just so fast. You don't have to wait for it to load. I know that's a really little reason, but I have to record it immediately or I won't record it. So if I test my sugar in lectures, I have to get my phone out to put it in" (Emily, 27, type 1 diabetes)*

The importance of controlling social exposure was also articulated by Charlotte, who used a food database app for calculating precise carbohydrate intake at home, but explained that, in a social situation, she would never perform the same kind of detailed calculation. In practice, this meant either eating things in their packaged quantities, or approximating the amount of insulin, both incongruent for someone who had directly emphasised the importance of technical mastery but

clearly insufficient to reshape behaviour in a social context, despite the availability of an app. One or two people described how they had used an app to solve specific issues relating to specific situations, such as work. Kate (26, asthma) had a part-time job working with vulnerable individuals and needed to keep track of medications she carried with her to make sure that none had been taken. She solved this problem by combining a medication tracker and reminder app with a dosette-box system she had devised, enabling her to reliably control and track when a dose had been taken. None of the participants shared their apps with family or friends and so their potential reactions did not feature in this discussion.

The role of emotions

Most participant accounts made references, sometimes in quite direct terms but often more obliquely, to the emotional dimension of living with a long-term condition, including feelings attached to specific activities such as the recording of personal data which ultimately shaped both the way apps were used and, for some, the decision to use a mobile tool at all.

Emotions were often most strongly communicated in relation to an individual's imagined future; a topic explicitly addressed towards the end of each interview but often elicited spontaneously during earlier discussion. While people with both conditions commonly explained feelings in terms of the possibility of sustained impacts on relationships and activities such as work, those with asthma also reported more inchoate worries about whether the nature of their illness could ultimately be pinned down, arising from experiences suggesting, to them, the fundamental unpredictability of their condition (despite clinical messages emphasizing that most asthma can ultimately be controlled). While also oriented towards future impacts, concerns about diabetes were more realistic in reflecting the substantial risk of life-altering complications, but less grounded in experience since only one participant had diagnosed early (microvascular) complications.

In responding to these concerns, one or two communicated a clear, positive sense of agency discovered in routines based around apps. Peter (43, asthma), had experienced a rapid, unexpected transition from successful executive, whose job involved frequent travel, to full-time patient, tied to medication routines and clinic visits. He faced multiple clinical issues for which, despite ongoing investigations, no clear explanation had been found. He showed how, every morning, he would diligently fill in all the fields of his asthma diary app. The possibility of contributing to the diagnostic process was a source of evident satisfaction, as was the positive response he had received from both GP and consultants; it was something that he could do, and do well, when much else felt "out of his hands." For example, Peter was unusual amongst interviewees in having little scope to adjust his medication because a fixed regime could not be agreed amongst his clinicians. Equally important

seemed to be the reflexive evidence of simply being able to sustain a routine in the face of a situation that felt largely out of control – something that did not sit easily with him:

> *"I should [his emphasis] know what to do to manage my own symptoms… and control myself… and know what to do." "It's important for me… to try and get a hold of it all. It's really important that I do this." (Peter, 43, asthma)*

In addition to logging assiduously, Peter used a separate app to set medication reminders, another for managing healthcare appointments and a fourth to monitor pollen levels. For others, a sense of technical proficiency could itself be a source of reassurance:

> *"Having mastery of the software or over the stuff is just like a tiny way of expressing that kind-of… feeling of genuine comfort, or of like… Almost like solidity, like some diabetics call themselves brittle if they can't get everything stable and so I think like that there's this feeling that you're just underlying stably running along… And then, a hypo, if you have a hypo it's no big deal." (Charlotte, 33, type 1 diabetes)*

Several participant accounts suggested an emotional content to activities involving reflecting about their overall condition state, made possible by the summary charts generated and updated automatically by their apps. Positive trends in measures such as peak flow were spontaneously pointed out as the possibility of "better things to come" or a sign of "end being in sight." Evidence of accumulating data, sustained over time, could itself be a source of satisfaction. For example, Alisha (30, asthma) was not unusual in maximizing the data range of the summary chart in her app, without prompting, to demonstrate the amount of data she had collected. Accumulated plots of stable data were often described as "pretty" or "nice to look at." While positive signs could be interpreted as signifiers of systematic shifts in their condition, participants almost always characterised negative aspects of data (if recognized) as being temporary, using words such as "blips" or "hiccups." Probing suggested that, for one or two, these terms were understood as only appropriately being used in comparison to an otherwise stable background.

The desire to control exposure to more nuanced data was highlighted in several accounts, for example from Alisha, who commented that the presence of a summary chart allowed her to "eyeball" progress without having to get "too involved." Like others, the alternative of more in-depth reflection was seen as both a potentially time and effort-consuming activity and an unwelcome reminder of the continuing presence of a long-term illness. Knowing that out-of-range values would be automatically flagged by an app did not always help. Emily (27, type 1 diabetes) expressed this most clearly, admitting that she had sometimes chosen to log only better measurements:

> *"When I see it's green, I feel like: 'Right, I'm getting there.' But I don't like the red… [it] makes you feel you've done it wrong again, it's punitive." (Emily, 27, type 1 diabetes)*

This attitude was also reflected in her choice of app, which incorporated playful elements such as a diabetes avatar and points rewarded for particular activities, and therefore wasn't, in her view, "too serious." This did not mean, however, that positive outcomes could not result. Emily nevertheless managed to generate enough data to enable meaningful joint discussions with her clinician (see quote in section 7.4.2.3 above). Similarly, Sarah's account indicated that she had been able to use log data to recognize situations where she needed to step up treatment where previously she had been a bit "kamikaze" (quote in section 7.4.2.1 above).

A choice not to engage in more active reflection was a challenge to commonly expressed desires to "get to the bottom of what was going on." This apparent contradiction reflected the way that issues of responsibility, self-management skills, pragmatic and emotional factors could interact to shape specifics of app use for different individuals. For a few, reflective activities were harder because they had yet to acquire skills to interpret the data being collected. Often, however, these individuals had not taken practical steps towards this, such as asking a professional for help or looking online, and it appeared that "not being able" could sometimes be a useful way to avoid data that might cause worry. David (46, type 2 diabetes) typified this approach. As far as he was concerned, responsibility for collecting the data might be his, but the burden of 'seeing him right' using those data was for his diabetic nurse. Sharing data with a professional was not at all unusual amongst participants, however few were as polarised in their assignment of responsibilities. When asked about whether he ever checked the data himself, David said he sometimes looked back, and was vocal in the importance of self-monitoring:

> *"It's a wake up. The Indians call this the posh, rich man's disease. Right people: Diabetes. Monitor. Your. Progress." (David, 46, type 2 diabetes)*

Yet he conveyed a sense of passive bemusement at a recent morning high because "he'd done everything right," and did not appear to view it as a cue to adjust his own management or to seek help. Suggestions of an emotional component to this apparent inertia came from the several unprompted references to 'horror stories' heard from family and colleagues, and a plainly stated fear that David wouldn't be able to continue to enjoy time with his grandchildren because of his diabetes.

Even for the one or two who demonstrated how they would try to use negative data for learning, reflection could be challenging. Charlotte's (33, type 1 diabetes) comments illustrated how effort was required not just to engage in reflection about her diabetes, but also to sustain it:

> *"The real kicker is that you can spend two or three days sorting out hypos, and those are the days that you don't use apps. Those are the days that you don't want to enter… You're really wrapped up in sorting things out and conducting regular life…" "Reflection is the most difficult aspect. Durable reflection that you know is going to happen and that you trust yourself to perform… Maybe some people are lucky and they never fall off the waggon." (Charlotte, 33, type 1 diabetes)*

Monitoring could also seem more or less appealing, depending on the demands of other, less negotiable activities relating to the condition, such as complex medication regimes, the availability of time to dedicate to management, and the desire to circumscribe illness-related activities so that they played less of a dominant role in everyday life. Tania (19, asthma), holding down full-time university and a demanding part-time carer job, explained this using the concept of "spoons", the reserve of energy available over a day, or a week, to expend on all activities, whether voluntary or related to asthma management:

> *"I know that after a weekend of exacerbations… By Friday I'm going to be exhausted – I'm going to run out of spoons." (Tania, 19, asthma)*

Streamlining parts of management could help, for example using a digital peak flow meter connected to an app could help take the "faff" (or effort) out of peak flow monitoring, but only up to a point.

Common to these accounts was the way that emotional content had been discovered in particular activities rather than being anticipated. While often reflecting features intrinsic to monitoring and reflection, specific aspects of the technology could nevertheless play a role. For example, because of the manual effort required to plot paper-diary data, few participants had had systematic exposure to the summary views of their condition offered by many apps, except perhaps in the form of ad hoc charts compiled and kept by an asthma or diabetic nurse. (Participants with diabetes were more likely to have used pumps or meters in the past that kept this kind of data, but only numbered one or two amongst those interviewed.)

In a few cases, however, anticipation of negative – but never positive –effects shaped the decision to use a mobile medical app at all. Anne (60, asthma), previously having experienced only mild, stable asthma, explained that she had feared for her life when suddenly admitted to hospital with deteriorating lung function. Although subsequently shown to be due to an undiagnosed pneumonia

rather than asthma, she had nevertheless embarked on a series of steps targeted at preventing any future asthma attacks as a result of this "wake-up call." These included setting up an app to provide alerts about the weather and negotiating with her general practitioner to be able to phone for advice. She had decided, however, not to keep peak flow measurements, which she felt would be an inevitable source of worry when trying to differentiate day-to-day variability from signs of deterioration, despite the availability of support from her practice. Another perspective came from Bernadette (46, asthma), who admitted that logging would simply serve to remind her that her asthma was suboptimal, something that she "knew but probably wasn't prepared to admit to herself."

7.5 Discussion

7.5.1 *Summary of results*

Mobile medical app use amongst adults with asthma and diabetes was:

- Dominated by data logging activities enabling shorter-term (in diabetes) and longer-term (in asthma) treatment self-adjustments. Data logged in apps also facilitated interaction with responsible healthcare professionals, even though clinicians did not always initiate this. Participants also used apps for reminders, to store prescriptions, for lookup-type information, such as nutrition databases in diabetes, and to receive contextual alerts, such as air pollution information in asthma, but not for general condition information, social network support or remote clinical communication.
- Task-focussed, based on specific activities grounded in existing self-management skill repertoires and directed towards particular goals. Speculative app use not directed towards any particular self-care goal was uncommon, and was not sustained at follow-up. Secondary emergent uses, such as benefits discovered in being able to reflect on log data collected for a more concrete day-to-day purpose, were not, by themselves, enough to sustain app use if the requirement for the original task was removed, for example if condition state improved necessitating less frequent monitoring.
- Linked to the greater perceived convenience and availability of mobile devices in those contexts where self-care tasks needed to be performed, such as being able to share data with a clinician in an emergency or planned consultation.
- Not guaranteed to displace existing established repertoires of self-care behaviour, such as existing methods for tracking peak flow, if these were satisfactory. Satisficing was also

evident in the way that individuals would tolerate deficits in chosen app(s) provided the main identified task could be completed.

These concrete aspects of mobile medical app usage appear to be shaped by an unexpectedly rich combination of factors. These include background elements, such as existing self-management capabilities and knowledge, external cues to action, such as recent changes in health status, the visibility of suitable apps, and cognitive and emotional responses that include judgements about whether an app is a good – or good enough – 'fit', evaluated both pragmatically in terms of compatibility with self-management tasks and in the broader context of life with a long-term condition. Emotional components include the desire to establish a sense of control, avoid negative emotions associated with the sense of 'being ill' and addressing fears about uncertain future consequences arising from long-term, incurable illness.

7.5.2 *Discussion and integration with existing research*

The following discussion focusses on the implications of the findings for the introduction of apps into clinical care. It explores the contribution that understanding of 'how' and 'why' mobile medical apps are used can make to the scope for offering apps on prescription, as well as identifying where limitations in the data leave gaps that require further work. In addition, the discussion aims to highlight the way that results are connected to existing literature on self-management.

The nuanced relationship revealed in the data between app interactions, self-management tasks and goals, is particularly relevant for discussions about the routine use of mobile medical apps. Almost without exception, app usage was directed towards specific goals framed by individuals in relation to their health. Goals were typically tightly defined, coupled to specific routine tasks, and limited in scope, for example, ensuring a particular high-risk medication was taken on time (as opposed to remembering to take *all* medications) or logging peak flow data with the intention of supply to a clinician in an ongoing diagnostic process (rather than broader opportunities to inform personal self-management decisions and reflection). Perceived needs, in turn, arose from personal exposure to specific cues, such as recent changes in health status, pre-existing self-management knowledge and skills and, sometimes, as a result of recommendations made by healthcare professionals. The role of professionals in reinforcing positive messages about self-care has been identified as a potential enabler in previous work[369], but in these data, at least some participants were able to sustain app use despite negative interactions with professionals. Concerns that mobile phone monitoring might encourage dependence on support from professionals raised in a previous focus group-based study[370] were not borne out here, although no participant shared data remotely, relying instead on feedback within traditional face-to-face consultations.

The findings provide a contrast to technology-oriented visions of mobile medical apps as hubs that integrate all aspects of self-management with an emphasis on data-driven decision making. Rather than acting to substantially structure what or how individuals did in relation to their asthma or diabetes, app use was itself structured by the requirements of specific, narrow tasks framed by individuals as they "constructed their own self-management program"[371]. This was evident in the way people approached the process of app selection by describing what it was they wanted apps to do in specific terms, for example recording a particular type of data rather than comprehensive logging, and in specific contexts, for example to fit within an established morning routine. This kind of variation, which continued to evolve over time, appears to be characteristic of multiple long-term conditions, including diabetes and asthma[372]. While app interfaces, particularly those involving structured forms with multiple data elements, plausibly offered a way to organise tasks, the influence of these was questionable. Although some individuals were initially willing to use comprehensive forms to cue activity, reporting a sense of satisfaction associated with "filling everything in", this was rarely sustained. Instead, app-related activities were filtered down towards those strictly necessary in terms of the goals to which activity was being directed. Strategies to promote recording such as alerts – that were commonly seen in app-supported interventions identified in chapter four – or mandated data entry elements, could be seen as coercive and ultimately lead to individuals switching apps. One explanation for this behaviour is the desire to balance the demands of self-management against other life pressures and to maintain a 'coherent identity' and normal social life[373]. The importance of purpose was also suggested by individuals who reported difficulty in finding a suitable app. For these participants, often with more stable disease, probing failed to uncover a specific need, recognised by the individuals, to which app use could be directed. While these participants might talk about apps in broad terms as an appealing method for monitoring couched in terms of something they felt they "ought to be doing," this was not sufficient to engage in the activity or sustain it for long. A positive association between perceived usefulness (in terms of satisfying concrete needs) and app use was also found in a separate qualitative study of an app-based intervention for diabetes[374]. An alternative interpretation of these data is the existence of distinct coping styles that occur independent of disease state and reflect personal dispositions. Collins et al.[375] drew a distinction between "proactive managers", "passive followers" and "nonconformists" in their analysis of self-care for diabetes. Certain characteristics of these groups were visible in the patients studied here, for example, patients who would log data but only take action once it had been reviewed by a professional. Grouping patients in this way may be helpful if it enables distinct approaches for clinical management.

A second aspect of the dependency between mobile medical app use and self-management activities concerned the sense of immediate value offered by completion of a task. For some uses, there was a clear connection between affordances offered by an app and successful task completion, such as a reminder, fired to a desired schedule, prompting medication-taking. However, this dependency was not always obvious, particularly for data logging activities where differences were seen between asthma and diabetes. For individuals performing insulin titration, there was a recurring need to recall previously administered insulin doses and times, and combine these with an overall assessment of condition state on a given day, in order to make dosing decisions for which an app-generated summary could be useful. While people with asthma also described a similar process of evaluating measurements in order to make treatment decisions and choices about activity, no participant communicated a clear process of data reflection that necessitated use of an app. Instead, decisions were made based on contemporary measurements which were often combined with internally held judgements about symptoms and illness to make decisions. For these people, logging was nevertheless purposive but, instead, oriented towards secondary, longer-term purposes, such as personal reflection, decisions about longer-period treatments such as steroids, or discussion with clinicians.

Common across these scenarios, however, was the way the act of data generation itself supplied value. This was suggested by the way that logging frequency appeared to be linked to proximate consequences of measurement for individuals, for example comparing diabetes, where missed measurements can lead to rapid deterioration, versus asthma where the consequences may be less immediate. This contrast was most visible at follow-up. Individuals with asthma often reported general improvements in their condition, a reduced need to measure peak-flow on a day-to-day basis, and a reduction in logging behaviour. These changes suggest that, while individuals might value the opportunity to reflect on log data, for example, because of the opportunity it offers to gain a sense of control over illness, a recognised phenomenon in previous studies[376], it may not be sustained if the act of data generation itself does not offer some value. In contrast, there had been little change in logging for diabetes. This did not mean that management was unchanged, however, for example both of the insulin-titrating patients had switched to an integrated pump system. However, while this changed the form of data capture and logging, unlike asthma, it did not fundamentally alter the need for it.

While mobile medical apps may not motivate self-care behaviour, the decision to use one nevertheless reflects evaluations about the extent to which a mobile tool is an appropriate solution.

In this way, apps can be characterised as modifying potential barriers to task completion. Participant accounts illustrated the range of ways in which this was possible:

- Directly addressing issues relating to forgetfulness, e.g. through the ability to configure reminders.
- Being available in work and other social situations where a pen and paper might be forgotten, but a mobile would almost always be carried. However, similar value could be found in more controlled situations, such as during morning routines.
- Reducing the perceived effort associated with a particular task, for example summarising data in graphical form.
- Addressing possible social stigma around self-management activities because, in contrast to using a medical device, interaction with a smartphone is not unexpected or unusual in social settings, particularly amongst younger people.

Despite the importance of these elements (which I have characterised as 'fit'), their role in app selection and use is balanced by a number of factors. Firstly, patients may have limited visibility of which of these are likely to be influential in advance. Secondly, the ability to find apps that effectively address these elements is constrained both by the way general app stores present information, but also by differences in the way individuals search and choose. Only one or two participants described stepwise approaches to app selection in which criteria were framed, or product descriptions and feedback reviewed. Dedicated mobile medical app stores may, in the future assist with this process, but underlying factors such as dispositional preferences for optimizing versus satisfying choices are unlikely to change. This was evident in the way that many participants were able to quickly articulate dissatisfaction with specific aspects of the apps they used, but were surprised at the suggestion that they could switch products. Even amongst the more technically proficient users, there was often surprise when assertions that "no app" supported a particular feature were (gently) challenged. Finally, despite attempt to attribute causes to data[377], it cannot be assumed that patients are equipped with the skills to negotiate all the phenomena that may be manifested in self-monitoring data. This kind of 'knowledge-action' gap has been described previously in relation to patients with type 2 diabetes[369, 378]. Ensuring that individuals can access timely professional support for self-care related needs, such as data interpretation,[379] and enabling individuals to make appropriate attribution of causes for changes in illness state, as a way of regulating and understanding negative impacts on quality of life[377], have been proposed as determinants of sustained self-care

While app use was directed towards specific needs, these could be emotional as well as practical. Fear of negative consequences of sustained poor health and, more positively framed, the development of a sense of control, were common narratives that have also been observed in other studies. For example, Newton et al. identified concern about the anticipative effects and autonomy as distinct management styles in patients with type 2 diabetes[376]. In contrast to more practically framed goals, however, emotional benefits were often discovered rather than anticipated, for example in the value offered by automatic graphical summaries that gave an overall sense of condition state. As a result, the role of these benefits in sustaining app use was less clear. There were also clear examples where anticipation of negative emotions could act as a barrier to app use, for example because of concerns about having to confront information about health status on a day-to-day basis. Self-care is recognised as emotionally demanding[373], and this kind of 'defensive coping' has previously been identified as a barrier to self-care for diabetes[369], however not in relation to mobile medical app use, specifically. The sense in which apps were a good fit was also a product of the capacity felt by an individual to reconcile what they knew they ought to be doing – in terms of messages received from healthcare professionals, family members and media sources – and what they felt they could. There were suggestions that aspects of app design, for example the incorporation of playful elements, could moderate these emotional aspects, and these should be explored further. The role of specific aspects of design to avoid perceptions of being 'judged' has previously been highlighted in relation to internet interventions for behavioural disorders[380].

The findings also indicate the potential for theoretically-grounded intervention designs that incorporate mobile medical apps. Parallels can be drawn between findings suggesting the relevance of contextual factors prompting the use of apps and subsequent internal evaluations of fit and constructs from established models of health behaviour change, such as the health belief model, which include ideas such as 'cues to action' and cognitive evaluations of barriers and benefits. While the data also highlight the importance of emotional factors such as fear and loss of control, these similarities highlight the opportunities to borrow from existing theoretically-grounded accounts when shaping app-based intervention designs and as part of subsequent evaluation of why apps do or do not work in practice. This is likely to be a dynamic process should app use continue to become embedded into care and other aspects of life.

7.5.3 *Limitations of study methods*

A major differentiator of qualitative and quantitative methods is the contrast in perspectives on the importance and meaning of external validity in relation to gathered data. In contrast to studies described in previous chapters, in this project (and in qualitative methods, in general) there was no

expectation that participants be a statistically representative sample of the population of app users implying a minimum viable sample size, nor that interpreted data be able to be characterised in frequentist terms. The omission of numerator-denominator-type statistics (except in the brief exposition of participant characteristics) and the use of imprecise quantifiers, such as 'some' or 'a few', were deliberate strategies, reflecting standard practices in qualitative research intended to avoid quasi-statistical interpretations while communicating the sense of patterns observed across participants. In stating this plainly I aim to recognize that, while compatible with the pragmatic epistemology underpinning the multimethod approach of this thesis (section 3.4.1 above), this strategy may be controversial to any reader whose research frame is primarily positivist. My rebuttal would be that it misunderstands the purpose of qualitative enquiry in providing a rich, credible account of *some* aspects human behaviour, without an expectation that this be definitive or holistic. For example, that the majority of participants displayed high levels of measured functional health literacy is an important qualifier of interpretation of the data presented here[373], without either implying that all app users are highly literate or denying the possibility that there are issues of equity affecting uptake of mobile medical apps for self-care. Both are potentially amenable to future quantitative work that aims to 'test' the extent to which observed phenomena hold for wider populations, however this aim of ensuring broad external validity was beyond the scope of this investigative study.

Other constraints that act as lenses through which the data should be viewed include:

- A planned focus on independent adults rather than children or vulnerable individuals, reflecting the potential ethical and practical challenges of collecting robust accounts from participants in these group.
- Inclusion of only those with a level of English comprehension enabling them to understand study recruitment materials and participate in study processes.
- The focus on individuals using an app regardless of clinical support availability. This reflected the currently (at the time of writing) limited state of organized clinical programs supporting the use of apps for self-care at the time of study planning. It cannot be discounted that those individuals choosing to use an app as early independent adopters have unique determinants of behaviour. Thematic similarities identified with existing qualitative research on self-care suggest that gross differences are unlikely. However specific motivational differences may exist. For example, although participant recruitment was able to achieve some balance across gender, condition and age, it proved

hard to recruit participants from ethnic minorities. The role of family and social context in shaping behaviour[378] was not explored in detail in this study.

- While patterns of app use were examined using a contextual technique, factors underpinning the process of app selection which had been performed at some point in the past relied on narrative accounts given by participants. As a result, these may have been at a higher risk of biases arising from recall and rationalisation effects.

While statistical representativeness, specifically, was not understood as a study limitation, the degree to which the experiences of recruited participants enabled a comprehensive account of themes identified from their data was a recurring concern. The recruitment process proved challenging, necessitating an extended campaign using social media in order to identify suitable participants within the timeframe and resource constraints imposed by the PhD. The final inclusion of fourteen participants, while not atypical for a qualitative study, reflected this challenge rather than an active decision to stop sampling. As a result, it was not possible to definitively satisfy a planned strategy to achieve theoretical saturation; the point at which recruitment of new participants does not lead to further elucidation of concepts identified in data. The limitation arising from this constraint is that, although the analysis emphasized patterns and contrasts identified across participants, there may be nuances of identified themes that have not been captured.

7.5.4 *Reflexive issues*

Another way in which this study differed from those described in previous chapters in the fundamentally interpretative, iterative process of result generation. This stands in particular contrast to the pre-specified, objective criteria underpinning the assessment of apps described in chapters five and six. The results presented here reflect choices made by me both during the interview process, in selecting which topics to probe further, and during subsequent analysis, in finding links between accounts and establishing ways of organizing these data. Unusually for a qualitative study, the work was motivated by specific questions arising from studies described in earlier chapters. As a result, I considered that there was a particular risk of bias arising from reflexive speculation about what might motivate individuals to use mobile medical apps before this study was planned, as well other unconscious preconceptions and expectations arising from experience with apps, as a clinician and as an individual with asthma. In addition to the selection of a qualitative method recommended for situations where existing knowledge may inform analysis, several strategies were used to try to control this risk:

- Prior to the start of the interview process I attempted to articulate my expectations in written form. The contrast between these expectations, which anticipated accounts substantially focussed on the design of specific functions within apps, and participant data, which emphasised less precisely articulated senses of 'fit' and emotional compatibility, suggests that the analysis was at least partially successful in moving beyond preconceptions.
- After each interview, I attempted to critique my conduct as interviewer. By reviewing audio-recorded dialogue, I was able to identify instances where I perceived a risk of influencing participant responses and where I had failed to explore alternative viewpoints in probing questions. I used this as learning to inform subsequent interviews. While in general, it proved easy to establish rapport with participants, I was aware of the need to balance encouragement, fostering a sense of safety and comfort, with more challenging probing that aimed to explore issues such as contradictions in participant accounts. The strategy I ultimately adopted involved revisiting these topics later in the interview once participants were at ease and this seemed to work, although at the risk of sometimes breaking the flow of conversation towards the close of the interview as loose ends were tied up.
- Finally, to gain an independent perspective, I discussed each stage of analysis, summarized in written form, with a supervising researcher, experienced in qualitative methods (Cecily Morrison).

For me, the most challenging of the interview process were discussions of clinical care where individuals communicated feelings of being disbelieved or uncared for. Although explicitly articulated by only one participant, I was left with the impression that some individuals were hoping that I could either offer them some kind of ongoing support or validate their perspective about gaps in clinical care. In these situations, I felt mixed emotions. As a human, I wanted to help. As an interviewer, I was aware of wanting to facilitate discussion to understand the issue in detail. Reflecting my clinical training, I also felt a sense of disappointment on hearing about poor care experience, but was also wary of being recruited into any form of collusion about situations for which I felt I only had a partial (patient-based) perspective. My response was to probe with questions raising the possibility of other more appropriate sources of support, for example to ask if an individual had discussed issued with consultant care with a trusted GP. Even when this was not done, participants occasionally noted that they had found the interview process "helpful" or "useful," suggesting that the process itself might have held some therapeutic potential. While this possibility

was anticipated as part of the ethics review process, it was not something I had expected to see in practice. The experience highlights the importance of considering potential participant impacts during qualitative study design, particularly those involving topics more sensitive than those addressed here.

7.5.5 *Issues identified for thesis discussion*

From a clinical point of view, the study provides a qualified view on evidence that current generation mobile medical apps are compatible with key self-management practices routinely recommended to patients with asthma and diabetes, such as carbohydrate counting, peak flow and glucose logging and routine medication taking. The goal-focussed way in which apps were used in response to an identified need poses both opportunities and challenges for their use in clinical practice. Patients may be more likely to consider starting to use an app after a recent change in disease state or if a healthcare professional can articulate a specific goal to which the individual also agrees, for example determining whether a new medication is effective or not. However, evaluations of need may differ between individuals and conditions. For example, while the experience of an acute exacerbation could be motivating in asthma, individuals with diabetes did not talk about general poor glycaemic control or hypoglycaemic episodes in the same way. Instead, motivation was more often related to changed perceptions about the negative consequences of sustained poor condition control. Efforts to introduce mobile medical apps will need to be sensitive to these kinds of differences, and the readiness of individuals to make a change in health behaviour. Consequently, there may be opportunities to borrow learning from strategies for health promotion, such as smoking cessation and weight loss, where similar sensitivities are needed. In particular, strategies that help individuals evaluate what factors might make an app a better or worse fit may be useful.

Secondly, pragmatic and affective factors also play a role in the suitability (of fit) of an app for an individual. Subtle aspects of design, for example the way feedback is presented, can shape the acceptability of an app for an individual, particularly for those whose previous experiences of self-monitoring have not been successful. Mobile medical apps are installed on personal devices for which users are accustomed to a substantial degree of autonomy. After accounting for factors such as age, literacy, numeracy and illness state, expectations that single products can support the needs of entire populations are probably unrealistic. Future work should explore the feasibility of multiple product support, the governance arrangements necessary to support this, and the ways that developers can facilitate this, for example by adopting common standards for data exchange and ensuring that expectations of good governance are met.

Thirdly, appropriate consideration is required of the specific technical skills and knowledge required to use mobile medical apps successfully. In this study, participants were able to draw on existing knowledge and skills, gained from health professionals and previous experience, for example using paper diaries, and effectively translate these into app use, as well as frame criteria for app selection. While acknowledging the possibility that study participants were unrepresentative of the broader population of people with asthma and diabetes, the apparent ease with which this was achieved is a positive sign, indicating that existing self-management education can provide a basis for strategies that incorporate app use. However, some activities, for example appropriate reflection on data demand a range of skills which may need to be evaluated and addressed as part of education. These include specific aspects of interpretation of data which may involve a degree of sophistication. For example, while many patients with asthma were able to interpret trends in peak flow, only one or two appeared to understand the importance of short-term variability in addition to magnitude. In addition, there may be aspects of self-management education that are not routinely performed, such as the provision of action plans, but influence the perceived value of logging. Several participants with asthma either expressed frustration that they did not have thresholds against which to evaluate log data or indicated that they had devised rules themselves. Not all individuals will be able to make these kind of judgements appropriately. For newly diagnosed patients, apps offer the potential to integrate skills training with tools. However, this was not expected by participants, all of whom had established diagnoses, and no app used in this study offered this kind of functionality.

Finally, expectations that monitoring behaviours, in particular, be sustained over long periods of time may be unrealistic. The scope for telehealth-style monitoring using mobile medical apps may be influenced by whether individuals in the target populations already engage in routine measurement and whether suitable value can be attached to such tasks. While attrition may result from changes in the perceived need for the activity to which app use is directly related (e.g. the need for reminders may change as medication is stepped up or down), app uses such as a data logging are also sensitive to the requirement for, and immediate value offered by, the measurement activities that generate data. In addition to these more concrete changes, follow-up accounts from some individuals who had reduced app use communicated a sense of loss of novelty which may itself be demotivating. These suggest that tailored attention must be paid not only to the context in which apps are introduced, but also aspects of intervention design that include strategies for promoting and sustaining attention and, potentially, creating perceived value in logging tasks, for example, by offering suitable feedback. However, participant experiences emphasise the importance of appropriate content and framing of messages. In addition, there is a role for routine clinical review

that recognize that patients may not act on problems experienced with app use, which may in time erode effective interaction, without external cues and support. One area that deserves further exploration is the feasibility of strategies for promoting habituation, in which logging becomes a largely unthinking activity. The possibility was highlighted by one participant account after an incident in which a measurement-logging-medication administration routine was short-circuited without conscious recognition.

7.6 Chapter summary

Chapter seven used the results of a qualitative interview study to explore factors influencing self-care mobile medical app use by adults with asthma and diabetes. It highlighted the motivating role of both practical and emotional factors, operating at a personal level and centring on perceptions of disease severity and self, as well as the possibilities arising from app-collected data in shaping interactions with healthcare professionals in both primary and secondary care. The data, although limited in scale, suggest that patients can and do use apps with the intention of personal health-related benefit; a possibility that should be qualified, in future work, by incorporating the perspectives of healthcare professionals responsible for supporting their care. The data show that, in addition to the small numbers of individuals to whom apps have been recommended by a professional, patient-initiated app use can and does impact on clinical relationships with individuals. This sets the scene for the discussion in chapter eight, which returns to the question of whether and how professionals should support the use of apps in routine care.

Chapter eight: Synthesis

8.1 Chapter introduction

This penultimate discussion chapter has two purposes. Firstly, it aims to highlight cross-cutting issues for which synthesis of data across studies can provide a more developed account than that offered by each study in isolation. Secondly it aims to return to, and critically examine, the idea that healthcare professionals should offer mobile medical apps on prescription. This was a key motivation for my thesis and remains, in 2015, a feature of NHS policy[5]. Although the included studies have generated findings with potential relevance for a range of stakeholders, including developers, researchers and the public, the focus here will be on the implications for professionals and policy-makers charged with making a vision of routine use of self-care apps work in practice. Through this implementation-focussed lens, the discussion aims to highlight relevance – and potential routes to action – for these actors.

During the work, a number of commentators have examined the possible pragmatic implications of a vision of mobile medical apps on prescription. McCartney[14] highlighted uncertainty about the empirical evidence base supporting apps. Boulous et al.[74] performed an unstructured literature review of app literature and identified content quality, usability, literacy, security and the use of consistent data exchange standards as relevant concerns. Charani et al.[77] focussed on mobile medical apps with a potential role in clinical care and argued that that regulation may be a necessary response to questions of quality, but should be targeted towards apps that actively affect clinical decisions, and designed to avoid stifling technological progress. Yang and Silverman[349] highlighted the potential for liability should safety risks in apps fail to be controlled adequately. However, none have been able to draw on a comprehensive set of data to shape their discussion. The contribution of this thesis is to be able to use data that have been collected across the included studies to provide an empirically grounded commentary about the role of quality and safety in the proposed integration of apps into routine care. The discussion will examine possible implications for healthcare professionals and policy makers in turn. Each section concludes with a set of recommendations for those audiences.

Separately, the discussion will also address implications for researchers, the third stakeholder group influencing the design of the thesis. This discussion will incorporate recommendations for future work arising from the thesis as well as commentary reflecting, specifically, limitations identified during the systematic reviews of app-supported interventions. The discussion will conclude with an examination of the strengths and weakness of the thesis as a whole.

8.2 Summary of results

Stand-alone results arising from the individual studies of this thesis and their relationship to existing literature have already been addressed in the respective discussion sections of chapters five, six and seven. Consequently, these will not be repeated, however, recognising that these are scene-setting for the discussion that follows, Table 8-1 provides an overview of key findings, grouped using the six IoM quality domains.

Table 8-1 **Summary of study findings**

Domain	Findings
Effectiveness	▪ Improved glycaemic control in app-supported patients with diabetes compared to established self-care. Unclear impacts on asthma outcomes, but no evidence that app-supported care is worse than usual care. ▪ Limited compliance of information-containing apps for asthma with evidence-based recommendations for the asthma self-management education content. ▪ Failure of self-care tools, such as action plan apps, to incorporate evidence-based recommendations for design.
Efficiency	▪ A single randomized trial reporting this outcome for asthma concluded that app-supported intervention incorporating nurse-led remote monitoring and support was not cost-effective compared to paper-based self-care. However, costs were similar when excluding the telemedicine component.
Patient-centredness	▪ Positive impacts on self-rated symptom severity, self-efficacy and quality of life for app-supported self-care, but not greater in magnitude than that enabled by paper-based care. ▪ Survey data indicating broadly positive attitudes towards app-supported self-care for diabetes in intervention study participants. ▪ Qualitative study data highlighting the role of app-supported data collection in facilitating insights into disease state, establishing a sense of control over unpredictable illness and facilitating conversations with clinical professionals. Such effects were not uniform, however, and influenced by personal factors such as emotions and contextual 'fit'. ▪ Very limited numbers of apps available through public marketplaces facilitating patient-centred approaches to care, such as communication with health professionals or peers, although remote

Domain	Findings
	support was a common feature in intervention studies.
Equitability	▪ Differential availability of specific apps according to mobile platform, although no clear differences in quality characteristics between platforms. ▪ Readability characteristics of information-containing apps for asthma requiring secondary school education or higher. ▪ High measured functional health literacy observed in all participants in qualitative interview study, despite attempts to recruit a balanced cohort.
Timeliness	▪ Limited survey data from a single pilot randomized trial of diabetes app indicating greater availability of data necessary for clinical decision making in app-users compared to control. ▪ Uncertainty about the extent to which app-supported self-monitoring, specifically, can be sustained over time, given limited duration of intervention studies and evidence of usage attrition in qualitative study participants. ▪ Rapid app turnover and attrition, and the proliferation of low-quality 'junk' self-care apps for asthma posing a potential resource challenge for app selection and quality appraisal. ▪ Very limited number of apps reported in intervention studies available for adoption through public app stores.
Safety	▪ Ubiquitous deficits in the design of insulin dose calculators for diabetes including both inadequate protection against accidental user error and apps yielding clinically inappropriate dose recommendations despite clinically correct inputs. Similar faults in predicted peak flow calculator apps for asthma. ▪ Clinically inappropriate first aid advice in information-containing apps for asthma.

Although the discussion seeks to make a commentary about quality with potential relevance for any mobile medical app intended to support self-care for asthma or diabetes, there is nevertheless a need to ground this in with specific examples that can draw together findings from the different studies that make up the thesis. However, with the exception of the analysis of insulin dose calculators, no study placed detailed constraints on the types of self-care support function that would be eligible for evaluation. As a result, there is heterogeneity within studies which poses a potential challenge to a unifying synthesis.

Across the studies, this approach was justified on the basis of the limited state of the early research literature on mobile medical apps. This made it hard to anticipate, for example, the types of function that intervention studies might be designed around, or which patients might actually use, sufficient to define inclusion and exclusion criteria. Indeed, reflecting this knowledge gap, characterising the range of supported functions was an explicitly defined aim of both the systematic literature review and systematic assessments of asthma apps. A common consequence of this discovery-based approach, however, is that a range of different app functions have been characterised, such as personal trigger alerts, food databases, calculators, etc. and that these app functions are explored to a different extent by each study.

To address this heterogeneity, my approach has been to substantially restrict discussion in this chapter to consider a limited set of app functions: information provision; personal diaries and treatment advice (which incorporates calculator apps). These categories are not universal in the sense that they are represented in every component study of the thesis, but each is represented in more than one and, consequently, permits specific contrasts to be made and each, I consider, exposes salient issues for discussion whether considered separately or together.

Finally, it is worth highlighting that the evaluation of individual findings within their respective literatures, which would typically be a major feature of a thesis discussion, has already been addressed within the study-specific discussions that conclude each results chapter. This was a deliberate choice in order both to manage the number of results arising from the different studies and to enable a focussed commentary here.

8.3 Implications for healthcare professionals and delivery organisations

Within the broader aim of examining the feasibility of health professionals offering mobile medical apps on prescription there are two questions. The first asks what implications study findings have for the recommendation of apps for self-care *in principle*. In other words, it seeks to address the question of whether professionals *should* be thinking about apps to support care. The second, related, question is what the study findings imply for *how* this process of 'prescription' could be approached. The following section examines each in turn.

8.3.1 *Do apps have a place?*

Chapter three laid out an *a priori* case for the consideration of mobile medical apps for self-care. This identified:

- opportunities for timely health support and intervention; arising from the way in which mobile devices are 'always carried' and 'always on',
- the possibility of intervention at scale; reflecting population-level uptake of smartphones,
- unmet health needs; reflected in low observed levels of self-care in long-term conditions including, specifically, asthma and diabetes.

The case anticipated consequential potential health benefits for individuals and populations where rates of effective self-care could be increased, supported by apps, and the possibility that this might be resource-competitive compared to other intervention strategies.

Study findings add a nuanced perspective to this pragmatic case. Mobile medical app-supported self-monitoring, whether backed by remote care or not, appears to support slightly improved glycaemic outcomes for diabetes and, for asthma, is no worse than existing paper-based methods. The impact on other parameters, such as quality of life, is less consistent. At least some patients, however, accessed through the qualitative study in this thesis appear to be able to find value in activities that enable a sense of control over their illness while enabling practical goals, such as negotiating aspects of their care with their healthcare professionals. However, app-use needs to 'fit' within the broader experience of day-to-day life, and individuals differ in the benefit they obtain. In particular, those with less severe condition-related symptoms or side-effects may find it harder to sustain monitoring. While, for asthma, this aligns with the possibility that technology-supported interventions are cost-effective only in more severe illness, the specific case for cost-effectiveness of app-supported interventions for either asthma or diabetes is hampered by the availability of research. There is also a gap in experimental studies examining strategies other than diary-based self-monitoring for either asthma and diabetes, and the possibility of novel interventions highlighted in chapter three, such as peer support networks has not yet been explored. At the same time, guideline-based assessment of apps available through public app stores highlights widespread quality issues including poor adherence to evidence-based recommendations for self-care education. Frank safety issues affect apps supporting higher-risk clinical decision making, such as insulin dose calculators. Within these populations of publicly-available apps, however, there are nevertheless examples of reliable, accurate education, safe insulin dose calculation and apps which take advantage of multimedia and contextual support, such as interactive inhaler technique training. Taken together, the available data (expectedly) suggest potential in apps for self-care but no blanket answer as to whether apps for self-care should or should not be used in routine practice.

8.3.2 *Making mobile medical apps on prescription work*

In translating the findings described above into practice, healthcare practitioners need to recognise the possibility of quality issues in mobile medical apps available through general app stores and take appropriate steps to identify and control the risks that these might pose. A number of general principles emerge from the available data. On both clinical governance and liability grounds [349], healthcare professionals should adopt a cautious stance towards apps for self-care available through public app stores, recognising that few will have undergone clinical research evaluation. All apps should be subject to review prior to use. Patients should be provided with common-sense guidance about selecting apps, such as treating information with the same caution as they would approach information found on the web. It cannot be assumed, however, that patients can proactively identify and manage quality issues in the apps they use.

More importantly, these general observations cannot circumvent the challenge that the patchy and variable evidence base poses to implementation. Proportionality is an established concept in the approach to regulation of medical devices, which has recently been extended to incorporate certain classes of apps that satisfy existing 'medical device' criteria[229, 233, 358, 381]. In a regulatory setting, the principle asserts that the degree of regulatory burden (in the form of testing, compliance certification, etc.) should be scaled according to the scope for benefit or harm arising from a particular medical technology. Under medical device regulation in the UK, Europe and the USA, this is operationalized as a series of classes into which medical technologies are assorted, with higher classes representing greater risk and incurring greater oversight.

In the UK, as for other countries, the scheme also applies to mobile medical apps. However, most apps for self-care fall out of scope of existing medical device guidelines[233]. Of the three types of mobile medical apps for self-care under discussion here, only those providing treatment advice qualify under medical device regulation as class 1 devices. In the UK, information apps and diaries are not subject to any device regulatory requirements. As a result, healthcare professionals cannot (currently) rely on regulators to address quality issues in any other than a few specific classes of self-care app where there are specific therapy-related functions, such as insulin dose calculation. Nor can it be assumed that regulation will address the range of quality issues relevant to implementation, such as feasibility in a given setting or acceptability to a particular patient group. This is because current regulation is concerned only with the veracity of specific therapeutic claims made by a mobile medical app, for example, the capability to correctly calculate an appropriate drug dose.

A number of factors recommend extending the principle of proportionality to guide the approach used by healthcare professionals when addressing questions of quality in the majority[350] of apps for self-care that will fall outside regulation. Here, the implied balance is between the effort expended by clinical staff (and others) in assuring quality versus questions of possible risk and benefit.

Firstly, although regulation operationalizes risk within discrete categories, there is an underlying continuum of potential harm and benefit on which all mobile medical apps lie and which is still relevant in apps falling outside regulation. For example, as the systematic review illustrated, self-care strategies incorporating diary apps may be intended to drive specific clinical outcomes, in contrast to information apps which were unrepresented in intervention studies and where only knowledge-based outcomes are expected. Conversely, poor quality emergency care information, such as that found in apps for asthma, where a patient may act alone without clinical support may pose a higher risk than diary apps whose outputs and implications for management will be regularly reviewed with a health professional. These suggest that risk and benefit need to be assessed on a case-by-case basis.

Secondly, the resources available to healthcare professionals and systems to assess issues of mobile medical app quality are finite. As experience with the systematic assessments demonstrated, evaluation of quality issues is potentially resource intensive. In the review of apps for asthma, a quarter of apps were updated at least once within an eighteen-month window, with consequent requirement for re-evaluation. Stratification of risk permits a rational approach to evaluating issues of quality that targets effort according to expected harm and benefit. Where apps act as a novel delivery mode for an existing intervention, such as diaries, expectations about superiority to existing intervention methods might reasonably be adjusted if, for example, cost savings can be demonstrated compared to alternative delivery modes, such as paper-based self-monitoring which requires physical media.

Thirdly, by adopting a risk-management approach that is consistent with existing regulatory approaches, a proportionate response recognises the variable degree of technical complexity required to evaluate quality issues and, potentially, allows tasks to be allocated appropriately. The review of diabetes apps highlighted the technical complexity of uncovering the breadth of safety issues implicit in those apps, underlining the value of centralised, standards-based controls under medical device regulation. Conversely, quality issues in information apps for asthma were evaluated with reference to standard guidance made available to all clinicians and, consequently, potentially amenable to evaluation by that group.

For information apps, the application of a principle of proportionate review suggests that a requirement for experimental evidence justifying their use might be excessive. Patient leaflets are routinely produced in practice without such evaluation and, as the review of asthma apps suggests, clinical guidelines and existing tools, such as the Health on the Net Principles[330] or NHS Information Standard[382], can provide a normative basis for evaluation that is accessible to professionals and easily justified. Higher-risk information content, such as specific medical procedures or emergency self-care is also unlikely to lie outside the capacity of a competent professional to judge. More relevant dimensions of quality include the ability to update and tailor information easily[383], and accessibility to the target audience For example, an app-based leaflet may be appropriate for teenagers, where mobile device uptake is near-complete, than for elderly patients. Through a lens of proportionate review, developments such as the newly recognised phenomenon of 'junk' mobile medical apps for self-care, are problematic only if they interfere with the ability of professionals to discern apps of suitable quality.

By contrast, for diary apps it would not be unreasonable to wish to solicit (or generate) evaluation evidence that can justify the potential cost and consequences of implementation because of the potential disruptive impact on routine care, in addition to examining questions of acceptability to desired target audiences. As the systematic review showed, the factors influencing successful implementation of apps for self-care require further elucidation, particularly sustained use over time. In addition to the requirement to manage the data that are collected, the interview study highlighted the importance of patient-specific factors, such as contextual fit, perceptions of disease severity, and readiness to initiate app use, with potential impacts for the design of care pathways involving diary apps that may be less relevant for others, including information apps, that may be intended to be used only once.

Systematic studies in this thesis were notable by the absence of identified studies or mobile medical apps offering novel support strategies for either asthma or diabetes, such as artificial pancreas systems for diabetes. For these uses, a proportionate response might nevertheless consider the scope for benefit and harm, the extent to which findings in intervention studies in related technology modes (such as through the web) provide justification sufficient to require or avoid new intervention studies, and the extent to which they are (or will be) captured by medical device regulation.

A proportionate response to judging the clinical suitability of particular mobile medical apps does not remove the need to evaluate patient perspectives or consider technical and information governance issues. Selected apps need to be accessible to, and usable by, target users. The requirement for technical support and training for clinical users expected to support apps needs to

be defined. Rapid turnover and attrition of asthma apps highlights the need for due diligence and possible contractual instruments to ensure that apps remain available for use and are supported by developers. Finally, apps need to adhere to information governance requirements. In addition to other quality domains, recent studies have highlighted poor privacy-related practices in mobile medical apps[384], including those previously approved by the NHS[385]. For example, failures to encrypt personal data being transmitted from mobile devices to online service by mobile medical apps appear to be ubiquitous. The secure exchange of data, in formats that can easily be utilised by existing clinical computer systems[74], will be more relevant for certain types of apps (such as diaries) than others (such as information apps), but must nevertheless be effectively addressed.

These findings introduce an additional dimension of technical compliance to questions of clinical quality already discussed. They suggest that the possibility of local app review is not only subject to questions of clinical capacity, it may demand technical skills and knowledge that many professionals do not possess. The successful application of a proportionate review process demands a systematic understanding of risk and benefit in order to triage apps for review, and clarity about where regulation should provide assurances. As discussed in chapter 5 (section 5.5.2), a number of authors have proposed checklist approaches to enable assessment of questions of usability and content attribution[69, 344, 345], however these have yet to be evaluated in detail and may not address underlying issues concerning the resourcing of evaluation processes. As a result, the feasibility of mobile medical apps on prescription may hinge on the ability of healthcare systems to provide more co-ordinated support to address app quality issues. The next section considers systematic responses, including newly-developed accreditation programs for apps.

8.3.3 *Recommendations*

Healthcare professionals responsible for prescribing mobile medical apps for patient use should:

- Recognise that, currently, many mobile medical apps intended to support self-care for asthma and diabetes have deficits of design and content that may be a source of confusion to patient users, jeopardise clinical benefit or create a risk of clinical harm. Consequently, they should:
- Exercise caution in recommending these apps to patients, or endorsing apps that patients have identified, unless those apps have undergone an appropriate process of clinical and/or information governance review. Methods described in chapters 5 and 6 offer a template for the evaluative strategies that could be incorporated into such a review process.

- In selecting mobile medical apps for use in practice, apply professional judgement to determine what kind of local decision process is necessary and proportionate given the scope for benefit and/or harm arising from the particular intended use, seeking external advice as required.
- In particular, the requirement for evidence for effectiveness should be evaluated on a case-by-case basis, taking into account the availability of existing evidence for benefit of intervention strategies using other delivery modes to consider whether a pragmatic case for translation to an app-based format can be developed. This need not preclude suitable implementation and process evaluation. Normative considerations of effectiveness should not displace other relevant considerations of quality, such as acceptability to local patients whose engagement, as users, is necessary if any clinical benefits are to be realised.
- Exercise judgement to delegate mobile medical app review activity, for example by drawing on external accreditation, given local competency to assess:
    - Clinical suitability to support desired aspects of self-care that conforms to normative standards, such as those established in clinical guidelines, but is also compatible with local medical practices and care pathways.
    - Accessibility to intended patient group, reflecting technical and health literacy and types of devices in use and willingness to engage in technology-supported care. Because research data are currently limited, pro-active engagement with target groups will be necessary.
    - Technical compliance with regulatory requirements including medical device regulation and data protection law.
    - Due diligence concerns sufficient to provide assurances about the likely longevity and support available for a given app, recognising phenomena such as ‘zombie apps’, where products no longer undergo updates, and unexpected withdrawal of apps may jeopardise clinical pathways that are built around the availability of particular products.
- Maintain awareness of – or know where to seek advice about – regulatory requirements governing classes of mobile medical apps for self-care, including uses for which only CE-marked apps should be prescribed, such as personal drug dose calculators.

- Anticipate impacts arising from self-care app use on existing clinical pathways and consultation models, such as diary data collected by patients that may need to be verified, and captured into clinical records if they are to be used for clinical decision-making. Consider how such processes can be efficiently integrated into consultations, for example, through review on patients own devices, with permission, with key values annotated into clinical notes, rather than necessitating complex processes for data transfer.
- Recognise that frequent app updates observed in self-care apps will necessitated repeated cycles of review, and consequently ensure that any local review process is adequately resourced.
- When first prescribing mobile medical apps for self-care to patients:
    - Tailor the timing of any prescription by considering the readiness of a patient to initiate app use. Heightened perceptions of condition severity and recent changes in health status may increase the likelihood that an individual is willing to attempt app use. Alternatively, app use may be used to extend specific interactions with individuals. For example, teaching points arising from face-to-face inhaler or insulin injection technique review may be reinforced by providing an individual with an interactive training app, such as the video training seen in apps for asthma.
    - Maximise initial engagement by supporting app installation in clinic and ensuring individuals are able to use the main intended feature(s) of the app correctly.
    - Set reasonable expectations about app use frequency and duration. Given current uncertainty about the sustainability of app-supported intervention engagement over time, consider managing this risk through explicitly time-limited 'prescriptions', where app use is intended to support a specific outcome, such as calorie counting, or to collect data sufficient to make a particular decision about treatment, rather than with the expectation that apps be used indefinitely.
    - Consider 'fit' for an individual: aspects of patient disposition and emotional factors, such as fear, which may influence motivation to engage with an app when selecting and configuring app features, such as reminders, which may be seen as an unwelcome reminder of an incurable long-term condition by some individuals. Consider selecting apps where such features can be customized, or incrementally activated.

- For self-monitoring apps involving data collection tasks, clarify data-driven decisions that may be made safely without clinical guidance and those for which professional support should be sought. Ensure monitoring activities are compatible with existing strategies for self-regulation, such as asthma action plans, for example by selecting apps where decision criteria can be stored alongside patient-supplied data.
- Recognise that patients may not sustain data collection tasks that act solely to furnish clinicians with data, rather than providing some capacity for autonomous action or reflection. Provide teaching/coaching as required to develop this capacity.
- Provide a route to technical support, setting reasonable expectations of local assistance (versus that available from the app developer).

▪ When following-up with patients to whom apps have been prescribed:

- Check that app use has been sustained according to agreed expectations. Anticipate that some individuals will have changed smartphone platform or app without notice.
- Encourage patients to participate in interpretation of self-collected data to facilitate joint decision-making. Provide support to help individuals differentiate reliable from unreliable data inferences, recognizing that individuals may have varying capacity to interpret data.
- Solicit information about unexpected app behaviour and, for patients whose self-management is suboptimal, actively investigate possible causes.

8.4 Implications for NHS systems and policy-makers

The previous section argued that systems-level responses to findings of variable quality in mobile medical apps for self-care may be both desirable and necessary on resource and capacity grounds. As discussed previously, certain responsibilities concerning the control of quality of apps are codified under medical device and data protection regulation. However, most apps fall out of scope and, consequently, many dimensions of clinical quality and safety will not be routinely addressed by existing mechanisms. Recently, however, a number of initiatives have emerged that aim to provide a process of central, co-ordinated review for mobile medical apps[5, 23, 386-388]. App accreditation programs have been introduced in the US, in Spain and in the UK. In 2013, the NHS introduced the Health Apps Library, a dedicated marketplace of self-care apps accessible to both patient and

professionals with its own process of clinical and information governance review. However, the programme was suspended in October 2015 after it was found to have failed to identify clinical and privacy-related risks in apps which were recommending ineffective procedures for certain conditions and transmitting personal data to online services without encryption. A US-based program was halted after similar failures were identified[389]. In the UK, the National Information Board, which holds responsibility for any future app review program, has commenced a process of review to consider how future app accreditation process should be designed[390]. Proposals under current consideration include peer-review to assess clinical quality. As a result, there is an opportunity to consider how findings from the thesis might influence future program design.

Several factors, beyond those already discussed, recommend that principles of proportional review be extended to the design of accreditation programs:

- Firstly, the pool of available mobile medical apps eligible for quality evaluation continues to grow rapidly (see e.g. Figure 5.2). This implies that a proportional response is relevant not only when considering individual apps but when managing risk in aggregate. Although there may be efficiencies in evaluating apps within co-ordinated programs, there are resource constraints operate at a health systems level that mirror those which affect healthcare delivery organisations. Others have highlighted concerns of scale that accreditation programs must address[74].
- Secondly, given a strategic desire to promote innovation in mHealth (discussed in section 2.2.2), systemic responses should take account of the possible cost barriers that appraisals processes may on new entrants. Single or small developer organisations, which appear to be characteristics of app development, may be less well-resourced than traditional technology providers. A proportionate response would scale costs according to the effort required to demonstrate compliance with expected quality standards.
- Finally, uncertainty about the optimal approach for assuring app quality and safety that motivates this discussion should itself act to caution against arbitrary commitments to uniform requirements for quality assurance. This is most relevant when considering what, if any responses, may be required to address apps that fall between the capabilities of local clinical review and those governed by existing structures for medical device regulation.

There are a number of consequences for accreditation programme design. Firstly, peer review may be an appropriate response if it allows review to take place at scale while also ensuring rigorous review. It is unclear, however, if a review process that relies on unstructured assessment and the

tacit knowledge held by experts will be effective in identifying all quality and safety issues and applying standards consistently. The capacity to identify issues will inevitably vary between professionals, and as this thesis has shown, quality issues span a range of domains and vary according to app function. A failure to consistently enforce information governance principle was a factor leading to the suspension of the previous NHS accreditation program. Experience from the systematic assessments included in this thesis suggests that it is possible to generate assessment criteria from existing evidence-based resources, such as clinical guidelines, that are simple to apply, but that the process of criteria development itself requires effort and thought. This suggests that, even if peer review is adopted as a model, it should be within certain structuring principles that guide assessment. A proportionate approach might also include divesting responsibility for the review of specific app components or functions according to technical expertise.

Secondly, programs should be mindful of variable clinical benefit and patient need, and consider prioritising apps for review. There is a risk that effort is disproportionately expended on mobile medical apps with low expected clinical benefit (or risk). Precedent for this lies in efforts to establish regulation programs for health information on the internet[391], for which there is little convincing evidence of harm[392]. As suggested above, the risks and benefits of these types of apps may reasonably be delegated to review in local settings.

Thirdly, accreditation programs should not cannibalise or short-circuit established mechanisms for assurance, such as medical device regulation. To avoid confusion, effort-duplication or accidental omission of high-risk apps, stakeholders including developers and healthcare professionals, need to be clear about who takes responsibility for what, what falls in and out of scope for review and the nature of guarantees offered by different review bodies. As noted above, if proportionate review is accepted as a principle, this should include guidance about how to assess the scope for benefit and harm, since this must be established before decisions can be taken about what elements should constitute review.

A broader question is the extent to which relevant dimensions of quality can always be operationalized for assessment by such programs. A freedom of information request to the NHS Health Apps library and published data relating to other programs[386]suggests that criterion-based methods are typical in app accreditation programs. For example, the NHS approach (prior to its suspension) incorporated a three-stage, 15-item, closed-question checklist[393] which aimed to triage apps into risk categories, but without defining detailed assessment criteria for specific use cases. While this creates an opportunity for criteria of the kind devised to assess insulin calculators to be applied, there remain questions about coverage. Certain properties, such as data validation in

calculator apps, are suitable for discretised judgement and their inclusion likely to achieve broad consensus across professionals. However, questions of expected clinical benefit and cost may be interpreted differently in different contexts and consequently require greater detail than discreet judgements, or fixed quality scores. As a result, there may be a place for accreditation programs to aggregate supporting evidence in addition to making categorical judgements about specific aspects of quality. Any programs with supra-national scope will also need to account for localization issues, such as the differing terminology and calculation conventions for insulin dose calculation adopted in different countries (see chapter six). Nevertheless, coordinated app review programmes will generate expertise and knowledge about what constitutes effective, safe app design. If the focus is on benefit maximisation, then the role of developer community capacity building that leverages this knowledge could be considered. Upskilled developers would mitigate risks before they ever reach accreditation, reducing the burden of review. This will require vision and investment.

Beyond health-specific accreditation programs, policy-makers should also consider the role of existing app marketplaces. Since these act as gateways for the majority of apps accessible to the public, they are potentially well placed to address quality issues. At the very least, commercial marketplaces should meet existing obligations to ensure apps satisfy regulatory requirements. A more proactive approach, that is also compatible with the commercial nature of these stores, might require that mobile medical apps have undergone review by at least one recognised accreditation program or simply to display prominently those apps that have. A recent suggestion is the incorporation of 'white boxes' which detail various common properties of mobile medical apps, such as authorship, underlying algorithms, testing procedures and intended uses[394]. While these properties will likely assist clinical review, the intended impact on developers in anticipating and remedying quality issues is currently unknown. Finally, app stores have access to uptake data that would be invaluable for future prioritisation and risk assessment efforts if made accessible to policy-makers and researchers.

The boundaries drawn between accreditation and regulation make sense only if regulation is being enforced. In the UK it is not currently clear if this is the case. None of the insulin dose calculator apps reviewed had undergone CE marking or registration with the MHRA, the UK medical device regulator. The MHRA took action to remove the apps that were identified, but this was only after publication of the results reported in chapter six and relied on research data provided to the MHRA in response to a request from them[395]. Others have highlighted the slow pace at which regulation is being enforced in other jurisdictions, such as the USA[348]. A failure to provide effective oversight

of high risk mobile medical apps will increase the burden of assessment that falls on other actors in health systems and, potentially, places patients at avoidable risk.

In respect of safety risks, which expectedly occur with low frequency and can be hard to predict, it may not be enough to run apps through a discrete checking process or rely on regulator intervention. Some kind of ongoing surveillance – similar to the yellow carding process used to track medication-related harms – may be necessary. Accreditation programs and health systems could, for example, require app developers to include a common mechanism for user feedback.

8.4.1 *Recommendations*

At a systems-level, the NHS should:

- Work to ensure that existing medical device regulatory requirements applicable to mobile medical apps, such as insulin dose calculators, are enforced.
- Work with app stores to ensure that the distribution of mobile medical apps that fall within existing regulation is controlled (i.e. to satisfy requirements under law). This could include exploring the feasibility of voluntary actions to promote self-care app quality, for example consensus agreement for rapid removal of apps with identified clinical safety risks.
- Adopt a co-ordinated stance for managing the risk/benefit of different classes of mobile medical apps for self-care, engaging clinical, commissioning and regulatory stakeholders to ensure clarity about where responsibility is expected to lie for ensuring that different app types and functions are effective and safe.
- Ensure that activities intended to assure mobile medical app quality, such as accreditation programs are robust, but also proportionate in their activity so that resource is expended on apps where either the scope for benefit/harm is substantial or where co-ordinated action is preferable to local review.
- Establish co-ordinated programs for collecting adverse events relating to mobile medical app use for self-care (and other domains), or ensure that data from existing programs can be disaggregated for analysis. Consider strategies to promote the collection of this information. Possible strategies could include communication to healthcare professionals, voluntary reporting by developers or yellow-card functionality included in self-care apps as a requirement for certification.
- Build on existing efforts, such as hackathons, to engage with developers to share expectations about clinical safety and quality, promote best practice around practical

strategies to satisfy these requirements and help foster a development culture where quality and safety are seen as part of a value chain.

In addition, clinical guideline developers should support a vision of mobile medical app-supported self-care by:

- Proactively collating evidence about apps, adopting a pragmatic stance that makes use of existing intervention-design evidence, acknowledges the different risk-benefit profiles of different activities and, where evidence is lacking, drives expert consensus to facilitate timely app adoption.
- Promptly address implementation-relevant factors, such as cost-effectiveness, as these data become available.
- Highlight technical concerns relevant to apps, such as regulatory requirements, which may not otherwise be apparent to healthcare professionals.

8.5 Implications for research

The implications for research can be divided into those affecting the design of future self-care app-supported interventions and further work exploring the meta-issue of app quality and safety.

8.5.1 *App-supported intervention research*

Recent systematic reviews of technology interventions have highlighted the importance of intervention design (and description) that facilitates evaluation of determinants of success and comparison between studies (e.g. [6]). In the systematic review of app-supported interventions for asthma and diabetes, estimates of effect attributable to apps could not be disaggregated because additional intervention components, such as professional support, were not replicated between intervention and control groups. There was a lack of detailed information about app design and secondary intervention components. Factors influencing the success of implementation-in-context, such as patient and clinician perspectives, were not explored in depth, making it hard to discern what factors should be considered when attempting to replicate studies in new settings. Nor was it possible to recommend rational targeting of app-supported interventions according to patient characteristics, such as disease severity, which has consequences for both clinical benefit and cost, has a place in the application of app-supported interventions for either asthma or diabetes. Together, these findings highlight gaps that should be remedied in future evaluations of app-supported interventions.

As the discussion above has argued, however, effort should be focussed on knowledge gaps which act as a barrier to translation, rather than blanket assumptions about the requirement for definitive trials of all mobile medical apps. For example, it is hard to argue a case for further randomized controlled trials of diary apps to support self-care for either diabetes or asthma unless they incorporate robust cost-effectiveness analysis. The identified need to better explore issues of sustainability of app use may, in the first instance, be better elucidated through observational data gathered in a pragmatic context before countenancing any further large-scale experimental evaluations. Above all, researchers need to engage with healthcare professionals to address the issue of whether superiority – rather than equivalence – in clinical outcomes should be the deciding factor for app-supported interventions when other factors such as cost and scale of deployment are concomitant potential benefits[396]. Lacking this discussion, intervention studies risk continuing to fail to incorporate balancing factors which represent potential distinctive concrete benefits of using apps to support clinical practice, such as the potential for cost savings. This thesis did not incorporate a study of clinical perspectives on app use, considering it premature given the state of app adoption in the NHS, however these findings suggest that such a study would be timely if it could help inform research priorities.

There is growing recognition of the potential value of theory in shaping the design and evaluation of interventions[48], including mobile medical apps[3, 397]. This originated in work on psychological interventions for behaviour change, but has been translated into methods applicable to other intervention types[48]. The value of a theory-based approach has been bolstered by systematic review evidence suggesting that theory-based internet interventions may be more effective than those without[123], although the determinants are probably complex. For example, the use of theory might simply be a predictor of the broader capabilities of the research team to execute well-planned research. Nevertheless, there is a parallel between a theory driven approach and the requirement for well-characterised interventions, particularly when generating explanatory accounts that attempt to link observed outcomes to aspects of intervention design. However, researchers working outside the social sciences, where theory based interventions have not been the norm, are likely to have a variable degree of comfort and experience with such approaches.

Aspects of quality characterised by the systematic app assessments and qualitative interview studies are a potential source of elements to structure intervention theory for self-care apps. For example, the requirement that an information-containing app for asthma satisfies a set of information domains represents an implicit theory about the role of that information in structuring successful self-management. Operationalized as criteria, these can be used, as in the studies in chapters five

and six, to evaluate the quality of existing mobile medical apps. There appears to be little reason why such criteria could not also be used to structure the design of new apps. Observations relating to the acceptability to patients of apps for self-care, such as the role of a recent change in health status or the nature of emotions in shaping positive and negative app use, suggest that these are also relevant concerns for the design of new app-supported interventions.

Consequently, future work could explore the possibility that quality-domain based criteria be used to address the requirement for principled app design while offering a route to theory-informed intervention design that is accessible to clinical researchers. Apps developed by researchers are not immune to quality and safety issues. An increased risk of clinically-relevant hypoglycaemia associated with automated insulin dose recommendation was seen in the systematic review of diabetes, mirroring concerns identified in dose calculator apps available through public app stores. Pragmatic factors, such as technical issues affecting app performance – which were a recurring issue in apps evaluated by the systematic assessments – are also readily captured by a criterion-based approach. Should app accreditation programs become established, there are potential benefits in an approach to theory that implicitly incorporates those criteria that will also be used to control access to app marketplaces.

8.5.2 *Mobile medical app quality research*

In addition to opportunities for intervention design, there are a number of opportunities for future work that develops the findings of the studies presented in the thesis.

Evidence examining three quality domains requires further work. The requirement for additional evidence that mobile medical apps can enable efficient care has already been discussed. The parallel concern of timeliness, which incorporates professional attitudes and experiences of app-supported care, was explicitly not addressed by the work because of the lack of implementation experience. Pragmatic studies and process evaluations embedded in real-world settings offer a route to develop the evidence base for both domains. Thirdly, issues of equitability require further elucidation. This should explore the experiences and needs of users with levels of functional health literacy lower than those seen in the current qualitative study, as extend explorations of contextual 'fit' to particular patient subgroups, such as adolescents where self-care for asthma and type 1 diabetes is often initiated, adults receiving new type 2 diabetes diagnoses, and those with comorbidity and those from groups who have historically been at risk of health inequality. The possibility that some groups are choosing *not* to use apps should also be considered in order to provide a more developed understanding of issues of equity.

As regulation and accreditation programs continue to develop, there is an ongoing requirement for scrutiny. This should assess whether review mechanisms are proving effective in controlling quality and whether proposed approaches, such as peer review are effective. The broader principle of proportionate review proposed in this discussion should also be revisited once the implementation evidence base is more developed.

There are a number of specific opportunities that could be pursued by future work:

- Should user uptake data become available, it will be possible to re-evaluate findings of the systematic assessments to allow issues to be reprioritised according to the scope for benefit/harm in terms of proportions and numbers of affected users.
- Similarly, there is an opportunity to balance interpretation of findings of safety-risks in self-care apps, such as dose calculators with data indicating the relative frequency with which harms do occur and the nature of those harms. Given the expectedly low frequency with which events will occur, this will require sustained longitudinal data collection.
- The predictive potential of proxy-markers for quality that can be easily determined, such as attribution of authorship as an indicator of information quality in patient education apps, should be explored further, since these offer a potential route to app screening instruments that are accessible to non-technical users. No significant predictive relationship was seen between authorship and content quality in the analysis of asthma apps, however this was a *post hoc* analysis which did not examine the range of possible predictive factors in detail nor control for covariates through, for example, a formal regression.
- Novel streams that can access user perceptions about apps, such as feedback and rating data submitted to app marketplaces, should also be explored. Online patient ratings have been successfully used to mortality measures in UK hospitals[398].
- The current qualitative exploration of factors influencing the use by patients with asthma and diabetes sets the scene for further work that could:
    - Explore issues of equity, as discussed above.
    - Triangulate phenomena, such as data-driven discussion with clinicians, against the experiences of other populations of app users. Survey-based methods could be used to identify issues that operate at population-scale.
    - Consider the experience of app-supported management from the perspectives of both patients and clinicians, since professional perceptions of successful

management may differ from those of patients. The current study highlighted the possibility discussions arising from patient-collected data that are challenging to clinical narratives or professional power, but relied on patient accounts. Future work should triangulate between commentary of patients and their responsible carers when using, for example, apps that support data-driven decision making.

- A small number of factors influencing developer attitudes towards clinical quality and safety, such as personal motivation, were uncovered during an informal process of engagement that was part of the assessment of diabetes apps. Further qualitative insight may be helpful if developer engagement is to play a role in future strategies for controlling app quality and safety. This should seek to understand both facilitators and barriers, such as commercial constraints, towards the development of self-care apps that satisfy clinical expectations of quality.
- Both the inconclusive findings of the systematic reviews and the observational datasets underpinning the app assessments provide a contemporary view on app quality for which future updates will be beneficial. Such updates will be necessary if unexpected developments, such as 'junk' asthma apps, are to be identified.

8.6 Strengths and limitations of work

Previous chapters have offered justification for the methodological approach underpinning the thesis as a whole (chapter three) as well as well as each component study (chapters four-seven). The strengths and weaknesses inherent in these strategies have also been discussed in relation to each. In addition, specific limitations in research topic coverage that offer opportunities for further study have been described in the previous section. Here, I offer my reflections on the strengths and limitations of the approach in contributing to the thesis as a co-ordinated whole.

It was anticipated that the use of a multiple methods approach (chapter three) could offer a richer perspective than that possible from a single methodological design and, potentially, respond to gaps identified in a research literature that, reflecting the emerging nature of the field, was expected to be incomplete. I would argue that findings support this perspective. Observational data offered by three systematic assessments not only permitted app categories not identified by the systematic reviews of intervention studies to be characterised, but also highlighted potential quality and safety implications of specific aspects of app design that, either through poor reporting or a lack of theoretical orientation, were not previously described in research literature. Having identified the value of patient perspectives in understanding acceptability as a distinct quality domain that had not

been addressed in intervention studies included in the systematic review, methods flexibility made it possible to plan and execute a distinct qualitative study component to explore this. This sequencing of studies allowed specific facets of quality, such as safety, to be probed in greater depth in response to deficits identified in earlier work.

The use of the IoM quality domains as a structuring taxonomy was justified on grounds of its widespread acceptance by healthcare professionals and policy-makers. The possibility that technology-specific concerns would a poor fit into the taxonomy was not anticipated at the start of the work. However, as recent findings of privacy risks from mobile medical apps suggest[385], there may be specific novel quality issues, such as information governance, that are a poor fit within existing taxonomy categories. Given the understandable sensitivities associated with the confidentiality of personal medical data, future examinations of quality and safety should incorporate information governance as a top-level concern.

Observational data are inherently limited in terms of generalisability and risk-of-bias compared to those generated by experimental studies. However, their use provides a rational basis for action that would not otherwise be available given the limitations of the available experimental evidence base. Observational data may even be preferable where the cost and latency of an experimental approach outweigh anticipated benefits or are incompatible with the breadth and pace of change in the field of study. In the context of this thesis, the use of a systematic assessment approach permitted a breadth of study – not least the ability to perform exhaustive census of available apps – that would have not been possible on resource or time grounds had the work instead been based on an intervention design. Although the data inevitably reflect the status of apps available at a particular point in time, it was possible to repeat assessment in the case of asthma apps to demonstrate that findings were persistent across app generations. The use of explicitly defined method using guideline-derived criteria provides a template for replication and a basis for future comparison.

The major limitation of this systematic method is that the demonstration of risks in principle does not imply that such risks are realised in practice. In the case of safety-related impacts, such as those relating to self-medication, exhaustive risk identification may be justified on a precautionary basis reflecting the scope for clinical harm from self-medication error demonstrated through surveillance data. The same may not be true for all types of mobile medical app function; for example, harms arising from inadequate information may be considerably lower and effectively attenuated by both patient capabilities to negotiate variable quality information and the redundancy offered by multiple avenues where patient education occurs, such as face-to-face clinical interactions. The qualitative study results highlight the risk, however, of assuming that patients alone can always effectively

mitigate against risks. For example, when errors were identified in app behaviour, such as incorrect data representation, participants would, almost without exception, ignore them rather than either explicitly consider their impact on clinical management, seek advice from a clinician, or notify a developer.

In addition to uncertainty about real-world impact, there is also the potential for availability bias when judgements are based on guideline-derived criteria. Such criteria have a rational justification, but as the assessments of mobile medical apps demonstrated, coverage of different types of app function may be variable or incomplete. For example, for asthma, it was not possible to define detailed criteria for self-monitoring apps in contrast to the multi-domain assessment of information apps. The lack of guideline coverage does not mean that particular issues will not be experienced in practice. As highlighted in the recommendations for policy-makers (section 8.4.1 above), there is an opportunity for guideline development groups to ensure that they factor technology-supported care into the design of future documents.

Together, these uncertainties about real-world consequences require new data, gathered either through pragmatic intervention studies or surveillance. The results of the systematic reviews and the limited implementation of apps in clinical practice suggest that such data do not yet exist in a meaningful volume. Nevertheless, the future availability and analysis of such data will be an important qualifier of the results described here.

Finally, the focus on the UK NHS justified the selection of English-language apps available through localised app stores across studies and a focus on UK-based mobile medical app users. For research users outside this context, this may be a limitation should the characteristics of apps and users vary substantially by geography. It is known, for example, that adoption of mobile technology varies according to demographic characteristics.

Chapter nine: Conclusions

Despite modest evidence for clinical benefit, the characteristics of successful app-supported self-management interventions for asthma and diabetes are not well defined or addressed by existing studies. At a functional level, mobile medical apps should incorporate features that are compatible with established evidence-based practices for self-care. In addition to mobile medical app design, patient-specific factors such as perceived need and emotional readiness to introduce app-supported self-care, and the match between features and personal dispositions are relevant concerns for intervention design.

The assumption that self-management apps available through public app stores will satisfy expectations of clinical quality and safety grounded in existing evidence-based norms are not necessarily well founded. Few mobile medical apps for self-care available through public app stores adhere to guideline-derived recommendations and some, such as insulin dose calculators, may pose an active risk of clinical harm to users. As a result, healthcare professionals should exercise caution before recommending apps to patient without review that considers both clinical norms and local standards of care.

Together, these highlight that a vision of mobile medical apps 'on prescription' as a 'fire and forget' activity that can take place in clinical settings without co-ordinated support and resource may be infeasible. Relevant challenges include the need to assure mobile medical app quality and safety, tailor the selection of apps to patient characteristics, address questions of technical support and training and ensure that app use can be appropriately integrated into clinical pathways. Questions of accessibility for audiences with different levels of health literacy, rational targeting of apps towards particular patient groups, and maintenance of self-monitoring over time remain unresolved. This creates a requirement for action by clinicians, commissioners, policy-makers, regulators and researchers.

Technology-related factors that influence quality and safety including rapid app turnover, globalised distribution, platform fragmentation and information-governance must also be considered. These will create an additional ongoing burden for clinical staff and health services and pose a challenge of scale for co-ordinated regulatory and accreditation programs.

A combination of factors, including the volume and variety of medical apps available, capacity of medical professionals to perform technology appraisals, impact on innovation, likelihood of

sustained app use, the unclear impact of certification schemes applied to certain type of consumer health product such as health information, burden of risk carried and expectations of clinical benefit recommend a proportionate response to identified gaps in quality and safety. App categories where existing operational guidance – or consensus clinical expertise – can be applied or where the expectation of clinical benefit and risk is attenuated, such as for apps that provide information only, should be amenable to local review. In contrast, those app uses with direct expectations of clinical benefit such as self-management, which may substitute for other strategies, should be subject to more stringent requirements both in terms of their safety profile and requirement to demonstrate efficacy. Self-care apps which are intended to replace established therapeutic interventions, such as those offering breathing training for asthma, should be subject to the greatest scrutiny and, where appropriate, de novo effectiveness evaluations. Responsibility for functions that are explicitly recognised as high risk by existing governance frameworks, such as medical device classification, should be retained by those bodies given the potential complexity and resource requirements associated with controlling safety-relevant issues. Regulators should take steps to ensure that mobile medical apps which fall within existing regulatory categories, such as dose calculators, do not escape oversight.

This proportionate demarcation of activity, which need not be static, would help to prioritise research activity and clarify communication to clinicians and developers about where responsibility should lie. Regardless of the accreditation/regulation models that are ultimately adopted, coordinated surveillance will be necessary to detect low-frequency harms arising from app use that would otherwise go undetected and to qualify the risks and benefits identified in this work.

Appendices

Appendix 1 Bibliometric analysis methods

A simple bibliometric analysis was performed of studies incorporating terms relevant to apps, smartphones or mobile health (mHealth) by searching the titles and abstracts of studies included in three medical citation databases (MEDLINE, EMBASE and PsycINFO), pooling and de-duplicating the results and then partitioning by year of publication to cover the period 2000-2014 inclusive.

The following Boolean sentences were used to conduct the search. Searches were performed on March 07 2015.

Apps

- (((mobile OR medical OR health OR tablet OR wellness OR software OR fitness OR apple OR android OR iOS OR phone OR portable) ADJ app?) OR (there's ADJ an ADJ app)).ab,ti.

Smartphones

- smartphone?.ab,ti.

mHealth

- ((mobile ADJ health$) OR m-health$ OR mhealth$).ab,ti.

Appendix 2 Systematic review search strategy

Boolean Search Components

Field

F1	m health OR mhealth	*Terms that stand alone for smartphone-related concepts relevant in all domains*
F2	care$ OR disease$ OR health$ OR medicine? OR well adj2 being	*Terms identifying medical topics to be used for filtering articles in generic databases*

Hardware

H1	smartphone$ OR smart phone$ OR (window? adj3 phone) OR (window? adj3 mobile) OR nokia OR palm OS OR palm pre classic OR INQ OR sidekick OR symbian OR iphone? OR ipad? OR iPod touch$	*Device terms that are sufficiently specific that they are likely to return relevant articles in medical databases when used alone.*
H2	PDA OR personal digital assistant? OR android OR blackberr$	*Device/technology terms that have historical use that complicates their interpretation (e.g. PDA) or may be confused with other domains (e.g. Blackberry and the fruit)*
H3	cellular phone [MeSH] OR phone$ OR telephone$	*Generic telephony terms that must be combined with software or use-case specific terms*

Software

S1	app OR apps	*Terms identifying the specific concept of a smartphone 'app'*
S2	applet? OR application? OR software OR twitter OR facebook	*Terms identifying the concept of software more generally*
S3	diar$ OR reminder$ OR telemedicine OR tele medicine OR telehealth OR tele health OR ehealth OR Clinical decision support OR Electronic outpatient booking? OR Electronic refer$ OR electronic hospital refer$ OR Electronic discharg$ OR electronic patient discharg$ OR electronic health record$ OR computerized patient record$ OR computerised patient record$ OR personal health record$ OR computerised intervention$ OR computerized intervention$ OR IHCA OR decision support technique$ OR interactive health communications application$ OR CDSS OR computer aid$ OR computer assisted OR computer$ reminder$ OR computer$ physician order entr$ OR CPOE OR data mining OR data repositor$ OR data warehous$ OR e health OR eprescri$ OR e prescri$ OR Electronic patient record$ OR electronic prescri$ OR e mail$ OR email$ OR Electronic mail OR health informat$ OR health technolog$ OR intranet? OR information system$ OR	*e-Health domain terms taken from* (Majeed et al. 2009)*; some UK-specific application terms have been removed.*

Computerized laboratory result? OR Computerised laboratory result? OR Electronic laboratory result? OR clinical laboratory information system? OR LIS OR Laboratory Information Management System? OR Medical information system? OR web based refer$ OR internet based refer$ OR e booking OR ebooking OR Electronic prescri$ OR Electronic Transmission of Prescription? OR bar cod$ OR barcod$ OR RFID OR radio frequency identif$ OR (CAD and (computer-assisted OR computer-aid$))

Sources with Boolean search strategies

Medical citation databases

Source(s)

The Cochrane Library	*http://www.thecochranelibrary.com*
MEDLINE 1988-Present	*http://gateway.ovid.com*
EMBASE 1988-Present	*http://gateway.ovid.com*
PsychInfo 1987-Present	*http://gateway.ovid.com*
CINAHL 1981-Present	*http://www.library.nhs.uk/booksandjournals*
CAB Direct Global Health 1973-Present	*http://www.cabdirect.org*

Boolean search strategy

F1 OR H1 OR ((H2 OR H3) AND (S1 OR S2 OR S3))

Limits

Search will be restricted to the abstract and title, where relevant (.ab,ti.)

Articles dated between January 01 1992 and January 31 2011 inclusive will be included.

No restriction by article type or language.

Medical general sources

Source(s)

Global Health Library	*http://www.globalhealthlibrary.net*
Controlled trials register	*http://controlled-trials.com/*

Boolean search strategy

(F1 OR H1 OR H2 OR S1)

Limits

Search will be restricted to the abstract and title, where relevant (.ab,ti.)

Articles dated between January 01 1992 and January 31 2011 inclusive will be included.

No restriction by article type or language.

Information technology citation databases

Source(s)

Compendex/Inspec/Referex	*http://www.engineeringvillage2.org*
IEEE Xplore	*http://www.ieee.org/ieeexplore*
ACM Digital Library	*http://portal.acm.org/dl.cfm*

Boolean search strategy

F1 OR ((H1 OR H2 OR S1) AND F2)

Limits

Search will be restricted to the abstract and title, where relevant (.ab,ti.)

Articles dated between January 01 1992 and January 31 2011 inclusive will be included.

No restriction by article type or language.

Information technology general sources

Source(s)

Mobile Active	*http://www.mobileactive.org/directory*

Boolean search strategy

F1 OR ((H1 OR H2 OR S1) AND [Health Category])

OR ((H1 OR H2 OR S1) AND F2 AND [All Categories])

Limits

Articles dated between January 01 1992 and January 31 2011 inclusive will be included.

No restriction by article type or language.

General-purpose databases

Source(s)

CiteSeer^{X}	*http://citeseer.ist.psu.edu*

Boolean search strategy

F1 OR ((H1 OR H2 OR S1) AND F2)

Limits

Search will be restricted to the abstract and title, where relevant (.ab,ti.)

Because date of article is not reliably recorded in CiteSeerX, any date will be allowed.

No restriction by article type or language.

Grey literature

Source(s)

Google	*http://www.google.com*
Google Scholar	*http://www.google.com/scholar*
ProQuest Dissertations	*http://proquest.umi.com/login*
ERIC	*http://www.eric.ed.gov*

Boolean search strategy

F1 OR ((H1 OR H2 OR S1) AND F2)

Limits

Articles dated between January 01 1992 and January 31 2011 inclusive will be included.

No restriction by content type or language however articles behind pay-per-view walls will not be accessed.

Grey literature 2

Source(s)

Kings Fund Library	*http://kingsfund.koha-ptfs.eu/*

Boolean search strategy

telehealth OR telecare OR smartphone OR mHealth

Limits

Articles dated between January 01 1992 and January 31 2011 inclusive will be included.

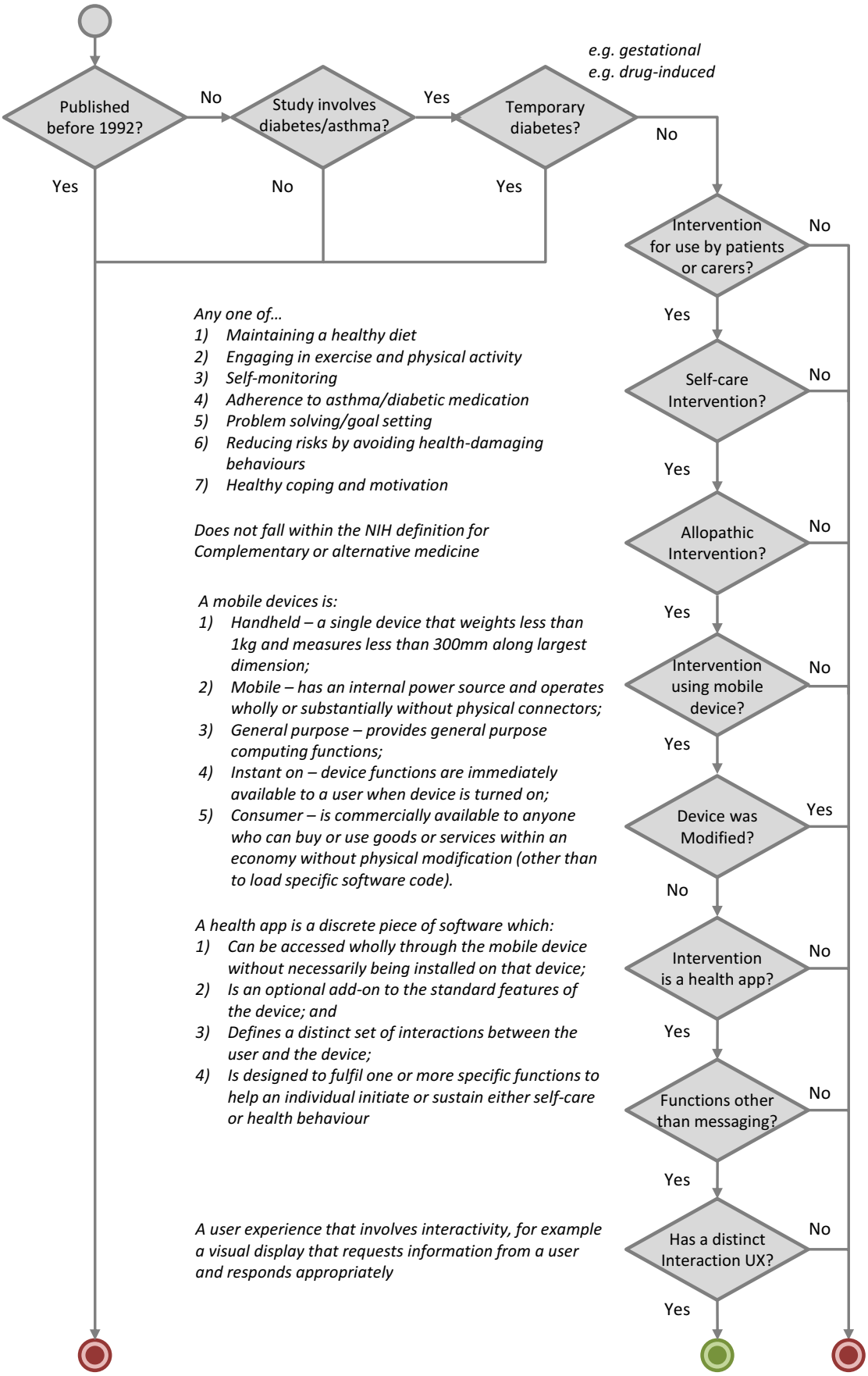
No restriction by content type or language however articles behind pay-per-view walls will not be accessed.

Changelog

Version	Date	Change	Reason
0.1	30/11/2010	Document created	
0.3	30/11/2010	Split 'Nokia Symbian' to 'Nokia OR Symbian' in Hardware	Typo
		Moved 'INQ handset' to specific hardware and dropped 'handset'	Specific hardware devices, handset term not required
		Moved Palm OS, Palm Pre Classic, Sidekick and iPod touch$ to specific hardware	Specific hardware devices
		Expanded S2 to include full list of e-Health terms	Authoritative search from Majeed et al., 2009
		Moved Mobile Active to generic search from IT citation databases	Does not support complex Boolean expressions
		Dropped SciVerse Scopus from generic citation database list	Not subscribed by Imperial
		Created a generic search section for Mobile Active and grey literature	Simpler search strategy needed for some sources
		Dropped language restriction	Desire for as generic a search as possible
		Dropped Appendix 1	Term list now included in S2
0.4	10/01/2011	Moved 'smartphone$ OR smart phone$' to H1 from H3	Sufficiently specific to be included in hardware term list
		Moved 'PDA or personal digital assistant' to H2	Preliminary search showed too generic so need combining with 'app' or use-case terms
		Created separate term block H4 for 'mhealth OR m health' and equivalent block F2 in generic searches	These terms stand alone in any source
		Dropped mobile$ from H3	Preliminary search showed too generic
		Converted app$ to 'app OR apps'	APPL is a gene name so simple truncation creates false positives
		Dropped 'questionnaire? or survey? or feedback$' from S2	Preliminary search showed too generic
		Standardised case and truncation for e-Health search strategy S2	Formatting change only
		Added barcode$ OR RFID OR radio frequency identif$ to S2	Scope for scanning applications using smartphones

		Updated search strategies to look at m-health terms alone	Standalone terms
		Updated mobile active search strategy to filter by Health Category and All Categories as appropriate	Feedback from preliminary search
0.5	12/01/2011	Removed redundant field group H5	Included in error
		Added 'apps and app' to information technology and generic citation database searches	Omitted in error
1.0	14/01/2011	Reformatted document	Simplified layout to remove citation source/generic term list split
		Renamed H4 (mhealth) to F1	Field specific and not hardware-specific term
		Renamed F1 (health care general terms) to F2	Required change to accommodate above
		Promoted 'app' to own section in software (S1)	Required change to allow all searches to be expressed
		Renamed S1 to S2 and S2 to S3	Required change to accommodate above
		Dropped UK-specific health informatics terms from e-Health search (S3) e.g. GP2GP	After discussion with JC agreed no need to respect the original search if terms are clearly meaningless
	20/01/2011	CiteSeerX changed to allow any date	Some entries do not have a date index
		Updated link for ProQuest Dissertations	Link incorrect
		Moved Controlled trials register to medical general sources search strategy	Not possible to perform complex Boolean searches using this tool (frequent crashes and some searches never complete)
	21/01/2011	OpenSIGLE dropped	No relevant items found and review suggests this resource is not being updated any more
1.1	03/03/2011	Added Kings Fund curated telehealth database	Generic search for terms to incorporate entire curated dataset relating to telehealth and telecare

Appendix 3 Systematic review screening flowchart



Appendix 4 Systematic review data extraction template

Template into which details of apps were recorded for subsequent analysis.

#	Field	Format
Basic details		
1.01	Authorship	Text
1.02	Intervention Name	Text
1.02	Year	Number
1.03	Study ID	Number
1.04	Study type	Pick from list
Risk of bias 1		
2.01	Sequence generation	Low/Unclear/High
2.02	Allocation concealment	Low/Unclear/High
2.03	Blinding to personnel	Low/Unclear/High
2.04	Blinding to outcome analysis	Low/Unclear/High
2.05	Ethical approval	Low/Unclear/High
2.06	Funding	Low/Unclear/High
Recruitment		
3.01	Country, City	Text
3.02	Power calculation performed	Yes/No
3.03	Number recruited	Number
Intervention group		
3.04	Number randomized	Number
3.05a	Number withdrawn	Number
3.05b	Number lost to follow-up	Number
Control group		
3.06	Control Number randomised	Number
3.07a	Number withdrawn	Number
3.07b	Number lost to follow-up	Number
Participant characteristics		
4.01a	Mean age	Number
4.01b	Age SD	Number
4.02	% women	Percentage
4.03a	% White	Percentage
4.03b	% Black	Percentage
4.03c	% Asian	Percentage
4.03d	% Chinese or Other	Percentage
4.04	Condition	Pick from list
4.05a	Mean Duration of Disease	Number
4.05b	Duration SD	Number
4.06	Comorbidities	Comma-separated list
2.07	RoB for Baseline Differences	Low/Unclear/High
4.08a	Baseline HbA1c	Number
4.08b	HbA1c SD	Number
4.09a	Baseline PEFR	Number
4.09b	PEFR SD	Number
Intervention characteristics		
5.01	Hardware	Text
5.02	Platform	Text
5.03	Mobile device provided	Yes/No
5.04	Monitored parameters	Text

#	Field	Format
5.05	Expected frequency	Text
5.06	Professional Feedback Content	Text
5.07	Professional Feedback Source	Text
5.08	Professional Feedback Frequency	Text
5.09	Automated Feedback Content	Text
5.10	Automated Feedback Frequency	Text
5.11	Data Summarisation	Text
5.12	Training	Yes/No
5.13	Reminders	Yes/No
5.14	Other intervention components	Comma-separated list
5.15	Control intervention	Comma-separated list
Study duration		
6.01	Study duration	Number
6.02	Post-intervention follow-up	Yes/No
6.03	Follow-up findings	Text
Other outcomes †		
7.01	Engagement	Text
7.02	Cost	Text
7.03	Adverse Events	Text
Risk of bias 2		
2.08	Incomplete outcome data	Low/Unclear/High
2.09	Selective outcome reporting	Low/Unclear/High
Publications		
8.01	Published Protocol?	Yes/No
8.02	Trial Registration?	Yes/No
8.03	CONSORT Checklist?	Yes/No
Notes		
9.01	Notes	Text

Appendix 5 Characteristics of excluded studies

The table below provides details of studies that were excluded after full text review and the reasons for exclusion.

Authors	Condition	Study type	Reason for exclusion
Anzaldo-Campos et al. (2014) [399]	Type 2 diabetes	Randomized study of mobile phone-based intervention	Insufficient information to evaluate
Awoyinka et al. (2011) [400]	Asthma	Case control study of perceptions of asthma control in overweight teens	Not a randomized study design
Boizel et al. (2007) [401]	Type 1 diabetes	Single group evaluation of PDA-based intervention	Not a randomized study design
Chiu et al. (2012) [402]	Asthma	Descriptive account of smartphone-based intervention	Not a randomized study design
Cho et al. (2009) [403]	Type 2 diabetes	Randomized study of mobile phone-based intervention	Control group not usual care
Chu et al. (2006) [404]	Asthma	Descriptive account of GPS-based allergy alert system	Not a mobile intervention
Dick et al. (2011) [405]	Type 1/2 diabetes	Single group feasibility study of mobile phone-based intervention	Not an app-based intervention (SMS)
Faridi et al. (2008) [406]	Type 2 diabetes	Randomized study of mobile phone-based intervention	Not an app-based intervention (SMS)
Farmer et al. (2005) [407, 408]	Type 1 diabetes	Randomised study of mobile phone-based intervention	Control group not usual care
Finkelstein et al. (2009) [409]	Asthma	Descriptive account of feature phone-based intervention	Not a randomized study design
Fischer et al. (2012) [410]	Type 1/2 diabetes	Quasi-experimental study of mobile phone-based intervention	Not an app-based intervention (SMS)
Forjuoh et al. (2008) [411, 412]	Type 2 diabetes	Before and after study of PDA-based intervention	Not a randomized study design
Franklin et al. (2006) [413]	Type 1 diabetes	Randomized study of mobile phone-based intervention	Not an app-based intervention (SMS)
Fukuo et al. (2009) [414]	Type 2 diabetes	Single group evaluation of PDA-based intervention	Not a randomized study design
Fukuoka et al. (2014) [415]	At risk of diabetes	Randomised study of mobile phone-based intervention	Participants lack diabetes diagnosis
Glykas et al. (2004) [416]	Asthma	Descriptive account of web-based intervention	Not a mobile intervention
Gomez et al. (2008) [417]	Type 1/2 diabetes	Randomized crossover study of PDA-based intervention	Cannot disaggregate first period for analysis
Gonzalez-Molero et al. (2012) [418]	Type 1 diabetes	Single group evaluation of email-based intervention	Not an app-based intervention (Email)

Authors	Condition	Study type	Reason for exclusion
Gupta et al. (2011) [419, 420]	Asthma	Descriptive account of smartphone-based spirometer	Not a randomized study design
Hanauer et al. (2006) [421]	Type 1/2 diabetes	Single group evaluation of PDA-based intervention	Not a randomized study design
Holman et al. (1996) [422]	Type 1 diabetes	Randomized crossover study of PDA-based intervention	Cannot disaggregate first period for analysis
Holtz et al. (2009) [423]	Asthma	Single group evaluation of mobile phone-based intervention	Not an app-based intervention (SMS)
Kerkenbush (2003) [424]	Type 1/2 diabetes	Protocol for PDA-based intervention	Insufficient information to evaluate (Study protocol only)
Kim et al. (2012) [425]	Type 2 diabetes	Controlled before and after study of mobile phone-based intervention	Not a randomized study design
Kollmann et al. (2007) [426]	Type 1 diabetes	Single group feasibility study of mobile phone-based intervention	Not a randomized study design
Kumar et al. (2004) [251]	Type 1/2 diabetes	Randomised study of mobile phone-based intervention	Control group not usual care
Kwok et al. (2005) [427]	Type 1/2 diabetes	Single group usability study of mobile phone-based intervention	Not a randomized study design
Kwon et al. (2004) [428]	Type 1/2 diabetes	Single group evaluation of mobile phone-based intervention	Not an app-based intervention (SMS/web)
Ładyżyński et al. (2007) [429]	Type 1 diabetes	Randomized trial of home telecare system	Not a mobile intervention
Larsen et al. (2010) [430]	Type 2 diabetes	Single group feasibility study of mobile phone-based intervention	Not a randomized study design
Lee et al. (2005) [431]	Asthma	Descriptive account of mobile-accessible web-based intervention	Not a randomized study design
Lee et al. (2005) [432]	Type 1/2 diabetes	Descriptive account of mobile phone-based intervention	Not a randomized study design
Lee et al. (2010) [433]	Type 1/2 diabetes	Descriptive account of mobile phone-based intervention	Not a randomized study design
Lim et al. (2009) [434]	Asthma	Single group evaluation of mobile video-based inhaler technique education	Not a mobile intervention
Mulvaney et al. (2013) [435]	Asthma	Single group evaluation of mobile phone-based intervention	Not an app-based intervention (Interactive Voice Response)
Pena et al. (2009) [436]	Type 1/2 diabetes	Survey of patient attitudes to mobile monitoring	Not a randomized study design
Popow et al. (2003) [437]	Type 1 diabetes	Descriptive account of mobile phone-based intervention	Not a randomized study design

Authors	Condition	Study type	Reason for exclusion
Preuveneers et al. (2008) [438]	Type 1/2 diabetes	Single group feasibility study of mobile phone-based intervention	Not a randomized study design
Prieto-Centurion et al. (2014) [439]	Asthma	Single group evaluation of gait-tracking software	Not a randomized study design
Rigla et al. (2008) [440-445]	Type 1 diabetes	Randomized crossover study of PDA-based intervention	Cannot disaggregate first period for analysis
Rollo et al. (2011) [446]	Type 2 diabetes	Single group feasibility study of mobile phone-based intervention	Not a randomized study design
Ryan et al. (2005) [447]	Asthma	Single group evaluation of mobile-phone based intervention	Not a randomized study design
Tiplady et al. (2000) [448]	Asthma	Randomized study comparing electronic and paper data collection	Not a mobile intervention
Tseng (1999) [449]	Type 1/2 diabetes	Descriptive account of PDA-based intervention	Not a randomized study design
Vähätalo et al. (2004) [253]	Type 1 diabetes	Single group evaluation of mobile phone-based intervention	Not a randomized study design
Waki et al. (2014) [450, 451]	Type 2 diabetes	Single group evaluation of mobile phone-based intervention	Not a randomized study design
Yoon et al. (2007) [452]	Type 2 diabetes	Randomized study of mobile phone-based intervention	Not an app-based intervention (SMS)
Zolfaghari et al. (2012) [453]	Type 2 diabetes	Quasi-experimental study of mobile phone-based intervention	Not an app-based intervention (SMS)

Appendix 6 Criteria for assessing inhaler technique education

Criteria covering eight domains. All criteria are sourced from their respective product literature[454-461] except where otherwise cited. Emboldened items are those necessary for delivery of drug into the lungs, extending previously developed criteria[462] with three further 'critical' issues[151]: removal of any mouthpiece cover; avoiding inhalation against closed teeth or through nose rather than mouth.

Domain	Criteria
Inhaler preparation	▪ ***All inhalers*** o **Mouthpiece cover removal** [151] ▪ *Accuhaler* o **Blister pack loading** o **Preparation by opening mouthpiece using thumb grip and then sliding lever until click heard** ▪ *Autohaler* o **Preparation by raising lever on inhaler top** ▪ *Clickhaler, Easyhaler* o 3-5 vigorous vertical shakes o **Preparation by pressing inhaler top once only until click heard**, **then releasing** ▪ *Diskhaler* o **Blister pack loading** o **Preparation by sliding tray in and out and opening lid to pierce blister** ▪ *Easi-breathe inhaler* o Vertical grasp not covering vents. ▪ *Handihaler* o **Blister insertion and piercing** without shaking ▪ *Pressurised Metered Dose Inhaler (pMDI)* o **Preparation by 4-5 shakes** (Justified by [463]) ▪ *pMDI with spacer* o As for pMDI, and: o **Spacer mouthpiece cover removal** o pMDI fitted firmly into compatible spacer ▪ *Turbohaler* o **Preparation by turning base grip as far as possible in one direction and then the other until click heard**
Inhaler positioning	▪ ***All inhalers*** o Comfortable but complete exhalation, not through inhaler o Sitting or standing position o Appropriate inhaler grasp o **Positioning inhaler/spacer mouthpiece in mouth and sealing lips without biting** (or in front of mouth for open mouth pMDI technique) [151] ▪ *Diskhaler* o Mouth seal not covering vents on mouthpiece.
Inhalation/actuation method	▪ ***All inhalers*** o **Inward breath through mouth not nose** [151]

Domain	Criteria
	▪ *Accuhaler, Clickhaler, Handihaler* o **Steady and deep inward breath** (no need for manual actuation) ▪ *Autohaler, Easi-Breathe Inhaler* o **Slow, deep inward breath that continues when actuation click is heard** (no need for manual actuation). ▪ *Diskhaler, Easyhaler, Turbohaler* o **Inward breath as deeply and as forcefully as possible** (no need for manual actuation) ▪ *pMDI* o Steady, deep inward breath o **Manual actuation just after inhalation starts and well before inhalation ends** o **Inhalation not interrupted by actuation** ▪ *pMDI with spacer* o **Single actuation into spacer followed immediately by steady deep inward breath** *or* **single actuation into large volume spacer during normal breathing**.
Breath holding and exhalation sequence	▪ ***All inhalers*** o Inhaler removed from mouth during breath holding o No exhalation through inhaler ▪ *Accuhaler, Autohaler, Easi-breathe inhaler* o Breath held for 10 seconds then slow exhalation ▪ *Clickhaler, Diskhaler, Easyhaler, pMDI* o Breath held for at least 5 seconds or as long as comfortable. ▪ *pMDI with spacer* o As for pMDI after removing spacer from mouth or continued tidal breathing for 5 breaths with exhalation/inhalation into spacer ▪ *Turbohaler* o Gentle exhalation after removing inhaler from mouth
Timing of additional dose(s)	▪ *Accuhaler* o Repeated immediately if needed by sliding thumb grip to original position, listening for click ▪ *Autohaler* o Repeated immediately if needed by lowering then raising lever on inhaler top ▪ *Clickhaler, Handihaler, Turbohaler* o Repeated immediately if needed ▪ *Diskhaler* o Repeated immediately if needed by repeating tray sliding method, opening blister only when needed ▪ *Easi-breathe Inhaler, Easyhaler* o Delay one minute prior to repetition, cap closed between repetitions ▪ *pMDI, pMDI with spacer* o Delay 30 seconds prior to repetition
Mouth rinsing	▪ ***All inhalers*** o Rinsing and spitting after steroid use to reduce risk of candidiasis [139, 140] or to remove taste
Identifying empty inhaler	▪ ***All inhalers*** o Cannot be judged by sounds made when inhaler shaken

Domain	Criteria
	▪ *Accuhaler, Diskhaler* o Dose counter showing 0 indicating need to replace blister pack ▪ *Autohaler, Easi-Breathe inhaler* o Empty when no propellant discharged during use ▪ *Clickhaler* o Dose counter background turns red when ten doses left and again when no doses remain ▪ *Easyhaler* o Dose counter numbers turn red when 20 doses left; cannot be judged by powder level seen in inhaler window ▪ *Handihaler* o Single capsule emptied after each inhalation sequence ▪ *pMDI* o Relies on tracking total number of doses stated on label ▪ *Turbohaler* o Appearance of red mark in dose indicator window when approximately 20 doses left
Inhaler care	▪ ***All inhalers*** o By replacing cover after use ▪ *Autohaler* o By wiping mouthpiece with dry tissue ▪ *Diskhaler* o Using supplied brush to remove excess powder ▪ *Clickhaler, Easi-breathe inhaler, Easyhaler, Turbohaler* o By wiping mouthpiece with dry tissue only; immersing no part in water ▪ *Handihaler* o Washing without detergent and air drying per manufacturer instructions ▪ *pMDI* o Risk of blockage preventing fine spray addressed by removing canister and rinsing plastic casing weekly ▪ *Spacer* o By washing in detergent and air drying per manufacturer instructions [139, 324]

Appendix 7 Asthma apps assessment data extraction template

Template into which details of apps were recorded for subsequent analysis.

#	Field	Format
0.1a	App ID	Number
0.1b	Product ID	Number
0.1c	Linked IDs	Comma-separated numbers
0.2	Date of latest review	Date
0.3	Reviewer	Text
0.4	Downloaded	Yes/No
0.5	Platform	Pick
0.6a	Include or Exclude?	Include/Exclude
0.6b	If 0.6a EXCLUDE, provide reason	Text
0.7	Brief description	Text
0.8	Taxonomy	Text
Basic details		
1.1a	App name	Text
1.1b	URL	Text
1.1c	Display name	Text
1.1d	Namespace	Text
1.1e	Bundle ID	Text
1.2	Version	Number
1.3a	Initial release date	Date
1.3b	Version release date	Date
1.3c	Latest Version	Number
1.3d	Latest version release date	Date
1.3e	Number of version releases	Number
1.4	Cost	£ or 'Free'
1.5a	Publisher	Text
1.5b	Publisher ID	Number
1.6	Source country	Text
1.7a	Publisher website	Link
1.7b	Website accessible?	Yes/No
1.7c	Website spoofed?	Yes/No
1.7d	Actual website	Link
1.7e	Published email	Email Address
1.8a	Original number of downloads	Number or Number Range
1.8b	Original download count census date	Date
18.c	Updated number of downloads	Number or Number Range
1.8d	Updated download count census date	Date
1.8e	Original user rating average	Number
1.8f	Original user rating count	Number
1.8g	Original user rating census date	Date
1.8h	Updated user rating average	Number
1.8i	Updated user rating count	Number
1.8j	Updated user rating census date	Date
1.8k	Content rating	Text
1.9a	Languages	Yes/No
1.9b	Is UI translated?	Yes/No
1.9c	Is content translated?	Yes/No
Functionality		

#	Field	Format
2.0	App description	Text
2.1a	Main function 1	Text
2.1b	Main function 2	Text
2.1c	Main function 3	Text
2.3a	Is the app intervention standalone?	Yes/No
2.3b	If 2.4a NO, provide details of intervention	Text
2.4	Is there a user setup wizard?	Yes/No
2.5	Does the app support multiple user profiles?	Yes/No
2.6a	Does the app require network access?	Pick from list
2.6b	Can the app request location information (GPS/WiFi/Cell triangulation)?	Pick from list
2.6c	Can the app request access to read contact data?	Pick from list
2.6d	Can the app request access to read calendar data?	Pick from list
2.6e	Can the app access the camera/images?	Pick from list
2.6f	Can the app access the microphone?	Pick from list
2.6g	Can the app set up Bluetooth connections?	Pick from list
2.6h	Can the app set up NFC connections?	Pick from list
2.6j	Can the app send or receive data by IR?	Pick from list
2.6j	Can the app start automatically (excluding notifications)?	Pick from list
2.6k	Does the app use push or local notifications?	Pick from list
2.6l	Can the app place phone calls?	Pick from list
2.6m	Can the app send SMS or MMS using native functions?	Pick from list
2.6n	Can the app modify/delete storage outside its sandbox?	Pick from list
2.6o	Can the app read the phone status or identifiers?	Pick from list
2.6p	Can the app read calls or SMS or other message content?	Pick from list
2.6q	Can the app prevent the device from sleep?	Pick from list
2.6r	Can the app modify global settings?	Pick from list
2.6s	Can the app read sync or account settings?	Pick from list
2.6t	Can the app modify WiFi settings?	Pick from list
2.6u	Can the app terminate or restart other apps?	Pick from list
2.6v	Can the app list other running apps?	Pick from list
2.6w	Can the app set preferred status for one or more purposes?	Pick from list
2.6x	Can the app control device vibration?	Pick from list
2.7	Is the app purpose clear from the product advert?	Yes/No
Diary features		
3.1	Does the app have diary, questionnaire or diagnostic/assessment features?	Yes/No
If 3.1 NO, skip to the section 4		
3.2a	Does the app have a diary to record peak flow readings (PEFR)?	Yes/No
3.2b	If 3.2a YES, provide details	Text
3.2c	If 3.2a YES, does the app use a predicted or % of PB to classify readings?	Predicted/PB/Both/No
3.2d	If 3.2c PREDICTED, what formula is used to calculate predicted PEFR?	Text or 'Unknown'
3.2e	If 3.2a YES, is there a PEFR summary visualization?	Yes/No
3.2f	If 3.2e YES, provide details	Text

#	Field	Format
3.3a	Does the app have a diary to record symptoms or asthma-related events?	Yes/No
3.3b	If 3.3a YES, provide details	Text
3.3c	If 3.3a YES, is there a symptom summary visualization?	Yes/No
3.3d	If 3.3c YES, provide details	Text
3.4a	Does the app have a diary to record medication?	Yes/No
3.5a	If 3.2a or 3.3a YES, does the app provide any alert based on changing PEFR/symptoms?	Yes/No
3.5b	If 3.2a or 3.3a YES, does the app provide any advice based on changing PEFR/symptoms?	Yes/No
3.5c	IF 3.5b YES, what advice is given?	Text
3.6a	Does the app include any diagnostic or assessment tools, questionnaires or calculators?	Yes/No
3.6b	If 3.6a YES, provide details	Text
3.6c	If 3.6a YES, provide sources	Text
3.6d	If 3.5a YES, are sources clear?	Yes/No
3.6e	If 3.6a YES, what is the purpose of the assessment questionnaire/calculator?	Pick from list
3.7a	Does the app allow data to be shared with a clinician?	Yes/No
3.7b	If 3.7a YES, provide details	Text
Alerts		
4.1a	Does the app provide pollen information?	Yes/No
4.1b	Does the app provide pollution information?	Yes/No
4.2a	If 4.1a or 4.1b YES, where are the data sourced from?	Text
4.2b	If 4.1a or 4.1b YES, are sources clear?	Yes/No
4.2c	If 4.1a or 4.1b YES, what areas are covered?	Text
4.2d	If 4.1a or 4.1b YES, is the information dated?	Yes/No
4.3a	Does the app provide any reminders or notifications?	Yes/No
4.3b	If 4.3a YES, provide details	Text
Information		
5.1	Does the app provide any information or guidance about asthma?	Yes/No
5.2	Are information sources attributed?	Yes/No
5.2a	Provide details of attribution (or failure of attribution)	Text
5.2b	Third-party sources	Text
5.2c	Is the content reproduced from free online resource(s) other than those of the publisher?	Yes/No
5.3a	Is information content dated?	Date
5.3b	Is a content expiration date set?	Date
Action plan		
6.1a	Does the app recommend the use of a personal asthma action plan?	Yes/No
6.1b	Does the app have a feature to store personal asthma triggers?	Pick from list
6.1c	Does the app have a feature to store a personal asthma action plan?	Yes/No
6.2a	Does the plan use a 3+1 stage template?	Yes/No
6.2b	If 6.2a NO, how does it differ?	Text
6.3a	Does the app use the plan to make treatment recommendations?	Yes/No
6.3b	If 6.3a YES, provide details	Text

#	Field	Format
Asthma education information domains		
Does the app…		
7.1a	State that asthma is a lung disease characterized by inflammation and narrowing of the airways.	Yes/No
7.1b	State that the four main symptoms of asthma are cough, wheeze, shortness of breath and chest tightness.	Yes/No
7.1c	State that asthma cannot be cured (although childhood symptoms may remit) but can be effectively controlled.	Yes/No
7.1d	State that the causes of asthma are multifactorial/not well understood (triggers defined below)	Yes/No
7.2a	Explain the basis of asthma treatment as a partnership between patient and caregiver in which the aim is guided self-management.	Yes/No
7.2b	State that partnership requires investment and will develop over time.	Yes/No
7.2c	Emphasize the importance of sharing information, expectations, fears and concerns with care providers.	Yes/No
7.2d	Explain the role of joint setting of realistic goals for asthma control and management.	Yes/No
7.3a	State that there are two classes of asthma medication: relievers and preventers.	Yes/No
7.3b	Explain possible side effects of medication (tachycardia/tremor in B2 agonists; thrush/cataracts/dysphonia for inhaled steroids; possible additional effects for high dose steroids).	Yes/No
7.3c	State that early treatment can prevent symptoms from worsening.	Yes/No
7.4a	State that recognizing and avoiding personal triggers is an important part of asthma control.	Yes/No
7.5a	State that preventer medication must be used regularly to be effective.	Yes/No
7.6b	State the importance of good inhaler technique (or demonstrates) and appropriate use of a spacer device.	Yes/No
7.6c	State the importance of ensuring inhalers are in date and are not empty.	Yes/No
7.7a	State that learning to recognize signs of change in asthma status is an important personal skill.	Yes/No
7.7b	States that both symptom recognition and peak flow measurements are valid approaches for self-monitoring.	Yes/No
7.7c	Explain the purpose of a peak flow meter and how to use it.	Yes/No
7.7d	State the importance of regular physician review.	Yes/No
7.8a	State that patients with asthma should have an up to date written action plan.	Yes/No
7.8b	Explain the purpose of an action plan (to step up and step down treatment, and to seek appropriate help in response to changing symptoms and/or peak flow).	Yes/No
7.9a	Describe signs/symptoms of worsening asthma (increasing wheeze; cough; night time disturbance; breathlessness limiting activity; reliever in halers not working).	Yes/No

#	Field	Format
7.9b	State the importance of changing treatment and/or seeking help promptly.	Yes/No
7.9c	Explain the steps involved in lay management of acute asthma.	Yes/No
7.10a	State that it is reasonable for most people to achieve minimal symptoms and limitation of activities.	Yes/No
7.10b	Ask patients to reflect on what they would consider as good asthma control.	Yes/No
7.11	Notes	Text
Evidence base compliance		
What stance does the app take on the following issues…		
8.1	The use of dust mite allergen control measures.	Pick from list
8.2	The removal of pets from the home to improve asthma.	Pick from list
8.3	The use of fungal allergen avoidance and control measures.	Pick from list
8.4	The use of cockroach allergen avoidance and control measures	Pick from list
8.5	Smoking cessation.	Pick from list
8.6	The avoidance of passive smoking.	Pick from list
8.7	The avoidance of exposure to outdoor air pollution.	Pick from list
8.8	The avoidance of a defined food allergen, once identified.	Pick from list
8.9	Immunotherapy for a define allergen to control asthma	Pick from list
8.10	Weight reduction in obese individuals as a way of controlling asthma.	Pick from list
8.11	Seasonal influenza vaccination in people with asthma.	Pick from list
8.12a	Dietary supplementation with selenium to improve asthma.	Pick from list
8.12b	Low sodium diet to improve asthma.	Pick from list
8.12c	Spinal manipulation to treat asthma.	Pick from list
8.12d	Homeopathic medicine to treat asthma.	Pick from list
8.12e	Yoga to improve asthma.	Pick from list
8.12f	Breathing techniques including Buteyko and Papworth methods to improve asthma.	Pick from list
8.12g	Relaxation techniques or hypnosis to treat asthma.	Pick from list
8.12h	Acupressure to treat asthma	Pick from list
8.12i	Acupuncture to treat asthma	Pick from list
8.12j	Herbal or Chinese medicine to treat asthma	Pick from list
8.13	Notes	Text
Emergencies		
9.1	Does the app provide advice on what to do during an asthma attack?	Yes/No
If 9.1 NO, skip to section 10		
9.2	If 9.1 YES, who is the guidance targeted towards?	Pick from List
9.3a	If 9.1 YES, does the advice explain what the symptoms of an asthma attack are (cough, wheeze, shortness of breath, chest tightness)?	Yes/No
9.3b	If 9.1 YES, does the advice address how to use a reliever inhaler appropriately?	Yes/No
9.3c	If 9.1 YES, does the advice include sitting patient up and encouraging to take slow steady breaths.	Yes/No

#	Field	Format
9.3d	If 9.1 YES, does the advice include staying calm and offering reassurance.	Yes/No
9.3e	If 9.1 YES, does the advice include seeking emergency help if no improvement or any concerns (blue finger tips, quiet breath sounds)	Yes/No
9.4	Notes	Text
Inhaler technique guidance		
10.1	Does the app provide guidance on how to user an inhaler?	If Yes, choose which inhalers. Otherwise 'No"
If 10.1 NO, skip to section 11		
10.2a	If 10.1 YES, what medium is used to communication guidance?	Text/Video/Animation
10.3a	If 10.1 YES, does the guidance correctly address inhaler preparation?	Correct/Incorrect/Not Addressed
10.3b	If 10.1 YES, does the guidance correctly address positioning?	Correct/Incorrect/Not Addressed
10.3c	If 10.1 YES, does the guidance correctly address the inhalation/actuation method?	Correct/Incorrect/Not Addressed
10.3d	If 10.1 YES, does the guidance correctly address exhalation sequence?	Correct/Incorrect/Not Addressed
10.3e	If 10.1 YES, does the guidance correctly address secondary doses?	Correct/Incorrect/Not Addressed
10.4a	If 10.1 YES, does the guidance correctly address mouth rinsing?	Correct/Incorrect/Not Addressed
10.4b	If 10.1 YES, does the guidance correctly address ensuring inhaler not empty?	Correct/Incorrect/Not Addressed
10.5	If 10.1 YES, does the guidance correctly address inhaler care?	Correct/Incorrect/Not Addressed
10.6	Notes	
Information and security governance		
11.1a	Does the app offer password or PIN protection?	Yes/No
11.1b	Can entered data be edited?	Yes/No
11.1c	Can entered data be individually deleted?	Yes/No
11.1d	Can all stored data be wiped (other than through uninstallation)?	Yes/No
11.2a	Does the app require a user account to be created?	Yes/No
11.2b	If 11.2a YES, provide details	Text
11.3a	Does the app offer cloud sync?	Yes/No
11.3b	Does the app offer a backup or data export mechanism (apart from cloud sync and/or backup services provided by OS)	Yes/No
11.3c	If 11.3b YES, detail the export mechanism.	Pick from list
11.3d	If 11.3b YES, is the export encrypted?	Yes/No
11.3e	If 11.3b YES, provide details	Text
11.3f	Does the app offer social sharing features?	Yes/No
11.3g	If 11.3f YES, provide details	Text
11.4a	Does the app include or link to a privacy policy or confidentiality policy?	Pick from list
11.4b	If 11.4a YES, what is the URL for the policy?	Link
11.4c	If 11.4a YES, does the URL work?	Yes/No
11.4d	If 11.4a YES, are there any disclosures in the privacy policy that are surprising/unusual?	Text

#	Field	Format
11.4e	Does the marketplace or supplier website include a privacy policy?	Yes/No
11.4f	If 11.4e YES, what is the URL for the policy?	Link
11.4g	if 11.4e YES, does the URL work?	Yes/No
11.4h	If 11.4e YES, are there any disclosures in the privacy policy that are surprising/unusual?	Text
11.5a	Can the app transmit data to a third party (other than advertisers or user-initiated actions)?	Yes/No
11.5b	If 11.5a YES, provide details	Text
Content and attribution		
12.1a	What is the app publishers funding model?	Pick from list
12.1b	Is the app publisher also the commissioner of the app?	Yes/No/Unclear
12.1c	If 12.1b NO, who commissioned the app?	Text
12.1d	If 12.1b NO, what is the website of the app commissioner?	Link
12.1e	If 12.1b NO, what is the app commissioner's funding model?	Pick from list
12.2a	What is the app copyright statement?	Text
12.2b	What is the marketplace copyright statement?	Text
12.3a	Does the app include adverts?	Yes/No
12.3b	What format adverts are used?	Pick from list
12.3c	If 12.3a YES, does the app publisher have an advertising policy?	Yes/No
12.3d	If 12.3b YES, provide details.	Text
12.4a	Does the app offer paid-for enhancements?	Yes/No
12.4b	If 12.4a YES, what is the nature of these enhancements?	Text
12.4c	If 12.4a YES, is the app functional (for asthma) without the enhancements?	Yes/No
12.4d	If 12.4a YES, what is the cost of the necessary enhancements?	£
12.5a	Is there a clinical disclaimer in the app?	Yes/No
12.5b	If 12.5a YES, quote appropriate text from disclaimer	Text
12.5a	Is there a general software disclaimer in the app?	Yes/No
12.5b	If 12.5a YES, quote appropriate text from disclaimer	Text
12.6a	Is the app accredited or endorsed by any third party (distinct from the app commissioner)?	Yes/No
12.6b	If 12.6a YES, provide details	Text
12.7a	Does the app offer a local help system?	Yes/No
12.7b	Does the app offer online help system?	Yes/No
12.8a	Is there a support contact?	Yes/No
12.8b	If 12.8a YES, is there a support website?	Yes/No
12.8c	If 12.8b YES, what is the support website link?	Link
12.8d	If 12.8a YES, is there a support email?	Email Address
12.8e	If 12.8a YES, provide any other details	Text
Quality assurance		
13.1a	Were any textual/grammatical errors found in written or multimedia informational content?	Yes/No
13.1b	If 13.1a YES, provide relevant example(s)	Text
13.2a	Were any textual/grammatical errors found in the user interface?	Yes/No
13.2b	If 13.2a YES, provide relevant example(s)	Text

#	Field	Format
13.3a	Were any software errors encountered during test use?	Yes/No
13.3b	If 13.3a YES, provide details	Text
13.4a	Were any network/resource errors encountered during use?	Yes/No
13.4b	If 13.4a YES, provide details	Text
13.5a	Does the app appropriately validate data entry?	Yes/No
13.5b	If 13.5a YES or NO, provide details.	Text
13.6	Any other problems/issues identified?	Text
Other		
13.7	Notes	Text

Appendix 8 Characteristics of excluded asthma apps

The table below provides details of apps that were excluded after download and review and the reasons for exclusion.

App	Platform	Developer	Version	Reason for exclusion
AcuPressure: Self Treatment	Android	Vital Acts Inc.	1.1	Contained no asthma-specific content or tools.
AcuPressure: Treat Yourself	Android	Vital Acts Inc.	1.1	Contained no asthma-specific content or tools.
Acupuncture For Asthma	Android	KRM Apps	2	Contained no asthma-specific content or tools.
All About Acid Reflux Ebook	Android	Quality MRRs ltd.	1	Contained no asthma-specific content or tools.
Allergy App Free	Android	Popolipo	1	Contained no asthma-specific content or tools.
Allergy Free Kids Ebook	iOS	Feel Social Inc.	1.0	Asthma app included in previous review that was subsequently withdrawn prior to the start of this review.
Allergy Glossary	iOS	Deep Powder Software	1.0	Asthma app included in previous review that was subsequently withdrawn prior to the start of this review.
Allergy Symptoms	Android	Jeddablue Enterprises	2	Contained no asthma-specific content or tools.
Aromatherapy Essential	Android	WaterLightApps	1	Contained no asthma-specific content or tools.
Asthma	Android	Internet Medical Association	1	Targeted clinicians rather than patients.
Asthma	Android	nic	1	Contained no asthma-specific content or tools.
Asthma	iOS	IndiaNIC Infocom Limited	1.4	Asthma app included in previous review that was subsequently withdrawn prior to the start of this review.
Asthma Control Tips	Android	KRM Apps	2	Contained no asthma-specific content or tools.
Asthma Guide	Android	Azurabiz	2	Contained no asthma-specific content or tools.
Asthma Guide	Android	Roadcred	2	Contained no asthma-specific content or tools.
Asthma Info	Android	BAWidgets.com	1.0	Contained no asthma-specific content or tools.
Asthma Management Guide	Android	Keith Pipers	2	Contained no asthma-specific content or tools.
Asthma Puff Counter	iOS	Trejay Rathore	1	Contained no asthma-specific content or tools.

App	Platform	Developer	Version	Reason for exclusion
Asthma Tester	iOS	Last Line of Code	1.1	Asthma app included in previous review that was subsequently withdrawn prior to the start of this review.
ASTHMA+++	Android	KulAppz	1	Targeted clinicians rather than patients.
Asthmapolis	iOS	Reciprocal Labs Corporation	1.10.1	Required login credentials not available to us.
AsthmaPulse	iOS	Enemra, Inc.	1.10	Asthma app included in previous review that was subsequently withdrawn prior to the start of this review.
Belladonna Secret	Android	CandiApp	2	Contained no asthma-specific content or tools.
Benefits of Acupuncture	Android	CandiApp	2	Contained no asthma-specific content or tools.
Breathefree App	Android	Breathefree	1.2	Targeted clinicians rather than patients.
Causes Of Pet Allergies	Android	My Mobile Kingdom	2	Contained no asthma-specific content or tools.
Chronic Diseases	Android	IndiaNIC Infocom Limited	1.0	Asthma app included in previous review that was subsequently withdrawn prior to the start of this review.
Common Allergy Symptoms	Android	Jeddablue Enterprises	2	Contained no asthma-specific content or tools.
Dealing with Bronchitis	Android	Figspops	2.2	Asthma app included in previous review that was subsequently withdrawn prior to the start of this review.
Emergencies, CPR & First Aid	Android	instamedic	10	Targeted clinicians rather than patients.
Emergency First Aid Guide	Android	phoneflips	4.0	Asthma app included in previous review that was subsequently withdrawn prior to the start of this review.
Everything About Asthma	Android	IndiaNIC Infocom Limited	1.0	Asthma app included in previous review that was subsequently withdrawn prior to the start of this review.
Everything You Wanted To Know About Asthma	iOS	Netlancer, Inc.	1.2	Asthma app included in previous review that was subsequently withdrawn prior to the start of this review.
Exercise & Asthma Guide	Android	KRM Apps	2	Contained no asthma-specific content or tools.

App	Platform	Developer	Version	Reason for exclusion
Fluffer Lost His Puffer	iOS	Biboplex Media Ltd.	1.01	Asthma app included in previous review that was subsequently withdrawn prior to the start of this review.
Food Allergy Guide	Android	Jeddablue Enterprises	2	Contained no asthma-specific content or tools.
Food Killer	iOS	Yung Wong	1	Contained no asthma-specific content or tools.
FREE Asthma Guidelines	Android	Infoapps	1.1	Contained no asthma-specific content or tools.
Goji Juice Info	Android	Jeddablue Enterprises	2	Contained no asthma-specific content or tools.
Good Days	Android	Alain Domissy	0.9-RELEASE	Contained no asthma-specific content or tools.
Good Days	iOS	Terje Norderhaug	1	Contained no asthma-specific content or tools.
Good Days San Diego	Android	Alain Domissy	0.9.3	Contained no asthma-specific content or tools.
Hay Fever, Allergy and Asthma	Android	eMobileWebsiteDesign	2	Contained no asthma-specific content or tools.
HealthLog	iOS	InnovaPath Solutions	2.1	Asthma app included in previous review that was subsequently withdrawn prior to the start of this review.
How to Control Asthma and Allergy	iOS	IndiaNIC Infocom Limited	1.1	Asthma app included in previous review that was subsequently withdrawn prior to the start of this review.
iMobile Care	iOS	Visionsync Inc	1.1	Asthma app included in previous review that was subsequently withdrawn prior to the start of this review.
Juicing Guide!	Android	bigo	1	Contained no asthma-specific content or tools.
Kyusho Health & Wellness	Android	Xavier Vila	1.0	Asthma app included in previous review that was subsequently withdrawn prior to the start of this review.
Learn To Inhale MDI	iOS	Saralsoft, llc	1	Contained no asthma-specific content or tools.
Medicinal Plants and Drugs	Android	Publish This, LLC	2	Contained no asthma-specific content or tools.
Miniatlas Asthma and Rhinitis	Android	Clyna S.A.	1	Targeted clinicians rather than patients.
My Asthma Log Pro	Android	Donal Morrissey	1.0.1	Asthma app included in previous review that was subsequently withdrawn prior to the start of this review.

App	Platform	Developer	Version	Reason for exclusion
My Mobile Guru	iOS	My Mobile Guru Limited	1.0	Asthma app included in previous review that was subsequently withdrawn prior to the start of this review.
Natural Cures & Remedies	Android	cwiggy	1.0	Asthma app included in previous review that was subsequently withdrawn prior to the start of this review.
Parsley Herb Guide	Android	AMobileAppsBuilder	2	Contained no asthma-specific content or tools.
Patient PFT Educational tool	Android	Liz Zampino	1	Contained no asthma-specific content or tools.
Plants For Medicine	Android	Pillar Apps	1	Contained no asthma-specific content or tools.
Pollen informations for Islamabad	Android	Rubiks Technologies	4	Contained no asthma-specific content or tools.
Pranayama	Android	Ram Niwas	1.0	Contained no asthma-specific content or tools.
Puffometer	iOS	Sublime Digital Limited	1.0	Asthma app included in previous review that was subsequently withdrawn prior to the start of this review.
Quick and Easy Yoga	Android	IndiaNIC Infocom Limited	1.0	Asthma app included in previous review that was subsequently withdrawn prior to the start of this review.
Quick Yoga Tips	iOS	Manvinder Singh	1.1	Contained no asthma-specific content or tools.
salt of the earth	Android	SMB Apps	1.0	Contained no asthma-specific content or tools.
Skyscape Medical Resources	iOS	Skyscape	1.18.25	Targeted clinicians rather than patients.
SmartinhalerLive	Android	Nexus6 Limited	0.4	Required login credentials not available to us.
Steroids Information Extreme	Android	applearningpurpose	1.1	Contained no asthma-specific content or tools.
The Complete Vitamins Guide	Android	Quality MRRs ltd.	1	Contained no asthma-specific content or tools.
Vinegar for your Health	Android	Figspops	1.2.2	Asthma app included in previous review that was subsequently withdrawn prior to the start of this review.
Warm Health	Android	Warm Health	1.5.3	Required login credentials not available to us.
Welcome to Homeopathy	Android	IndiaNIC Infocom Limited	1.0	Asthma app included in previous review that was subsequently withdrawn prior to the start of this review.

App	Platform	Developer	Version	Reason for exclusion
Workout and Exercise	Android	Figspops	2.0.3	Asthma app included in previous review that was subsequently withdrawn prior to the start of this review.
Yoga For Asthma Guide	Android	KRM Apps	2	Contained no asthma-specific content or tools.
Yoga for cure	Android	zingy minds	1	Contained no asthma-specific content or tools.
Yoga Made Easy	Android	Shreyas Marketing	1.2.16.836	Contained no asthma-specific content or tools.
Yoga-Depression-Laura Hawes	Android	i-Mobilize Inc	1	Contained no asthma-specific content or tools.
Yoga-Fertility-Laura Hawes	Android	i-Mobilize Inc	1	Contained no asthma-specific content or tools.

Appendix 9 Coverage of educational topic coverage by platform and payment model

The tables summarise the numbers of apps addressing each of 8 topics defined for asthma self-management education by platform and payment model. Each app was assessed as either addressing the domain wholly, partially or not at all, using defined sub-criteria which are described separately.

	By platform													
	Android-only (n=28)				iOS-only (n=20)						Multi-platform (n=11)			
Educational topic	No	Partially	Wholly	% †	No	Partially	Wholly	% †	P value ‡	(Threshold)	No	Partially	Wholly	% †
Basic facts about the nature of the condition	6	15	7	79%	4	14	2	80%	0.394	(0.010)	0	8	3	100%
Allergen and trigger avoidance	16	11	1	43%	12	7	1	40%	1.000	(0.050)	5	6	0	55%
The nature of treatment: relievers and preventers	15	10	3	46%	9	10	1	55%	0.609	(0.017)	4	5	2	64%
Recognising and responding appropriately to acute exacerbations	19	5	4	32%	17	3	0	15%	0.217	(0.007)	5	4	2	55%
How to use treatment	20	8	0	29%	11	8	1	45%	0.281	(0.008)	5	6	0	55%
Self-monitoring and assessment skills	17	10	1	39%	13	7	0	35%	1.000	(0.025)	6	3	2	45%
The role of a written, personalised action plan	24	0	4	14%	14	4	2	30%	0.055	(0.006)	8	2	1	27%
Personalising the definition of good asthma control	19	9	0	32%	16	4	0	20%	0.512	(0.013)	6	5	0	45%

† The proportion of information apps that wholly or partially address a given educational topic.

‡ Two-tailed probability obtained from the Freeman-Halton extension to Fisher's exact test of the comparison of topic coverage in Android- and iOS-only apps. After applying a Holm-Bonferroni correction to control the family-wise error rate at less than or equal to 5%, no comparisons achieved significance.

	By payment model									
	Free (n=35)				Paid (n=24)					
Educational topic	No	Partially	Wholly	% †	No	Partially	Wholly	% †	P value ‡	(Threshold)
Basic facts about the nature of the condition	7	21	7	80%	3	16	5	88%	0.866	(0.025)
Allergen and trigger avoidance	22	13	0	37%	11	11	2	54%	0.177	(0.006)
The nature of treatment: relievers and preventers	16	17	2	54%	12	8	4	50%	0.300	(0.008)
Recognising and responding appropriately to acute exacerbations	26	5	4	26%	15	7	2	38%	0.385	(0.010)
How to use treatment	21	14	0	40%	15	8	1	38%	0.563	(0.017)
Self-monitoring and assessment skills	22	11	2	37%	14	9	1	42%	0.903	(0.050)
The role of a written, personalised action plan	29	2	4	17%	17	4	3	29%	0.466	(0.013)
Personalising the definition of good asthma control	22	13	0	37%	19	5	0	21%	0.252	(0.007)

† The proportion of information apps that wholly or partially address a given educational topic.

‡ Two-tailed probability obtained from the Freeman-Halton extension to Fisher's exact test of the comparison of topic coverage in free and paid-for apps. After applying a Holm-Bonferroni correction to control the family-wise error rate at less than or equal to 5%, no comparisons achieved significance.

Appendix 10 Consistency of information apps with evidence by platform and payment model

The table compares the proportion of apps containing particular management advice that is consistent with evidence-based recommendations between 2011 and 2013 by platform and payment model. The expected advice is shown in parentheses. We use the term 'qualified benefit' when additional factors such as personal sensitivity to particular allergens or aspects of personal choice are relevant concerns and unconditional recommendations are therefore inappropriate. Apps focusing solely on CAM were excluded. Statistical comparison between apps in 2011 and new apps in 2013 was performed but is not shown because all comparisons, performed using Fisher's exact, yielded an exact probability of 1.0.

	By platform										
	Android-only (n=28)			iOS-only (n=20)					Multi-platform (n=11)		
Statement	n	Consistent	(%)†	n	Consistent	(%)†	P value ‡	(Threshold)	n	Consistent	(%)†
Removal of pets from the home (Unclear Benefit)	6	0	(0%)	0	0	(0%)	1.000	(0.013)	2	1	(50%)
Fungal allergen avoidance and control measures (Unclear Benefit)	9	0	(0%)	2	0	(0%)	1.000	(0.006)	2	0	(0%)
Cockroach avoidance and control measures (Unclear Benefit)	4	0	(0%)	1	0	(0%)	1.000	(0.007)	2	0	(0%)
Cessation of active smoking (Effective)	8	8	(100%)	5	5	(100%)	1.000	(0.008)	6	6	(100%)
Avoidance of passive smoking (Effective)	10	10	(100%)	6	6	(100%)	1.000	(0.010)	5	5	(100%)
Avoidance of exposure to air pollution (Unclear Benefit)	10	0	(0%)	5	1	(20%)	0.333	(0.006)	2	1	(50%)
Immunotherapy in atopic asthma (Effective)	4	4	(100%)	1	1	(100%)	1.000	(0.017)	0	0	(0%)
Weight reduction in obese patients (Effective)	3	3	(100%)	1	1	(100%)	1.000	(0.025)	3	3	(100%)
Seasonal influenza vaccination (Unclear Benefit) *	6	1	(17%)	2	0	(0%)	1.000	(0.050)	2	1	(50%)

N is the number of apps that took a stance on a given topic, for example by stating that a given action is definitely effective in controlling asthma symptoms.

† The proportion of apps whose stance is consistent with the evidence base.

‡ Two-tailed probability obtained from the Freeman-Halton extension to Fisher's exact test of the comparison of topic coverage in Android- and iOS-only apps. After applying a Holm-Bonferroni correction to control the family-wise error rate at less than or equal to 5%, no comparisons achieved significance.

* Seasonal influenza vaccination is routinely offered to asthmatic patients, however it is unclear if vaccination reduces the severity or frequency of flu-related asthma exacerbations[325].

	By payment model							
	Free (n=35)			Paid (n=29)				
Statement	n	Consistent	(%) †	n	Consistent	(%) †	P value ‡	(Threshold)
Removal of pets from the home (Unclear Benefit)	5	1	(20%)	3	0	(0%)	1.000	(0.050)
Fungal allergen avoidance and control measures (Unclear Benefit)	6	0	(0%)	7	0	(0%)	1.000	(0.006)
Cockroach avoidance and control measures (Unclear Benefit)	3	0	(0%)	4	0	(0%)	1.000	(0.007)
Cessation of active smoking (Effective)	13	13	(100%)	6	6	(100%)	1.000	(0.008)
Avoidance of passive smoking (Effective)	14	14	(100%)	7	7	(100%)	1.000	(0.010)
Avoidance of exposure to air pollution (Unclear Benefit)	10	1	(10%)	7	1	(14%)	1.000	(0.013)
Immunotherapy in atopic asthma (Effective)	3	3	(100%)	2	2	(100%)	1.000	(0.017)
Weight reduction in obese patients (Effective)	5	5	(100%)	2	2	(100%)	1.000	(0.025)
Seasonal influenza vaccination (Unclear Benefit)	6	2	(33%)	4	0	(0%)	0.467	(0.006)

N is the number of apps that took a stance on a given topic, for example by stating that a given action is definitely effective in controlling asthma symptoms.

† The proportion of apps whose stance is consistent with the evidence base.

‡ Two-tailed probability obtained from the Freeman-Halton extension to Fisher's exact test of the comparison of topic coverage in free and paid-for apps. After applying a Holm-Bonferroni correction to control the family-wise error rate at less than or equal to 5%, no comparisons achieved significance.

* Seasonal influenza vaccination is routinely offered to asthmatic patients, however it is unclear if vaccination reduces the severity or frequency of flu-related asthma exacerbations[325].

Appendix 11 Summary of ethical disclosures and software issues by platform and payment model.

The tables compare the proportion of apps satisfying best practices for content attribution and ethical disclosures (detailed in Table AF4), and those with software issues identified during testing (detailed with examples in Table AF5), between 2011 and 2013 by platform and payment model.

	By platform							
	Android-only (n=73)		iOS-only (n=57)				Multi-platform (n=17)	
Quality domain	n	(%)†	n	(%)†	P value ‡	(Threshold)	n	(%)†
HON compliance								
Attribution of authorship §	19	(31%)	14	(33%)	1.000	(0.050)	6	(35%)
Purpose clearly stated	71	(97%)	53	(93%)	0.404	(0.013)	17	(100%)
Privacy policy available	18	(25%)	16	(28%)	0.691	(0.025)	10	(59%)
Information versioning	3	(4%)	1	(2%)	0.631	(0.017)	0	(0%)
Contact details provided	32	(44%)	42	(74%)	<0.001*	(0.008)	16	(94%)
Funding model clear	9	(12%)	32	(56%)	<0.001*	(0.007)	8	(47%)
Editorial/advertising policy	5	(7%)	0	(0%)	0.067	(0.010)	0	(0%)
Software issues								
Data entry validation issues **	6	(30%)	7	(32%)	1.000	(0.050)	3	(43%)
Functionality issues	6	(8%)	8	(14%)	0.394	(0.008)	1	(6%)
User interface issues	25	(34%)	17	(30%)	0.849	(0.025)	4	(24%)
Crashes	8	(11%)	4	(7%)	0.549	(0.013)	1	(6%)
Network issues	11	(15%)	10	(18%)	0.811	(0.017)	4	(24%)
Other issues	11	(15%)	12	(21%)	0.488	(0.010)	5	(29%)

† The proportion of information apps that satisfy a particular domain. Unless otherwise stated, the denominator is the total number of apps shown in the relevant heading.

‡ Two-tailed probability obtained from Fisher's exact test of the comparison of topic coverage in apps available in Android- and iOS-only apps. After applying a Holm-Bonferroni correction to control the family-wise error rate within each domain at less than or equal to 5%, two comparisons were significant. These are indicated with asterisks (*).

§ Denominator for proportions reflects only apps with attributable content, e.g. written information, measurement scales, pollen/pollution data. (Attribution of the software itself lies with the developers whose details are always released).

** Data entry validation concerns steps taken to prevent out-of-range or inappropriate data being stored in an app, for example, textual values allowed in a numeric field. As a result, the denominator reflects only apps permitting data entry, e.g. calculators, diaries.

	By payment model					
	Free (n=80)		Paid (n=67)			
Quality domain	n	(%)†	n	(%)†	P value ‡	(Threshold)
HON compliance						
Attribution of authorship §	27	(39%)	12	(24%)	0.115	(0.010)
Purpose clearly stated	75	(94%)	66	(99%)	0.220	(0.013)
Privacy policy available	33	(41%)	11	(16%)	0.001*	(0.007)
Information versioning	3	(4%)	1	(1%)	0.626	(0.017)
Contact details provided	48	(60%)	42	(63%)	0.865	(0.025)
Funding model clear	27	(34%)	22	(33%)	1.000	(0.050)
Editorial/advertising policy	5	(6%)	0	(0%)	0.063	(0.008)
Software issues						
Data entry validation issues **	10	(42%)	6	(24%)	0.232	(0.017)
Functionality issues	8	(10%)	7	(10%)	1.000	(0.050)
User interface issues	23	(29%)	23	(34%)	0.377	(0.025)
Crashes	10	(13%)	3	(4%)	0.143	(0.013)
Network issues	18	(23%)	7	(10%)	0.077	(0.008)
Other issues	19	(24%)	9	(13%)	0.141	(0.010)

† The proportion of information apps that satisfy a particular domain. Unless otherwise stated, the denominator is the total number of apps shown in the relevant heading.

‡ Two-tailed probability obtained from Fisher's exact test of the comparison of topic coverage in apps available in free and paid apps. After applying a Holm-Bonferroni correction to control the family-wise error rate within each domain at less than or equal to 5%, one comparison was significant. This is indicated with an asterisk (*).

§ Denominator for proportions reflects only apps with attributable content, e.g. written information, measurement scales, pollen/pollution data. (Attribution of the software itself lies with the developers whose details are always released).

** Data entry validation concerns steps taken to prevent out-of-range or inappropriate data being stored in an app, for example, textual values allowed in a numeric field. As a result, the denominator reflects only apps permitting data entry, e.g. calculators, diaries.

Appendix 12 Insulin dose calculator test case generation procedures

A set of test cases was created for each app where the calculation formula had been identified. Test cases were generated using the following procedure:

1. The full set of input parameters required for calculation were identified through inspection of the formula.

2. For each numeric-valued input parameter:
    a. Physiological minimum, typical and maximum values were established using a lookup table (Table A11-1). This table was pre-populated based on an informal literature review and clinical expertise. Values were selected based on the unit system supported by the app. If the app supported multiple unit systems, values were selected separately for each.
    b. Numeric parameter values were then modified by adding a small amount of random noise. Noise was added conservatively such that the adjusted values did not exceed the range defined by the original lookup values.
    c. The precision of the resulting values was amended by rounding to the maximum precision supported by the app. In the case where an app allowed the user to customize the precision of input values, values were rounded to 2 decimal places.

3. For binary and categorical parameters (e.g. exercise level) the range of possible values was defined by simply copying the full set of states supported by the app (e.g. none/some/moderate/intensive).

4. For those parameters that were optional for calculation, a 'null' value was added to the list of possible values to represent the case when that value was missing. For example, a blood glucose measurement might be reasonably omitted from calculation if a patient has not performed a recent test.

5. In the case where certain parameters could have different values depending on the time of day (for example, insulin sensitivity) we repeated steps 2-4 for each supported time period (e.g. morning/ afternoon/evening). In the case where the user could define their own time

periods, we used a minimum of three randomly-constituted time periods spanning a complete 24 hour period.

6. Considering each supported unit system separately, the set of possible values for each parameter were then permuted against each other to generate an exhaustive set of test cases applicable at a particular point in time.

7. For each test case, an expected output was generated by feeding the selected parameter values into the formula. Outputs were rounded to the maximum precision supported by the app.

8. The set of test cases, each consisting a set of input values and an expected output for a particular unit system and time of day (if supported), were written out into a standard form in preparation for testing.

Evaluation proceeded by stepping through each test case. For each, the app was first configured by selecting the appropriate unit system and, if required, setting the time. The pre-specified values were then entered manually into the calculator. The calculation was then triggered and the output compared to the expected value to identify any discrepancies in formula implementation.

Table A11-1 **Typical and maximum value lookup table for calculation input parameters**

Description	Units	Minimum	Typical	Maximum
Measured blood glucose	mmol/L	1.0	5.6	19.4
	mg/dL	18.0	100	350
Blood glucose reduction per unit of insulin (Insulin sensitivity)	mmol/L/IU	0.1	2.0	16.7
	mg/dL/IU	1.8	36	300
Insulin required per unit change in blood glucose	IU/mmol/L	0.1	1.0	9.0
	IU/mg/dL	0.01	0.06	0.5
Carbohydrate	grams	0.0	130	900
	carbs	0.0	13.0	90.0
	10g portions	0.0	13.0	90.0
	12g portions (bread units)	0.0	10.8	75.0
	15g portions (exchanges)	0.0	8.7	60.0
Carbohydrate intake offset by one unit of insulin (carbohydrate factor)	grams/IU	1.0	8.0	300.0
	carbs/IU	0.1	0.8	30.0
	10g portions/IU	0.1	0.8	30.0
	12g portions (bread units)/IU	0.1	0.7	25.0
	15g portions (exchanges)/IU	0.1	0.5	20.0
Insulin required per unit of carbohydrate	IU/grams	0.01	0.1	1.0
	IU/carbs	0.1	1.0	10.0
	IU/10g portions	0.1	1.0	10.0
	IU/12g portions (bread units)	0.1	1.2	12.0
	IU/15g portions (exchanges)	0.1	1.5	15.0

Appendix 13 Characteristics of excluded diabetes apps

The table below provides details of diabetes apps that were excluded after download and review and the reasons for exclusion.

App name	Platform	Version	Developer	Description	Reason for exclusion †
BG Monitor Diabetes (Donate)	Android	2.0	Gordon Wong	Diabetes diary with insulin dose suggestion.	Duplicate
Diabetes Personal Calculator	iOS	1.2	iTenuto Soft	Insulin dose calculator. Lite version.	Duplicate
DiaLog: Diabetes Logbook Demo	Android	1.2.3	David Froehlich	Diabetes diary with suggested insulin dose calculator.	Duplicate
GliControl (Demo)	Android	4.5.0	softbycloud.com	Diabetes diary with separate meal dose insulin calculator. Demo version.	Duplicate
Glucool Diabetes	Android	1.4.3.1	3qubits	Diabetes diary with separate insulin calculator. Light version.	Duplicate
Glucose Companion Free	iOS	2.3	Maxwell Software	Diabetes diary with separate insulin calculator. Free version.	Duplicate
Infusion Calculator	Android	1.4	CityJams	Collection of calculators including questionnaire-style insulin dose calculator. Standalone version.	Duplicate
Insulin Dose Advisor ControlWizard	iOS	2.61	Piet van der Wal	Meal bolus calculator. Previous version of app including in testing.	Duplicate
mDiab Lite	Android	1.0	INFOKOM Informations- und Kommunikationsgesellschaft mbH	Diabetes diary with separate insulin calculator. Lite version.	Duplicate
mDiab Lite	iOS	1.1	INFOKOM Informations- und Kommunikationsgesellschaft mbH	Diabetes diary with separate insulin calculator. Lite version.	Duplicate
Glucosurfer	Android	2.6	Glucosurfer.org	Diabetes diary. No insulin calculator.	No calculator
Your Personal Health	Android	1.0.0	Darren Gates	Medical triage assessment questionnaires. No calculators.	No calculator

App name	Platform	Version	Developer	Description	Reason for exclusion †
B. Braun SGC Tutorial	iOS	2.0	B. Braun Melsungen AG	Tutorial for clinical insulin infusion system. No functional insulin calculator. Targeted at clinicians.	No calculator
Drips and Pumps	Android	2.0	CocoLabz	Collection of infusion rate calculators including insulin. Targeted at clinicians.	Other calculation
Hospital Diabetes	Android	1.4	David Carmody	Information about diabetes management with unit conversion calculators. Targeted at clinicians.	Other calculation
IV Drip Rate Professional	Android	1.0	geekpro	Collection of infusion rate calculators including insulin.	Other calculation
IV Drips	Android	3.1	Jonsap	Collection of infusion rate calculators including insulin.	Other calculation
Med Tools	Android	1.0	Darren Gates	Collection of medical calculators. No insulin calculator. Targeted at clinicians.	Other calculation
MedCalc 3000 Complete	Android	13.3.1	Foundation Internet Services	Collection of management algorithms and medical calculators including insulin resistance calculator. Targeted at clinicians.	Other calculation
MEDGuide Emergency	Android	1.6	JUAN C.L.C.	Emergency management algorithms including insulin infusion preparation calculator. Targeted at clinicians.	Other calculation
Medi Converter	Android	1.2	CocoLabz	Collection of unit conversion calculators. No insulin calculator. Targeted at clinicians.	Other calculation
Medical Calculators	Android	1.0	Darren Gates	Collection of medical calculators. No insulin calculator. Targeted at clinicians.	Other calculation
MedicCalc Paramedic Calculator	Android	1.1	LINC Mobile Applications	Collection of medical calculators. No insulin calculator. Targeted at clinicians.	Other calculation

App name	Platform	Version	Developer	Description	Reason for exclusion †
Nurse's Toolbox	Android	1.0.1	Medical Wizards, LLC	Collection of management algorithms and medical calculators including pediatric insulin infusion calculator. Targeted at clinicians.	Other calculation
OmniMedix Medical Calculator	Android	3.0	Omnimedic Solutions	Collection of medical calculators. No insulin calculation. Targeted at clinicians.	Other calculation
Paramedic Meds	Android	3.1	Jonsap	Collection of medical calculators including insulin infusion preparation calculator.	Other calculation
Daily Carb - Carbohydrate, Glucose, Medication, Blood Pressure and Exercise Tracker	iOS	1.7	Maxwell Software	Food and weight diary with BMI calculator.	Other calculation
Hypo	iOS	1.1	Philippe Mougin	Glucose to offset hypoglycemia calculator.	Other calculation
MedCalc 3000 Endocrine	iOS	9.1	Foundation Internet Services, LLC	Collection of management algorithms and medical calculators including insulin resistance calculator. Targeted at clinicians.	Other calculation
Skyscape Medical Resources	iOS	1.18.25	Skyscape	Medical information including medical calculators. No insulin calculation. Targeted at clinicians.	Other calculation
BS3 Basic Tools Pack	Android	1.0	ABCGO s.r.l.	Collection of calculators including insulin required to offset glucose bolus calculator. Targeted at clinicians.	Other insulin calculation
DiAppBetes	Android	1.0	Horizon Strategic Partners Ltd	Insulin prescribing and hypoglycemia management information. Includes insulin initiation and total dose adjustment calculators. Targeted at clinicians.	Other insulin calculation
Insulin Quantity Calculator	Android	1.1	DunnRight Software	Insulin consumption calculator.	Other insulin calculation

App name	Platform	Version	Developer	Description	Reason for exclusion †
Insulin Therapy	Android	1.0	Prestaciones Médicas RCCC	Insulin initiation and dose adjustment calculators.	Other insulin calculation
Smart e-SMBG - Diabetes	Android	1.1.1	ARKRAY, Inc.	Diabetes diary with carbohydrate:insulin and insulin sensitivity calculators.	Other insulin calculation
BasalCalc	iOS	1.1.0	Guilherme de Paula	Insulin pump initiation basal rate calculator.	Other insulin calculation
BG to Insulin (Correction) Factor Calculator	iOS	1.1.0	Guilherme de Paula	Insulin sensitivity calculator.	Other insulin calculation
Diabetes Carb/Ins RatioWizard PRO	iOS	1.2	Piet van der Wal	Carbohydrate:insulin ratio calculator.	Other insulin calculation
Diagnosis and Management of Gestational Diabetes	iOS	1.1	Greggory DeVore	Information about management of gestational diabetes. Includes insulin initiation calculator. Targeted at clinicians.	Other insulin calculation
DiAppBetes	iOS	1.1	Horizon Strategic Partners Ltd	Insulin prescribing and hypoglycaemia management information. Includes insulin initiation and total dose adjustment calculators. Targeted at clinicians.	Other insulin calculation
EZ Insulin Calculator	iOS	1.02	Crystal Clear Solutions	Insulin pump initiation basal rate calculator.	Other insulin calculation
Glucontrol	iOS	1.01	hans-peter van leeuwen	Insulin infusion rate adjustment calculator. Targeted at clinicians.	Other insulin calculation
Insulin Dosing Algorithm	iOS	1.6	Austin Physician Productivity, LLC	Insulin initiation and dose adjustment calculators.	Other insulin calculation
Insulin TDD and BMI Calculator	iOS	1.1.0	Guilherme de Paula	Insulin total dose and BMI calculators.	Other insulin calculation
Insulin To Carb (I:C) Ratio Calculator	iOS	1.1.0	Guilherme de Paula	Insulin:carbohydrate ratio calculator.	Other insulin calculation
Insulin-On-Board (IOB) Calculator	iOS	1.0.0	Guilherme de Paula	Insulin on board calculator.	Other insulin calculation
SugarPal Diabetes Manager	iOS	1.0	L F Tiemeijer	Basal dose calculator.	Other insulin calculation

App name	Platform	Version	Developer	Description	Reason for exclusion †
NutriPlus-Sweet Control	Android	2.8	ReFleX Wireless	Diabetes diary with insulin calculator. Requires device to use.	Requires device

† Reasons for exclusion: Other insulin calculation = the app performed some calculation relating to insulin administration other than rapid acting insulin dosing, for example calculating the amount of insulin to add to an intravenous infusion set. Other calculation = the app performed one or more calculations but they were unrelated to insulin.

Appendix 14 Insulin dose calculator app characteristics detail

App ID †	App Name	Version	Developer	Region (Country)	iOS	Android	App Type
5194	BG Monitor Diabetes	6.2	Gordon Wong	North America (USA)	No	Yes	Diary with Suggested Dose
1140	Bolus	1.0	Krunoslav Djakovic	Europe (Serbia)	Yes	Yes	Standalone Calculator
1086	BolusCalc	1.0.0	Guilherme de Paula	North America (USA)	Yes	No	Standalone Calculator
4037	D Sharp Diabetes	1.0	D Sharp Diabetes	North America (Canada)	No	Yes	Diary with Suggested Dose
5309	D.O.T. Beta (Insulin Calc)	1.2.1	VoidFlinger	North America (USA)	No	Yes	Standalone Calculator
1223	DAFNE Online	1.6.2	Simon Fisher	Europe (UK)	Yes	No	Diary with Suggested Dose
949	Diabetes 360 Lite	1.6.4	Joseph DiMaggio	North America (USA)	Yes	No	Diary with Suggested Dose
1023	Diabetes Manager	1.3	iTenuto Soft	North America (USA)	Yes	No	Calculator with Log
5310	Diabetes Tracker	1.34	Daniel Development	Australasia (Indonesia)	No	Yes	Diary with Suggested Dose
4465	Diabetic Dosage Calculator	1.1	Kalianne Neumann	North America (USA)	Yes	Yes	Standalone Calculator
5468	DIABETooL Insulin Calc	1.3.9.1	Hornetbzz	Europe (France)	No	Yes	Calculator with Log
5269	DiaLog: Diabetes Logbook	1.2.3	David Froehlich	Europe (Germany)	No	Yes	Diary with Suggested Dose
1041	Diamedic	3.1.1	Nicholas Martin	North America (USA)	Yes	No	Diary with Separate Calculator
1205	DM Diary	1.7	Ingemar Jacob	Europe (Germany)	Yes	No	Calculator with Log
1120	GliControl	4.2	Hugo Ferreira	Europe (Portugal)	Yes	Yes	Diary with Separate Calculator
4608	Glucool Diabetes Premium	1.4.3.1	3qubits	Europe (France)	No	Yes	Diary with Separate Calculator
1045	Glucose Companion	2.3	Maxwell Software	Asia (China)	Yes	No	Diary with Separate Calculator
4175	Glucose Meter	1.6.3	Francisco J Belchi	Europe (UK)	No	Yes	Diary with Separate Calculator
1005	HelpDiabetes	2.0.5	Johan Degraeve	Europe (Netherlands)	Yes	Yes	Diary with Suggested Dose

App ID †	App Name	Version	Developer	Region (Country)	iOS	Android	App Type
975	iBolusCalc - Diabetes Blood Glucose Helper	1.12	effective delivery, inc.	North America (USA)	Yes	No	Standalone Calculator
1097	iCare-D	1.0.3	Pyeonghwa Uhealth Co. Ltd.	Asia (Korea)	Yes	Yes	Diary with Separate Calculator
5543	Insulin Bolus Calculator	1.3	Felix Software Company Limited	Asia (Hong Kong)	No	Yes	Calculator with Log
1047	Insulin Calc	1.0	Maxwell Software	Asia (China)	Yes	No	Standalone Calculator
1017	Insulin Calculator	1.0	Jagdeep Nagpal	Europe (UK)	Yes	Yes	Standalone Calculator
987	Insulin Calculator	1.3.2	Chris Bowley	Europe (UK)	Yes	No	Standalone Calculator
1099	Insulin Dose Advisor ControlWizard-2	3.1	Knowledge is Power Solutions	Europe (Netherlands)	Yes	Yes	Diary with Suggested Dose
3908	Insulin Dose Calculator	1.0	CityJams	North America (USA)	No	Yes	Standalone Calculator
1123	Insulin Dose Calculator Pro	1.2	STRUCTIVA	Europe (Sweden)	Yes	No	Standalone Calculator
3538	Insulin Unit Calculator	2.0	Jason Timm	North America (USA)	No	Yes	Standalone Calculator
1193	Insulin Units	1.2	Kenneth Wallace	North America (USA)	Yes	No	Standalone Calculator
1177	InsulinPlus	1.0.2	SquareMed Software GmbH	Europe (Germany)	Yes	No	Standalone Calculator
1015	mDiab	1.1	INFOKOM Informations- und Kommunikationsgesellschaft mbH	Europe (Germany)	Yes	Yes	Diary with Separate Calculator
4666	My Diabetes	1.3.4	Rossen Varbanov	Europe (Bulgaria)	No	Yes	Diary with Separate Calculator
1175	myBolus	2.1.0	Christian Schurk	Europe (Germany)	Yes	No	Standalone Calculator
1179	Pumps4kids	1.2	Debbie McCann	Australasia (Australia)	Yes	Yes	Information and Separate Calculator
990	RapidCalc Diabetes Manager	1.4.1	Gilport Enterprises Pty Ltd	Australasia (Australia)	Yes	No	Calculator with Log
941	Track3 - Diabetes Planner, Logbook and Carb Counter (SI version)	4.5	Coheso, Inc	North America (USA)	Yes	No	Diary with Separate Calculator

† A unique ID assigned to the app for the study, can be used to reconcile apps between Appendix 15 and Appendix 16.

Appendix 15 Insulin dose calculator app formula details

See Appendix Table 15 for details of each app corresponding to App IDs listed below.

	Inputs						Outputs			
App ID	**Method**	**Glucose Units**	**Glucose Adjustment Factor [a]**	**Carb Units**	**Carb Adjustment Factor [b]**	**Additional Inputs**	**Meal Bolus [c]**	**Correction Bolus [d]**	**Corrected Meal Bolus [e]**	**IOB Compensation [f]**
941	Manual	mmol/L	BG:I	grams	I:C	*	Yes	Yes (±)	Yes	No
949	Manual	mg/dL, mmol/L	BG:I	Carbs	I:C	*	Yes	Yes (±)	Yes	No
975	Manual	mg/dL	BG:I	Carbs	I:C	Activity Levels	Yes	Yes (±)	Yes	Yes
987	Manual	mg/dL, mmol/L	I:BG	grams	I:C	*	Yes	Yes (±)	Yes	No
990	Manual	mg/dL, mmol/L	BG:I	grams, 10g portions, 12g portions (bread units), 15g portions	Fixed	Activity Levels	Yes	Yes (±)	Yes	Yes
1005	Manual	*	*	grams	I:C	*	No	Yes (+)	No	No
1015	Manual	*	*	12g portions	Fixed	*	No	Yes (+)	No	No
1017	Manual	mmol/L	I:BG	grams	Fixed	*	Yes	Yes (±)	Yes	No
1023	Manual	mg/dL, mmol/L	BG:I	Carbs	I:C	*	Yes	Yes (±)	Yes	No
1041	Manual	mg/dL, mmol/L	BG:I	grams	I:C	*	Yes	Yes (+)	Yes	No
1045	Manual	mg/dL, mmol/L	BG:I	grams	I:C	*	Yes	Yes (±)	Yes	No
1047	Manual	mg/dL, mmol/L	BG:I	grams	I:C	*	Yes	Yes (±)	Yes	No

	Inputs						Outputs			
App ID	**Method**	**Glucose Units**	**Glucose Adjustment Factor [a]**	**Carb Units**	**Carb Adjustment Factor [b]**	**Additional Inputs**	**Meal Bolus [c]**	**Correction Bolus [d]**	**Corrected Meal Bolus [e]**	**IOB Compensation [f]**
1086	Manual	mg/dL	I:BG	grams	I:C	Activity Levels	Yes	Yes (±)	Yes	Yes
1097	Manual	mg/dL, mmol/L	I:BG	grams	I:C	*	Yes	Yes (±)	Yes	No
1099	Manual, Learned[g]	*	*	Carbs	I:C	*	No	Yes (+)	No	No
1120	Manual	*	*	grams	I:C	*	No	Yes (+)	No	No
1123	Manual	mg/dL, mmol/L	BG:I	grams, exchange units	I:C	Activity Levels	Yes	Yes (±)	Yes	Yes
1140	Manual	(Unit Agnostic)	BG:I	grams	I:C	Ketones Present	Yes	Yes (±)	Yes	No
1175	Manual	mg/dL, mmol/L	I:BG	BU (user customizable grams/BU)	Fixed	*	Yes	Yes (±)	Yes	No
1177	Manual	mg/dL, mmol/L	BG:I	BE, KE, portions	I:C	*	Yes	Yes (±)	Yes	No
1179	Manual	mg/dL, mmol/L	BG:I	(Unit Agnostic)	I:C	*	Yes	Yes (±)	Yes	No
1193	Manual	mg/dL	BG:I	grams	I:C	*	Yes	Yes (+)	Yes	No
1205	Manual	mg/dL, mmol/L	BG:I	KE, BE, KH	Fixed	*	Yes	Yes (+)	Yes	No
1223	Manual	mmol/L	BG:I	CP	Flexible	Activity Levels	Yes	Yes (±)	No	Yes
3538	Manual	mg/dL	BG:I	grams	I:C	*	Yes	Yes (±)	Yes	No
3908	Manual	(Unit Agnostic)	I:BG	grams	I:C	Activity Levels	Yes	Yes (±)	Yes	Yes
4037	Manual	mg/dL, mmol/L	I:BG	grams	I:C	*	Yes	Yes (±)	Yes	No

	Inputs						Outputs			
App ID	**Method**	**Glucose Units**	**Glucose Adjustment Factor [a]**	**Carb Units**	**Carb Adjustment Factor [b]**	**Additional Inputs**	**Meal Bolus [c]**	**Correction Bolus [d]**	**Corrected Meal Bolus [e]**	**IOB Compensation [f]**
4175	Manual, Bluetooth [h]	mg/dL, mmol/L	BG:I	Carbs	I:C	Activity Levels	Yes	Yes (±)	Yes	Yes
4465	Manual	mg/dL, mmol/L	BG:I	(Unit Agnostic)	Fixed	*	Yes	Yes (±)	Yes	No
4608	Manual	mg/dL, mmol/L	BG:I	Carbs	I:C	Activity Levels	Yes	Yes (±)	Yes	Yes
4666	Manual	mg/dL, mmol/L	BG:I	grams	I:C	*	Yes	Yes (±)	Yes	No
5194	Manual	mg/dL, mmol/L	BG:I	grams	I:C	*	Yes	Yes (+)	Yes	No
5269	Manual	mg/dL, mmol/L	BG:I	10g portions, 12g portions (bread units)	Fixed	Activity Levels	Yes	Yes (±)	Yes	No
5309	Manual	(Unit Agnostic)	BG:I	Carbs	Flexible	*	Yes	Yes (+)	Yes	No
5310	Manual	(Unit Agnostic)	BG:I	Carbs	Fixed	*	Yes	Yes (+)	Yes	No
5468	Manual	mg/dL, mmol/L	BG:I	grams	C:I	Lipid Intake, Activity Levels	Yes	Yes (±)	Yes	Yes
5543	Manual	mg/dL, mmol/L	BG:I	grams, 15g portions (exchanges)	I:C	*	Yes	Yes (+)	Yes	No

Abbreviations: Carb = carbohydrate

a BG:I = blood glucose to insulin ratio (Insulin sensitivity), I:BG = blood glucose to insulin ratio.

b C:I = Carbohydrate to insulin ratio (Carbohydrate factor), I:C = insulin to carbohydrate ratio.

c Meal Bolus = Dose of rapid acting insulin calculated to offset planned or actual carbohydrate intake.

d Correction Bolus = Dose of rapid acting insulin calculated to offset difference in measured and target blood glucose. Symbol in parentheses indicates if correction boluses only calculated when blood glucose exceeds target value (+) or if negative values are also allowed (±). A negative correction bolus arises when blood glucose is below target value and indicates that any meal bolus should be reduced accordingly.

e Corrected Meal Bolus = The total dose calculated as the sum of meal and correction boluses.

f IOB = Insulin on Board, If Yes indicates that the app adjusts any dose according to insulin that has previously been administered but not yet fully metabolized.

g This app learned carbohydrate adjustment factor using 2-hour post-meal glucose measurements to measure the response to administered insulin.

h This app supported automatic transfer of glucose readings from a Bluetooth-enabled glucose meter.

Appendix 16 Interview study participant recruitment adverts

Advert for print media



Advert for online forums and email

Title

Do you use a smartphone or tablet app for your asthma or diabetes?

Body

Hi *or* Dear *X*,

Do you use a smartphone or tablet app to help with your diabetes? If so, we like to hear from you.

I'm writing on behalf of a research group based at Imperial College looking at how and why people with long-term conditions use mobile apps. By understanding this better, we hope to be able to advise clinicians about how apps can fit safely into routine care. By understanding what features people use and value, and why, we also hope to be able to drive the design of better apps in the future.

If you're currently using an app for diabetes then your experience – good or bad – would be extremely useful. Taking part would involve a one-off face-to-face discussion with a researcher to

hear your story, and a short follow-up telephone call about six months later to see if you're still using an app.

If you would like to find out more please visit the study website at www.healthapps.org.uk. If you have any questions, please don't hesitate to get in touch.

Best wishes,

Kit Huckvale

Facebook advert

Do you use a smartphone or tablet app for your asthma or diabetes?

Would you be prepared to talk to a researcher about your experiences?

If so, we'd love to hear from you.

Find out more: http://www.healthapps.org.uk

Google AdWords advert (asthma)

Do you use an asthma app? - If so we'd like to hear from you.

www.healthapps.org.uk

Take part in our research study.

Google AdWords advert (diabetes)

Using a diabetes app? - If so we'd like to hear from you.

www.healthapps.org.uk

Take part in our research study.

Twitter advert (asthma)

Do you help manage your #asthma with a smartphone/tablet app? Some of our researchers would love to hear from you: http://www.healthapps.org.uk

Twitter advert (diabetes)

Do you help manage your #diabetes with a smartphone/tablet app? Some of our researchers would love to hear from you: http://www.healthapps.org.uk

Appendix 17 Interview study participant information sheet

Title of study

How and why do people with long term conditions choose to use a smartphone or tablet app for their condition? A qualitative interview study.

This is information sheet version 1.5, produced on 01/06/2013.

What is the purpose of this study?

The study aims to find out why people with asthma, type 1 or type 2 diabetes would choose to use an app to help manage their condition. Apps have been around for about five years now and we know that people are using them, but very little is known about the experience of this for people with long term conditions like asthma and diabetes. Understanding what people with these conditions want their apps to do, how they use them and any problems they encounter will help design better apps in the future, and guide clinical staff about how best to support people with long term conditions who want to use an app.

What does taking part involve?

If you are eligible to take part, we will contact you by telephone to find out a bit more about your asthma or diabetes, and how you use smartphones or tablet computer. This will take about ten minutes.

We will then arrange a convenient time for a researcher to meet you to talk with you about how you use your smartphone app to help your asthma or diabetes. The interview will involve going through the app on your smartphone or tablet to show the researcher how you use it. We'll also ask you about your asthma or diabetes more generally to understand how the app fits into your condition as whole. This will take about an hour and a half and can be at a time and place that is convenient for you. We will take an audio recording of the interview.

Finally, we'll follow up with a short telephone call about four-six months later to see if anything has changed with how you use the app. We expect this will take up to twenty minutes.

Are there any benefits for taking part?

Taking part won't affect the care you receive in any way. Because we're not involved in your medical care, we can't give you specific advice about how to manage your condition. However, you might find that talking through aspects of your asthma or diabetes in detail is helpful to you.

Your input will help other people with asthma or diabetes in the future by helping us understand how to build better apps for these conditions and provide advice about how to choose the right app.

We will cover any travel costs that you incur. To say thank you for taking part, we are offering all participants a £10 Google Play Gift Card or iTunes Voucher.

Can I take part?

We are looking for people who are currently using an app on either a smartphone or tablet computer to help manage either asthma, type 1 or type 2 diabetes.

If so, we'd like to hear from you. To make sure you are eligible there is a short online questionnaire to complete, please visit http://www.healthapps.org.uk

What if I change my mind about taking part?

You can change your mind about taking part at any time and you don't have to give a reason.

Is the research confidential?

Yes. When we talk with you we'll be focussing on your asthma or diabetes and how you use the app. Everything you say to us will be treated in strict confidence. If you don't want to talk about a particular topic then we will always respect this.

We follow strict rules about keeping the information you give us private and this includes removing information that can identify you when we analyse the results.

Does the study have ethics approval?

Yes, the study has been approved by the Imperial College Research Ethics Committee (Approval Number ICREC_13_3_4)

Who is running the study?

The study is being run by researchers in the Global eHealth Unit at Imperial College London. The principal investigator is Josip Car (020 7594 0799 josip.car@imperial.ac.ukmailto:c.huckvale@imperial.ac.uk)

What if I have any questions about this study?

Please contact Kit Huckvale (020 7594 7016 c.huckvale@imperial.ac.uk

Appendix 18 Interview study consent form

Imperial College London

Department of Primary Care and Public Health
Imperial College London

Room 320, Reynold's Building
St Dunstan's Road
London W6 8RP
Tel: +44 (0)20 7594 0799

Study Protocol Number: 1.5 / ICREC_13_3_4

Informed Consent Form (Version 1.5, 01/06/2013)

Full Title of Project: **How and why do people with long term conditions choose to use a smartphone or tablet app for their condition? A qualitative interview study.**

Name of Principal Investigator: **Dr Josip Car** (josip.car@imperial.ac.uk)

Please initial box

1. I confirm that I have read and understand the subject information sheet dated 01/06/2013 version 1.5 for the above study and have had the opportunity to ask questions which have been answered fully. ☐

2. I understand that my participation is voluntary and I am free to withdraw at any time, without giving any reason, without my medical care or legal rights being affected. ☐

3. I give permission for an audio recording of my spoken responses to questions asked as part of the study. ☐

4. I agree to take part in the above study. ☐

Name of Subject	Signature	Date
Name of Person taking consent (if different from Principal Investigator)	Signature	Date
Principal Investigator	Signature	Date

1 copy for subject; 1 copy for Principal Investigator

Appendix 19 Interview study survey question schedule

The online questionnaire is divided into a series of sections. After completion of each section responses are validated. If an individual appears not to be eligible to take part on the basis of their responses (those that are underlined below) they are directed to a thank you screen and no further responses are collected. Responses from those are not eligible will be discarded.

Section 1 – Basic eligibility criteria

Thank you very much for considering taking part in this research study being run by researchers from Imperial College London.

This confidential questionnaire will help you decide if you are eligible to take part in this study. There are eleven questions and it shouldn't take more than 3-5 minutes to complete.

Question 1

How old are you?

Under 18, 18-34, 35-49, 50-64, 65 or older

Question 2

What is your gender?

Male, Female

Question 3

What is your ethnicity?

White (White British, Irish, Any Other White Background), Asian (Asian, Asian British, Chinese), Black (Black African, Caribbean, Black British), Other, Mixed (Mixed or Multiple Ethnic groups), Rather not say

Question 4

What is the highest level of education you have received?

GCSE, NVQ, Scottish Highers, A-Levels or equivalent, Undergraduate Degree, Postgraduate Degree, Rather not say

Question 5

Where do you currently live?

England, Wales, Scotland, Somewhere else

Question 6

Do you own a smartphone or tablet computer?

Smartphone, Table Computer, <u>No</u>

Skip to End Screen A if any underlined responses in Questions 1-6 are given, otherwise continue to Section 2

Section 2

Question 7a

Have you been told by a doctor that you have asthma?

Yes, No

Question 7b

Have you been told by a doctor that you have diabetes?

Yes, No

Skip to End Screen A if responses to Questions 7a and 7b are both No. Skip to Section 4 is response to Question 7a is No. Otherwise continue to Section 3.

Section 3

Displayed only if response to Question 7a is Yes

Question 8

In the last month have you had difficulty sleeping due to your asthma (including cough symptoms)?

Yes, No

Question 9

In the last month, have you had your usual asthma symptoms (e.g. cough, wheeze, chest tightness, shortness of breath) during the day?

Yes, No

Question 10

In the last month, has your asthma interfered with your usual daily activities (e.g. school, work, housework)?

Yes, No

Question 11

Do you currently use one or more apps to help you manage your asthma?

Yes, No

If response to Question 7b is No and response to Question 11 is No skip to End Screen A, if response to Question 7b is No and response to Question 11 is Yes then skip to End Screen B, otherwise continue to Section 4

Section 4

Displayed only if response to Question 7b is Yes

Question 12

What type of diabetes have you been diagnosed with?

Type 1 Diabetes, Type 2 Diabetes

Question 13

Do you use insulin to help you manage your diabetes?

Yes, No

Question 14

Has your diabetes caused you any problems with your feet, kidneys or eyesight?

Yes, No

Question 15

Do you currently use one or more apps to help you manage your diabetes?

Yes, No

If responses to Question 15 and Question 7a are both No (or not given) then continue to End Screen A otherwise skip to End Screen B.

End Screen A – Not Eligible

Unfortunately it looks like you are not eligible to take part in this research study.

At this stage, we're looking for adults living in England, Wales or Scotland with a clinical diagnosis of asthma, type 1 or type 2 diabetes who are currently using one or more apps to help manage their condition.

In the future, we plan to extend our study to understand the perspectives of people who would consider using an app (but aren't necessarily yet doing so).

End Screen B – Likely Eligible, Consent for Contact

Your responses suggest you are eligible to take part in this study.

The next step is to arrange to speak to Kit, the researcher who is leading this project, who can tell you a bit more about what taking part will involve.

So we can contact you, please fill in the details below. By filling in your details and pressing Done you give us permission to get in touch with you.

We won't use your details for anything else.

Question 16

Name

Question 17

Contact Telephone or Email

Question 18

Preferred Time to Call

Appendix 20 Interview study ethics approvals

Imperial College London

Imperial College Research Ethics Committee

Imperial College London
Room 5L10D, 5th Floor, Lab Block
Charing Cross Hospital
Fulham Palace Road
London
W6 8RF

Tel: +44 (0)203 331 0208 Fax: +44 (0) 203 311 0203

researchethicscommittee@imperial.ac.uk

19 April 2013

Dr Josip Car
Director, Global eHealth Unit
Department of Primary Care and Public Health
320 Reynolds Building
St Dunstan's Road
London
W6 8RP

Dear Dr Josip Car,

Study Title: How and why do people with asthma choose to use a smartphone or tablet app for their condition? A qualitative interview study.

ICREC reference: ICREC_13_3_4

The above study was approved by your HoD on 14th March 2013 and by the Joint Research Office on the 19th April 2013.

Under the Imperial College Research Ethics Committee process, a study that has been reviewed by the Joint Research Office and Head of Division/Department (or Principal), where no significant ethical issues have been identified in the protocol or ethics application, can be approved without requiring it to go to full committee.

Documents
The documents reviewed were:

- ICREC Application form
- Research Proposal and Protocol Version 1.4 22/03/13
- Recruitment Advertisement Version 1.4
- Participant Information Sheet Version 1.4 22/03/13
- Participant Consent Form Version 1.4
- Online questionnaire Version 1.4
- Sponsorship and Insurance registration form

Yours sincerely,

Gary Roper,
Head of Regulatory Compliance,
Imperial College London

Imperial College of Science, Technology and Medicine

Imperial College
London

Imperial College Research Ethics Committee

Imperial College London
Room 5L10D, 5th Floor, Lab Block
Charing Cross Hospital
Fulham Palace Road
London
W6 8RF

Tel: +44 (0)203 331 0208 Fax: +44 (0) 203 311 0203

researchethicscommittee@imperial.ac.uk

Dr Josip Car
Director, Global eHealth Unit
Department of Primary Care and Public Health
320 Reynolds Building
St Dunstan's Road
London
W6 8RP

8th July 2013

Dear Dr Josip Car,

Study Title: How and why do people with long-term conditions choose to use a smartphone or tablet app for their condition? A qualitative interview study.

ICREC reference: ICREC_13_3_4

The above study was approved by your HoD on 14th March 2013 and by the Joint Research Office on the 19th April 2013.

The Joint Research Compliance Office (JRCO) have reviewed your Notice of Amendment on 8th July 2013 and would like to grant full approval to this study on the basis described in the Notice of Amendment.

Documents
The documents reviewed were:

- ICREC Application form
- Consent form V1.5 01/06/13
- Interview topic guide v1.5 01/06/13
- JRO sponsorship and insurance request form v1.5 01/06/13
- Online questionnaire schedule v1.5 01/06/13
- Participant info sheet v1.5 01/06/13
- Protocol v1.5 01/06/13
- Recruitment advertisement v1.5 01/06/13

Yours sincerely,



Gary Roper,
Head of Regulatory Compliance,
Imperial College London

Imperial College
London

Imperial College Healthcare NHS
NHS Trust

Joint Research Compliance Office
Academic Health Science Centre
Imperial College London and
Imperial College Healthcare NHS Trust
Room 5L10A, 5th Floor, Lab Block
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London W6 8RF
Tel: +44 (0)20 3311 0205
Fax: +44 (0)20 3311 0203
Becky.ward@imperial.ac.uk/
www.ic.ac.uk/clinicalresearchgovernanceoffice

Becky Ward
Research Governance Manager

31/10/2013

Dr Josip Car
DPCPH Imperial College London
3rd Floor Reynolds Building
St Dunstan's Road
London, W6 8RP

Dear Dr Car

RE: How and why do people with long term conditions choose to use a smartphone or tablet app for their condition? A qualitative interview study

Joint Research Compliance Office Reference number: 13IC1813

This is to confirm that the above named research project utilises human participants, their organs, tissue and/or data as defined under the sponsorship requirements of the Research Governance Framework for Health and Social Care 2005, incorporating the Medicines for Human Use (Clinical Trials) Regulations 2004.

On behalf of Imperial College of Science, Technology and Medicine, we undertake to act as the identified Research Sponsor for this project.

This letter confirms:

- The research proposal has been discussed, assessed and registered with the Joint Research Compliance Office, Imperial College Academic Health Science Centre, Imperial College London and provisional sponsor approval granted.
- The Chief Investigator has undergone a process of scientific critique commensurate with the scale of the project.
- Indemnity and insurance arrangements have been put in place to cover the project.
- Resources and support are available to the research team to aid delivery of the research as proposed.
- Management, monitoring and reporting responsibilities for the research have been approved.
- Imperial College will undertake and enforce those sponsor duties set out in the NHS Research Governance Framework for Health and Social Care.

Imperial College Sponsorship is conditional on the project receiving applicable ethical and regulatory approval for all research related aspects of its conduct. It is also conditional on successful contract and agreement negotiations and sign off via the Joint Research Office, where relevant, and before the study commences.

A copy of the ethics approval letter **must** be sent to the Research Governance Manager prior to the study commencing. Sponsorship is dependant on obtaining R&D Office approval for all NHS sites where the research is being conducted.

Yours sincerely

Ms Becky Ward
Research Governance Manager

Appendix 21 Interview study indemnity

Arthur J. Gallagher International

29th July 2013

TO WHOM IT MAY CONCERN

We, the undersigned Insurance Brokers hereby certify that we have place the following Insurance:

VERIFICATION OF INSURANCE

Unique Market Reference:	B1262FI0114913
Type:	No Fault Compensation for Clinical Trials and/or Human Volunteer Studies
Insured:	Imperial College London
Period:	From: 1st August 2013 To: 1st August 2014 Both days inclusive at Local Standard Time.
Interest:	This Policy will indemnify/cover the Insured in respect of their Legal Liabilities arising out of the Insured's activities and as more fully disclosed within the Policy Wording.
Limit of Indemnity:	GBP 10,000,000 Any One Claim and GBP 12,500,000 in the Aggregate, including costs and expenses
Excess:	GBP 2,500 Each and Every Claim, including costs and expenses
Underwriter:	100.0000% Newline Syndicate 1218

This document is for information only and does not make the person or organisation to whom it is issued an additional Insured, nor does it modify in any manner the Contract of Insurance between the Insured and the Insurers. Any amendment, change or extension to such Contract can only be affected by specific endorsement attached thereto.

Should the above mentioned Contract of Insurance be cancelled, assigned or changed during the above policy period in such manner as to affect this document, no obligation to inform the holder of this document is accepted by the undersigned or by the Insurers. The information provided is correct at the date of signature.

Authorised Signatory
Gallagher London.

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