An Advanced Bolus Calculator for Type 1 Diabetes: System Architecture and Usability Results

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Abstract—This paper presents the architecture and initial usability results of an advanced insulin bolus calculator for diabetes (ABC4D), which provides personalised insulin recommendations for people with diabetes by differentiating between various diabetes scenarios and automatically adjusting its parameters over time. The proposed platform comprises two main components: a smartphone-based patient platform allowing manual input of glucose and variables affecting blood glucose levels (e.g. meal carbohydrate content, exercise) and providing real-time insulin bolus recommendations; and a clinical revision platform to supervise the automatic adaptations of the bolus calculator parameters. The system implements a previously in-silico validated bolus calculator algorithm based on Case-Based Reasoning (CBR), which uses information from similar past events (i.e. cases) to suggest improved personalised insulin bolus recommendations and automatically learns from new events. Usability of ABC4D was assessed by analysing the system usage at the end of a six-week pilot study (n=10). Further feedback on the use of ABC4D has been obtained from each participant at the end of the study from a usability questionnaire. On average, each participant requested 115 ± 21 insulin recommendations, of which 103 ± 28 (90%) were accepted. The clinical revision software proposed a total of 754 case revisions, where 723 (96%) adaptations were approved by a clinical expert and updated in the patient platform.

Index Terms—Diabetes Mellitus, Insulin Bolus Calculator, Decision Support Systems, Case-Based Reasoning.

I. INTRODUCTION

At present, the majority of people with Type 1 diabetes mellitus (T1DM) control their blood glucose levels by drawing blood from the fingertips and measuring glucose concentration with a blood glucose meter (i.e. self-monitoring of blood glucose) [1], and by administering insulin through multiple daily injections or continuous subcutaneous insulin infusion pumps. Insulin boluses are usually calculated by estimating the insulin required to cover the ingested carbohydrates and by adding the insulin needed to correct elevated pre-meal glucose levels to target (i.e. correction bolus). Existing technologies used in diabetes management, such as insulin pumps and some blood glucose meters, incorporate bolus calculators [2] that help users to simplify these calculations

and potentially improve glycaemic control [3]–[6]. A standard insulin bolus calculator can be described as follows:

$$B = \frac{CHO}{ICR} + \frac{G - G_T}{ISF} - IOB, \quad (1)$$

where B is the calculated bolus; CHO the amount of estimated carbohydrates consumed; ICR is the insulin-carbohydrate ratio which describes the grams of ingested carbohydrates that are covered per one unit of insulin; G the current blood glucose measurement; G_T is a predefined glucose target and ISF the insulin sensitivity factor which describes the reduction in blood glucose concentration per one unit of insulin. Bolus calculators also consider the remaining active insulin from previous boluses, commonly referred to as insulin-on-board (IOB). The tuning of bolus calculator parameters depends on various factors such as: the time of the day, physical activity level, hormonal cycles, psychological stress, alcohol and illness. Therefore, it is important to adapt parameters to these situations and re-adjust them over time. Different algorithms have been proposed to automatically adapt bolus calculator parameters [7]–[9]. However, to our knowledge, none of them have been commercially adopted for use in diabetes management [10]. One of the main hurdles for adoption and utilisation is down to usability and acceptability of the systems for both patients and clinicians [2]. In this paper, we present the architecture of an advanced insulin bolus calculator that tackles the aforementioned hurdles that so far prevented clinical and commercial adoption. The platform has been designed with feedback from patients and clinicians with focus on safety and enhanced usability. Finally, we present results of a pilot study assessing the usability and acceptability of the proposed platform.

II. MATERIALS AND METHODS

A. An Advanced Bolus Calculator for Diabetes (ABC4D)

The proposed bolus advisory system implements an in silico validated advanced insulin bolus calculator [11] based on Case-Based Reasoning (CBR) [12], [13], which provides personalised insulin recommendations and automatically adapts its parameters over time. CBR is an artificial intelligence technique that solves newly encountered problems by applying the solutions learned from solving similar problems encountered in the past (i.e. cases). In CBR, a case is defined by three components: the problem description, the solution to the problem and the outcome [13]. The problem is described by a set of parameters that could potentially affect glucose levels (e.g. meal, exercise, time of the day), the solution is defined

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Fig. 1. Manual and automatic case parameters used to generate an insulin advice on the patient platform (left). All used cases are periodically (e.g. once a week) sent to the clinical platform (right) for revision. After all case adaptations have been approved by a clinical expert, the updated case base is sent back to the patient platform via encrypted email.

by the parameters of a bolus calculator (i.e. ICR and ISF) and the outcome is a glycaemic metric assessing the postprandial glucose excursion which can be evaluated using continuous glucose monitoring (CGM) data.

Adapting Insulin Therapy with Case-Based Reasoning: The CBR algorithm can be described in four steps [13]:

- **Retrieve** cases from the case base and select the one that is most similar to the current situation (i.e. meal scenario) using a selected similarity metric (e.g. k-nearest neighbours).
- **Reuse** the solution of a successfully retrieved case. If necessary, the solution can be further adjusted to the current scenario.
- **Revise** the glycaemic outcome (e.g. postprandial hypoglycaemia or glucose area under curve) of the applied solution, if the user accepted the bolus advice. In case the outcome is unsatisfactory, adaptation of the solution of the retrieved case may be required [9].
- **Retain** the adapted case in the case base or create a new case describing the current meal scenario if no similar case has been found.

B. System Architecture of the Patient and Clinical Platform

The proposed ABC4D system comprises a patient platform consisting of a smartphone application and a computer-based clinical platform (Figure 1). The patient platform allows manual user input of relevant glucose-related data and provides real-time bolus advice. The clinical platform aims to guarantee patient's safety by allowing the clinician to easily analyse and accept changes to the insulin therapy proposed by the CBR algorithm. In order to warranty patient safety, the proposed platform separates the CBR cycle into two parts. The first part, comprising the retrieval and adaptation steps, is integrated into

the patient advisory platform; while the second part, containing the revision and the retention steps, is performed within the clinical platform (see Figure 2). The functional separation of the CBR cycle ensures that only clinically safe adaptations are performed.

Fig. 2. Implemented CBR cycle proposed by Aamadt and Plaza [13], split into a patient and clinical platform.

For practicality reasons, case revisions can be performed periodically by a clinical expert (e.g. weekly). Periodic revision also has the advantage to filter out potential outliers if a case has been used more than once.

Figure 3 shows the software system architecture of both the patient advisory and clinical supervision platforms. The main difference in the structure of the architecture between the two platforms lies in the algorithm layer. The algorithm layer of the patient platform contains the bolus calculator formula as described in Equation 1, as well as CBRs retrieval

Fig. 3. Software architecture and user interaction of the ABC4D patient smartphone platform (left) and clinical revision platform (right).

and reuse steps, while the same layer of the clinical platform implements the revision and retention steps of the CBR cycle.

ABC4D Patient Smartphone Platform: The system architecture of the patient platform is structured as follows:

- 1) The presentation layer holds the logic for the graphical user interface, which is responsible for retrieving manual input parameters and presenting requested bolus recommendations to the patient.
- 2) The algorithm layer contains the retrieval and reuse steps of the CBR cycle and the bolus calculator formula. Whenever the user requests a new bolus advice, the retrieval algorithm compares the current scenario with existing cases in the case-base and returns the solution (i.e. bolus calculator parameters) and, if necessary, adapts the retrieved solution to the current scenario (reuse step). The bolus calculator formula uses this solution to calculate the recommended insulin dose, which is sent to the presentation layer to display the advice, through the graphical user interface, to the patient.
- 3) The safety layer implements risk mitigation and risk control measures to ensure maximum safety of the system. Risk mitigation is implemented to ensure that only safe (i.e. physiological) values are entered via the user interface as well as to verify each parameter retrieved from the database. Risk control limits the maximum amount of insulin to be advised which can be pre-defined for each user by the clinical expert.
- 4) The data layer is responsible for storage, maintenance, security of data stored in the local databases as well as providing secure transmission to the clinical platform. The data layer contains three databases: 1) An event-database which contains log book entries and information about all glucose related user entries and insulin requests; 2) a case database (i.e. case base) containing all generated cases and information about their usage and 3) a settings-database to store security

information, patient details and personal settings. The data layer also manages access to automatic input parameters (e.g. exercise information through external accelerometer.)

ABC4D Clinical Revision Platform:

- 1) The presentation layer is responsible for the graphical user interface of the revision platform. It allows the clinician to import the log book and cases retrieved from the patient platform as well as additional data (e.g. CGM data) required by the revision algorithm. During the revision process, the user interface displays glucose graphs, meal information, selected parameters (e.g. exercise) and retrieved cases used for each scenario where an insulin advice has been requested. A suggested adaptation to the solution of the retrieved case is presented to the clinical expert who needs to approve or decline each case adaptation.
- 2) The algorithm layer holds the revision and reuse steps of the CBR algorithm. The revision algorithm calculates adaptations to the solution of each case that has been used. After all case adaptations have been revised, the approved cases are updated into the case base of the patient platform (retain step).
- 3) The safety layer of the clinical revision platform ensures that all essential data have been imported and checks the databases for validity. In order to avoid overly aggressive adaptations, safety constraints limit the maximum allowed change to a case solution by a pre-defined percentage.
- 4) The data layer is responsible to synchronise and store data that has been uploaded from the patient platform. It contains a duplicate of all databases from the phone in addition to usage information and historical data from previous case adaptations.

Fig. 4. Main screen of ABC4D patient platform to enter manual input parameters and request an insulin advice (left) and display of an insulin bolus recommendation with the option of accepting or declining the advice, or to request more information on how the advice has been generated (right).

C. Implementation

CBR Algorithm: Several algorithms exist for case retrieval [14] and adaptation of bolus calculator parameters (i.e. case solution) [7], [8] which can be integrated in the proposed platform. The CBR cycle implemented in the proposed ABC4D system is based on [11]. Following case parameters are used by ABC4D: Range of glucose level, time-of-day, exercise, alcohol and absorption rate. All parameters were weighted equally (i.e. weight = 1) for case retrieval. Parameter time-of-day was used to differentiate cases within the case-base between breakfast, lunch and dinner, which is used to account for potential changes in insulin sensitivity during the day. Therefore, a case retrieved in the morning will only be compared to 'breakfast' cases; a lunch scenario only compared with cases using parameter lunch, and so on. The time is automatically retrieved from the system time of the phone when requesting an advice. Glucose data from a CGM is used for case revision to assess the outcome of a suggested insulin bolus by evaluating the minimum postprandial glucose value within a pre-defined time window. The length of the time window (e.g. 4 hours) is depended on the insulin-action-time of the individual user and can be defined a priori by the clinical expert. For more details about the adaptation metric, the reader is referred to [9].

Patient Smartphone Platform: The ABC4D patient platform is built on the presented architecture and has been implemented in an off-the-shelf smartphone (Hardware: iPhone 4S, Apple Inc. California; Programming Environment: X-Code/Objective-C; Database: SQLite3). Special attention was put on designing the graphical interface to make it as user-friendly as possible. Feedback obtained from a focus group meeting (i.e. five adults with T1DM and similar demographics compared to the study group) was used to improve the usability of the patient platform prior the development of the software (see section III-A).

Figure 4 (left) shows the main screen of the smartphone

Fig. 5. Clinical revision software reviewing a breakfast scenario with exercise and proposing an adaptation to the insulin-carbohydrate-ratio (ICR) of a case.

application used for requesting a new recommendation. It contains input elements to enter manual parameters (i.e. amount of carbohydrates, meal absorption, current blood glucose level, alcohol consumption and exercise) and a button for requesting insulin bolus advice. The insulin recommendation is then presented to the user via a graphical user interface (see Figure 4 (right)). Each recommendation needs to be accepted or declined manually, while the latter option requires the user to input the actual insulin dose that has been delivered. Users could give reasons for declining bolus advice through selecting one of following check-boxes:

- Too much insulin
- Too little insulin
- Other/Manual user comment

Declined recommendations by the user were used for revision. However, instead of the solution of the retrieved case, the solution proposed by the user is revised and, if non-optimal outcome, adapted.

All user input and recommendations are locally stored in a relational database management system (i.e. SQLite3) on the phone. This enables the user to have access to past glucose information and recommendations at all times. Data essential for case revision can be exported as an Excel (Microsoft) file and sent encrypted via email to the clinical expert.

Clinical Revision Platform: The clinical revision platform has been implemented in MATLAB (The MathWorks, Inc) and is designed to run on a desktop computer. Figure 5 shows a screenshot of the clinical revision software, displaying the revision of proposed adaptation for the solution (i.e. ICR and ISF) of a presented case. In case the user administered additional insulin or consumed another meal with insulin within 4 hours after the bolus advice, then this scenario will be excluded for revision as it is not clear if a potential bad glycaemic outcome was the result of the initial bolus advice or because of the user intervention. However, cases solutions are still revised in scenarios when participants consumed carbohydrates without administration of insulin to correct for hypoglycaemia. After

TABLE I
USAGE OF PATIENT PLATFORM DURING A SIX WEEKS PILOT STUDY

Part	N° Bolus	N° Logbook	N° Accepted	N° Declined	Bolus Advice/Day		Logbook-Entries/Day		Usage Time (s)	
	Advices	Entries	Advices	Advices	Week 1	Week 6	Week 1	Week 6	Week 1	Week 6
1	70	16	66(94.3%)	4(5.7%)	2.4	1.7	0.3	0.9	52±34	33±16
2	135	212	127 (94.1%)	8 (5.9%)	3.7	2.4	6.4	3.0	133±106	63±55*
3	126	214	122 (96.8%)	4 (3.2%)	2.9	3.4	5.6	4.3	39±25	18±23**
4	132	154	132 (100%)	0 (0.0%)	3.1	3.3	5.4	4.3	170±99	140±65
5	97	186	51 (53.6%)	46 (47.4%)	2.7	2.1	5.3	2.3	122±44	96±29*
6	111	60	105 (94.6%)	6 (5.7%)	2.9	2.1	3.1	0.7	98±68	30±18**
7	96	207	76 (79.2%)	20 (20.8%)	2.1	2.4	9.9	5.0	98±89	88±48
8	124	15	114 (91.9%)	10 (8.1%)	2.9	3.1	0.7	0.0	111±63	58±42**
9	126	106	106 (84.1%)	20 (15.9%)	3.0	3.0	2.1	2.0	71±45	33±26**
10	132	44	127 (96.2%)	5 (3.8%)	3.3	3.4	2.6	0.0	102±61	61±37**
Total	1149	1214	1026	123	-	-	-	-	-	-
Mean±STD	115±21	121±83	103±28(90%)	12±14(10%)	2.9±0.4	2.7±0.6	4.1±2.9	2.3±1.9*	100±63	62±36**

*p <0.05 **p <0.01

the revision of the cases has been completed, the software shows a summary of all adapted cases to the clinician.

If one case has been used and revised multiple times, an average of all adaptations is calculated which, in turn, needs to be manually approved. Finally, the case base on the patient platform needs to be updated. This can be performed either on the phone itself through an authorised settings menu or remotely via email.

D. Evaluation of Patient and Clinical Platform

The usability and acceptability of the patient platform was evaluated as part of a clinical pilot study. Regulatory approvals were obtained from the regional ethics committee (REC 13/LO/0264) and the MHRA. Participants were recruited from the Imperial College Healthcare NHS Trust. Inclusion criteria were: diagnosis of T1DM for >1 year, age >18 year, HbA1c <86 mmol/mol (<10 %) and completed structured education. Ten adults with T1DM with a mean (SD) age of 42(17) years, diabetes duration of 21(15) years and HbA1c = 64(15) mmol/mol (8.1(1.4%)) participated in the study. Although ABC4D can be equally used by people using CSII, all participants were on multiple daily injections (MDI) in order to be consistent when analysing the usability of the system. Each participant used the patient platform continuously for six weeks to receive insulin bolus advice and log additional diabetes events such as snacks, additional capillary blood glucose measurements and correction boluses of insulin. A blinded CGM was worn by the participants for the whole duration of the pilot study. Its glucose data was uploaded once a week by the research team for case revision. At the end of the study, all participants were asked to complete a usability questionnaire. Furthermore, we recorded the number of times the software had been used and the time needed to request and review a bolus advice. A clinician, a clinical research nurse and an engineer used the clinical platform at the end of each study week to approve case adaptations for each accepted bolus advice. Safety measures

(e.g. maximum amount of recommended insulin dose) and initial cases with clinically safe solution, based on subject-specific insulin:carbohydrate ratios, were set by a clinical expert at the start of the study and were not accessible to the user.

III. RESULTS

A. Patient Platform

Implemented changes on the graphical user interface of the patient platform following feedback from the focus group meeting prior the study included: Simplification of the main menu, changing the input methods for entering carbohydrates and glucose levels (i.e. changing scroll wheel to numeric keypad) and adding explanatory text that informs the user in detail on how recommendations have been generated.

Table I shows the ABC4D usage of all subjects (n=10) participating in the six-week pilot study. On average, 115±21 insulin recommendations have been requested of which 103±28 (90%) were accepted by the participants. For the majority of all declined recommendations participants found the proposed insulin dose was not enough (64%), while for 32% of all declined advice participants felt the insulin dose was too much. No reasons were provided by the user for the remaining 4% of declined advice. While participants used the log book function of the application less in the last week of the study (p<0.05), no statistically significant change was observed when analysing the average number of requested bolus recommendations when comparing the initial study week with the last week. The mean time spent for requesting a bolus advice using the application (i.e. time from opening the software until closing it) was 100±63 seconds in the first week. This value was significantly (p<0.01) reduced to 62±36 seconds in the last week. Table III shows the outcome of the questionnaire assessing system usability and acceptability after completion of the six week study. The majority of people considered the ABC4D platform as user-friendly, to trust the generated advice and to be happy to use the platform. However, some

TABLE II
RESULTS OF CLINICAL REVISION PLATFORM ANALYSING PROPOSED
BOLUS RECOMMENDATIONS

N ^o of total meal scenarios available	1149
N ^o of scenarios eligible for revision	754
N ^o of approved revisions by clinician	723 (96%)
N ^o of declined revisions by clinician	31 (4%)

participants reported that using ABC4D software for insulin bolus advice was more time consuming compared to their conventional calculation.

B. Clinical Platform

Table II shows the use of the clinical revision software, which has been used periodically during the six-week study to revise the outcome of bolus recommendations. A total of 1149 bolus recommendations have been imported to the revision platform of which 754 advice were eligible for revising the outcome of the cases. Other bolus advice were ignored for revision because of either missing glucose sensor data or exclusion criteria of the adaptation metric (e.g. user has given additional insulin or consumed a snack shortly after the advice received). Out of all eligible imported bolus advice, 723 (96%) proposed adaptations were approved by the physician and uploaded to the patient platform. Only 4% of all proposed adaptations have been declined manually by the clinician, which was due to either human error (e.g. wrong value entered by patient) or artefactual sensor data.

IV. DISCUSSION

Human factors are key components to ensure adherence of patients and clinicians to information technologies for therapeutic purposes. For maximum performance, a decision support system for insulin dosing needs to be as user-friendly as possible for both patients and clinicians. This is why end users were involved from the beginning in the design and the development phase of the proposed system. Results from a pilot study over six weeks evaluating the usability of ABC4D are encouraging where almost 90% of all bolus recommendations have been followed by the participants. The difference in usage of the patient platform between the first and last study week has been highlighted in Table I. While participants used the log book less at the end of the study phase to enter daily diabetes related events (e.g. snacks, exercise or stress), the number of insulin advice requests did not significantly change over the study period. Further findings show, that the time needed to request an insulin advice was significantly reduced in the last week compared to the start of the study. As the software did not provide a function to re-use previously entered manual inputs (e.g. library of profiles), this reduction results from the learning curve of the user to enter data more efficiently when becoming more familiar with the software. However, some participants still found the use of ABC4D more time consuming compared to their conventional way of calculating the insulin dose. To address this, future work could see the system being integrated into a blood glucose meter or insulin

pump to reduce the number of manual user inputs. Also, pre- and post-meal physical exercise could be measured using existing commercial devices such as heart rate monitors or accelerometers (e.g. Fitbit Inc, San Francisco, CA, USA). Safety, as well as perceived safety, are other key aspects for adoption of ABC4D. The proposed separation of the CBR cycle into a patient platform for advice retrieval and a clinical platform for supervision ensures patients that all changes of their insulin therapy are approved by a clinical expert. After completion of the study, 80 % participants stated that they trusted the insulin advice which was generated by ABC4D (Table III). A decision support system that would automatically adapts insulin therapy without approval by a clinical expert might receive less acceptance by patients. However, we show in our pilot study that 96% of all proposed adaptations have been approved by the clinical experts which indicates the potential of further automation and reduced remote supervision. It is important to note that the presented platform can hold various algorithms for each of the CBR steps. While the ABC4D can potentially hold other revision algorithms that do not rely on CGM data (e.g. post-prandial capillary measurements [15]), the algorithm implemented in the presented system utilises retrospective CGM data to learn from previous case outcomes and further adapt the bolus calculator parameters. However, even without CGM, the patient platform is able to provide real-time bolus advice. In this scenario, the revision and retain steps will not be performed. For long-term usage, and once the bolus calculator parameters have been optimised, CGM could be used periodically (e.g. one month every four months) to adapt to changes in the users environment. This is important as CGM sensors are expensive and some users may not want to continuously use CGM for longer periods. The overall clinical performance of the system depends strongly on the implemented algorithms to retrieve, reuse and adapt cases. Further studies are on-going to assess the clinical efficacy of ABC4D based on the presented architecture and the algorithm proposed in [9] and [11].

V. CONCLUSION

Commercially available bolus calculators lack the ability to automatically adapt over time and require frequent revisions. We present the system architecture and initial usability results of an advanced bolus calculator for diabetes (ABC4D) which provides personalised and adaptive insulin recommendations. ABC4D implements an in-silico validated algorithm based on case-based reasoning (CBR), which differentiates between various scenarios and adapts bolus calculator parameters according to changes in the diet and life-style of the patient by analysing the postprandial glucose excursion. In order to ensure that only safe adaptations of the bolus calculator parameters are performed, we propose to split the CBR cycle into a patient platform and a clinical platform for supervision. We show promising initial results of the presented system in a pilot study assessing usability and acceptability, which are key factors for the adoption of decision support systems for insulin dosing.

TABLE III
RESULTS OF THE ACCEPTABILITY/USABILITY QUESTIONNAIRE OF PATIENT PLATFORM (N=10)

	Strongly Agree	Agree	Neither Agree Nor Disagree	Disagree	Strongly Disagree
Acceptability Questions					
I trusted the insulin dose advice generated by ABC4D.	2	6	0	2	0
The use of continuous glucose monitoring was acceptable.	4	6	0	0	0
Using ABC4D for insulin calculation caused more anxiety.	0	3	0	4	3
Overall, I would be happy to use ABC4D system for bolus calculation.	6	3	0	1	0
Usability Questions					
The ABC4D main screen is clear and was easy to read.	5	5	0	0	0
Entering data on the screen was straightforward.	6	4	0	0	0
Using ABC4D for insulin calculations was time consuming.	3	2	1	3	1
I would consider the ABC4D app user-friendly.	5	5	0	0	0

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