Wearable technology and the cardiovascular system: the future of patient assessment

Gareth J Williams, Abdulaziz Al-Baraikan, Frank E Rademakers, Fabio Ciravegna, Frans N van de Vosse, Allan Lawrie, Alexander Rothman, Euan A Ashley, Martin R Wilkins, Patricia V Lawford, Stig W Omholt, Ulrik Wisløff, D Rodney Hose, Timothy J A Chico, Julian P Gunn, Paul D Morris

The past decade has seen a dramatic rise in consumer technologies able to monitor a variety of cardiovascular parameters. Such devices initially recorded markers of exercise, but now include physiological and health-care focused measurements. The public are keen to adopt these devices in the belief that they are useful to identify and monitor cardiovascular disease. Clinicians are therefore often presented with health app data accompanied by a diverse range of concerns and queries. Herein, we assess whether these devices are accurate, their outputs validated, and whether they are suitable for professionals to make management decisions. We review underpinning methods and technologies and explore the evidence supporting the use of these devices as diagnostic and monitoring tools in hypertension, arrhythmia, heart failure, coronary artery disease, pulmonary hypertension, and valvular heart disease. Used correctly, they might improve health care and support research.

Introduction

To predict, prevent, diagnose, and treat cardiovascular diseases, physicians require an assessment of symptoms, activity, comorbidity, and context before prescribing targeted investigations and recommendations for treatment. The patient also needs information on what the physician considers their state of health to be, the basis for this view, and the risks and benefits of any treatment. Here we examine the potential for wearable technologies to enhance care in all these areas of cardiovascular medicine. We review devices that are accessible to the public, the underlying sensor technologies, the data acquired, and their application, providing a perspective on where these tools could sit within cardiovascular health care, the challenges that need to be resolved, and the studies required to confirm their utility. We also discuss the incorporation of sensor technologies into wearable clothing, apparel, and cutaneous patches and how these have been applied to clinical research in cardiovascular medicine.

Devices, data, and apps

Wearable medical devices such as ambulatory blood pressure and Holter (GEHealthCare, Chicago, IL, US) electrocardiogram (ECG) monitors, have been used in health care for decades; nowadays, devices purchased by the public, including smartphones, wristbands, watches, scales, shirts, rings, and eyeglasses are equipped with this type of functionality (figure 1). Patients instinctively recognise the potential of these technologies, and often present their doctor with health app-derived data. Although doctors recognise their potential usefulness, they are uncertain about the evidence base and appropriate use of such data. Measurements range from established parameters such as heart rate, blood pressure, and oxygen saturation, to step counts, minutes of activity, heart rate variability, and intrathoracic impedance. Wireless technology allows multiple sensors to integrate different signals, enabling body area sensor networks that can augment measurement accuracy (eg, heart rate) or compute parameters indirectly by combining different signals (eg, blood pressure). WiFi connectivity permits near-constant data upload to cloud storage, enabling continuous and simultaneous monitoring of multiple parameters, which can alert clinicians to significant changes (figure 2). A summary of relevant wearable sensor technologies is shown in the table. Software apps are designed to process, curate, and present data from raw sensor signals into relevant information within a user-friendly graphical display, usually on a smartphone, smart watch, or linked to a personal computer. These data can be presented in familiar formats such as resting heart rate and daily step count, with multiple sensor signals combined by the app and displayed in device-specific formats (eg, the Apple Move Ring, the Garmin Fitness Age, or the Fitbit Sleep Score). Apps can also provide user functions, such as providing health advice based on physical activity

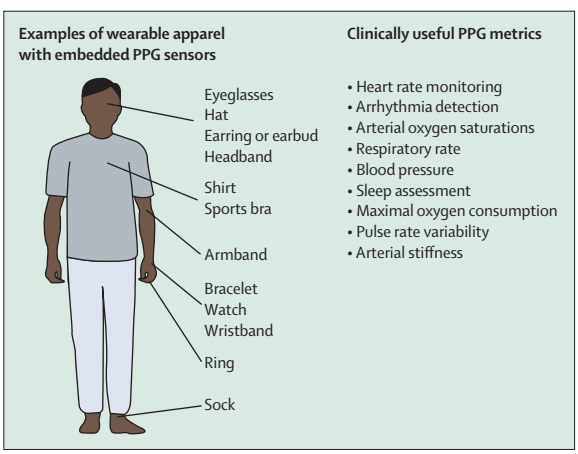

Figure 1: **The use of PPG in wearable apparel and its application to cardiovascular health assessments**
PPG has been adapted to a variety of wearable apparel in published literature (left panel) and how signals generated from this sensor can be applied to cardiovascular health assessments (right panel). PPG=photoplethysmography

Lancet Digit Health 2023; 5: e467–76

Department of Infection, Immunity and Cardiovascular Disease, (G J Wiliams BMBS, A Al-Baraikan MSc, A Rothman PhD, Prof P V Lawford PhD, Prof D R Hose PhD, Prof T J A Chico MD, Prof J P Gunn MD, P D Morris PhD)**, and Insigneo Institute for In Silico Medicine,** (Prof P V Lawford, Prof D R Hose, Prof T J A Chico, Prof J P Gunn, P D Morris)**, University of Sheffield, Sheffield, UK; Faculty of Medicine, Department of Cardiology, KU Leuven, Leuven, Belgium** (Prof F E Rademakers MD)**; Dipartimento di Informatica, Università di Torino, Turin, Italy** (Prof F Ciravegna PhD)**; Department of Biomedical Engineering, Eindhoven University of Technology, Eindhoven, Netherlands** (Prof F N van de Vosse PhD)**; National Heart and Lung Institute, Faculty of Medicine, Imperial College London, London, UK** (Prof A Lawrie PhD, Prof M R Wilkins MD)**; Academic Directorate of Cardiothoracic Services, Sheffield Teaching Hospitals NHS Foundation Trust, Sheffield, UK** (A Rothman, Prof T J A Chico, Prof J P Gunn, P D Morris)**; Department of Medicine, Stanford University, Stanford, CA, US** (Prof E A Ashley Dphil)**; Department of Circulation and Medical Imaging, Norwegian University of Science and Technology, Trondheim, Norway** (Prof S W Omholt PhD, Prof U Wisløff PhD)**; School of Human Movement & Nutrition Sciences, University of Queensland, QLD, Australia** (Prof U Wisløff)**; BHF Data Centre, Health Data Research UK, London, UK** (Prof T J A Chico)

Correspondence to:
Dr Paul D Morris, Department of Infection, Immunity and Cardiovascular Disease, University of Sheffield, Sheffield S102RX, UK
paul.morris@sheffield.ac.uk

levels or forwarding relevant sensor data directly to health-care providers.

All devices that claim to provide measurements of human physiology need to show safety, accuracy, reliability, and reproducibility in a variety of settings. An example of this is blood pressure devices, for which stringent, overarching guidelines are offered by standards organisations such as the International Organization for Standardization.[1] These validating bodies approve and regulate the use of such devices to ensure that health app-derived data can be relied on by patients and health-care providers to accurately identify or exclude cardiovascular disorders. Here, there is a specific need for greater involvement of clinical bodies in the development of regulatory guidelines and evaluation methods.

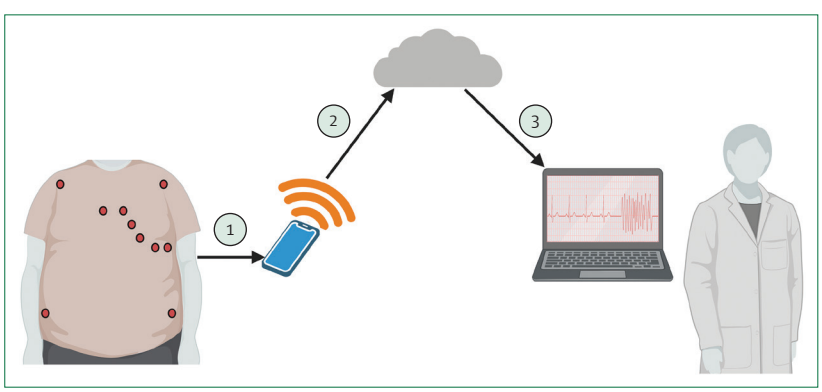

Figure 2: **ECG data transmission from wearable technology**
ECG data are sent via Bluetooth to a device with internet connectivity (eg, a mobile phone; step 1). Data are transferred to the cloud storage database from the device via internet connectivity (step 2). A local platform connects to the cloud storage database and the ECG recordings are reviewed by a health-care provider. ECG=electrocardiogram

Symptoms

Symptom context (duration, frequency, and association with physical activity, eating, sleeping stress, etc) is crucial to medical decision making. Traditionally, this information is obtained by asking patients to recall what they were doing when they had symptoms. This information is subjective and might be misleading, especially for patients with memory or communication difficulties. Mobile and wearable devices allow the user to record symptoms and physical parameters simultaneously and has been successfully applied to mental health and Parkinson's disease.[2,3] The MyHeart Counts App study showed the feasibility of large-scale physical activity measurement through self-reported questionnaires, and smartphone and wearable movement data from accelerometer and gyroscope sensors with a global positioning system (GPS). This study recruited 48 968 participants and discovered relationships between patterns of physical activity and self-reported health.[4] The authors did, however, observe recording fatigue, limiting long-term effectiveness. Nevertheless, there is potential to discriminate cardiac from non-cardiac symptoms and identify patients warranting further assessment, investigations, or monitoring.

Activity

Cardiovascular diseases such as heart failure and angina are classified according to the level of physical activity a person reports; this, in turn, drives important treatment decisions. Although useful, this approach is subjective and imprecise. Wearable device data provide objective measurements over long periods of time. Physical activity can be quantified by accelerometers to measure parameters such as step count, or more sophisticated

	Sensor principle	Applications	Wearable device
Accelerometer	Force sensor to measure the acceleration in a single or multiple directions	Movement classification and recording: step counting, physical activity, and fall detection	Smartphone, wristwatch, wrist band, armband, or belt
Ballistocardiography	Measures the body's mechanical recoil from ventricular contraction to quantify cardiac outputs and dynamics	Cardiac energetics and cuffless blood pressure measurement	Wristwatch or wristband
Electrocardiogram	Measurement of electrical activity of cardiac impulse	Heart rate monitoring, and heart rhythm assessment	Wristwatch or shirt or vest
Impedance-plethysmography (bioimpedance)	Detect changes in blood electrical conductivity to measure cardiovascular characteristics (radial pulse volume, and blood volume in ascending aorta)	Cuffless blood pressure measurement, and measurement of intrathoracic impedance in heart failure	Wristwatch, wristband, shirt, or vest
Magnetoplethysmography or giant magnetoelastic effect	Hall effect sensors track cardiovascular activity via movement of magnets, and giant magnetoresistance sensors use the diamagnetic property of water to detect magnetic flux created by pulsatile blood flow	Cuffless blood pressure measurement	Wristwatch or wristband
Phonocardiogram	Detects subaudible vibrations created through the opening and closing of heart valves	Heart rate	Patch
Photoplethysmography	Optical sensor to detect blood volume changes within the microvascular structure of perfused tissue	Heart rate and rhythm, blood oxygen saturation, VO_2 max, and cuffless blood pressure measurement	Wristwatch, wrist band, or eyeglasses
Remote dielectric sensing	Quantifies the dielectric coefficient of tissues, which correlates with fluid concentration	Detection of pulmonary oedema	Shirt or vest

Table: **Summary of the sensor technologies used in wearable technologies in cardiovascular disease research**

GPS-based measurements of speed, location, and terrain tracking over weeks or months. Ready access to such detailed and objective data at a patient-specific level will allow for a more personalised approach to medicine in terms of individually tailored exercise advice, as well as monitoring response to treatment, which is consistent with the concept of precision medicine.

Heart rate

The relationship between heart rate and cardiovascular risk is well established, with long-term studies showing an association between a higher resting heart rate and cardiovascular disease and adverse clinical outcomes.[5] Heart rate monitors using chest strap electrodes have been used in sports for decades. Photoplethysmography-based measurements from wrist-worn devices provide continuous monitoring with greater convenience. Although individual device accuracy varies, recent devices typically utilise peak detection algorithms which report median error ranges of less than 5% in comparison with telemetry in healthy individuals.[6] Improvements in photoplethysmography sensor miniaturisation has enabled incorporation into other common apparel, including rings and eyeglasses (figure 3).[7,8] Peak detection algorithms can be confounded by irregular rhythms—including atrial fibrillation and premature atrial or ventricular contractions—which produce photoplethysmography signals that vary from the underlying electrical activity. This can lead to incorrect measurements of heart rate. Sophisticated algorithms have been developed to reduce the errors of photoplethysmography signals in this context.[9] Modern smartwatches can offer ECG recording functions alongside limited rate and rhythm analysis software.[10] The development of self-powered wearable devices using triboelectric nanogenerator technology with pulse-sensing capabilities also shows the potential for uninterrupted heart rate monitoring over prolonged periods.[11] By harvesting the biomechanical energy released by the radial artery pulse in the wrist, the self-sustaining sensor converts the mechanical movement into energy as well as a signal with a strong agreement with ECG (R^2 0·98).

Respiratory function

Commonly used respiratory parameters can also be measured by wearable devices. Photoplethysmography can be used to measure oxygen saturation. Many fitness devices also estimate maximal oxygen consumption during exercise (VO_2 max). Respiratory rate can be measured with smart clothing using accelerometer, gyroscopic, or magnetometer-based detection of chest wall movements, circumference, or impedance pneumography.[12] There has been a significant rise in the use of wearable devices to assess respiratory function since the COVID-19 pandemic.[13]

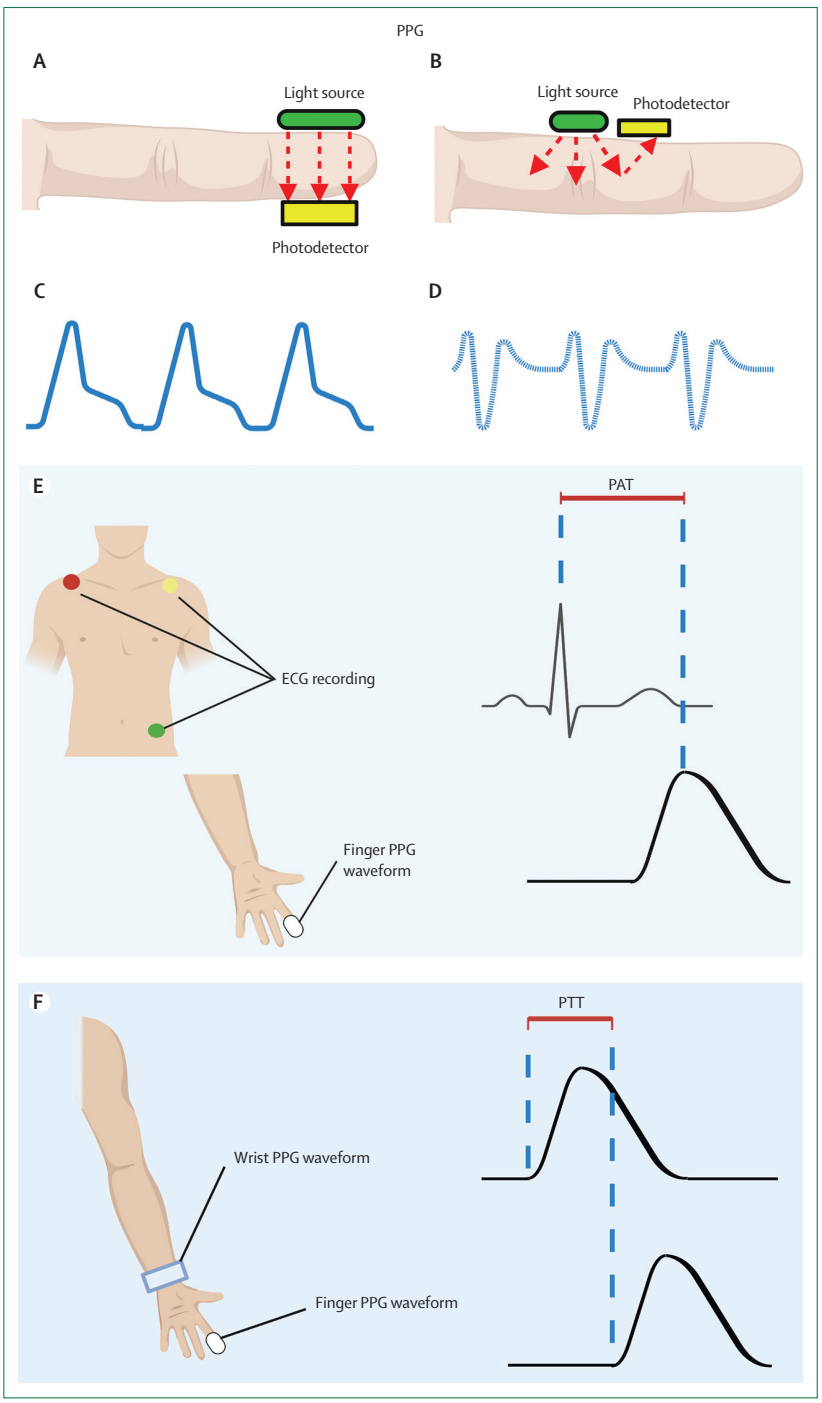

Figure 3: **PPG sensor principles**
The intensity of either transmitted (A) or reflected (B) non-absorbed light reflects variations in blood volume. A range of cardiovascular metrics can be calculated from the dynamic signal intensity (C). Analysis of derivatives of this signal (D) yield additional information about blood acceleration, pressure, and arterial stiffness. PPG signal analysis can be combined with other sensor modalities to generate parameters such as PAT (the time interval between the R wave and the PPG waveform) (E) and PTT (the time interval between the troughs of the proximal distal PPG waveforms) (F), which can be used to estimate blood pressure. ECG=electrocardiogram. PPG=photoplethysmography. PAT=pulse arrival time. PTT=pulse transit time.

Ultrasonography

Ultrasound is central to cardiovascular assessment in secondary care but is not widely available in primary care. Patch-based ultrasound devices now enable continuous haemodynamic measurements of arterial Doppler waveforms and can detect changes in stroke volume.[14] Obtaining such data in the community without the need for constant specialist oversight and interval hospital visits might enhance early detection of haemodynamic deterioration, particularly in valvular and ventricular disease.

Promoting physical activity to reduce cardiovascular disease

Physical inactivity is considered the fourth leading risk factor for global mortality, associated with 6% of deaths and 30% of ischaemic heart disease worldwide.[15] In patients with symptomatic disease, activity improves event-free survival and might delay disease progression.[16] Despite these messages, global estimates suggest more than 25% of people do not achieve recommended activity levels.[17] Multiple smartphone apps have been developed to reinforce healthy behaviours. One example is Active 10, which records activity levels.[18] Analysis of 129 010 users showed a significant improvement in physical activity, including those with a very low initial baseline activity levels. There are many other similar initiatives, including the Smart Walk and MyHeart Counts apps.

Wearable technology lends itself to personalised feedback and guidance. The Personal Activity Intelligence (PAI) system personalises activity targets using maximal heart rate data, questionnaires, and clinical data, as opposed to standard generic targets (10 mins brisk walking, 10 000 steps, etc).[19] In 39 298 participants, obtaining 100 PAI points per week was associated with a 23% reduction in cardiovascular disease mortality in women and 17% in men when compared with those achieving zero PAI points per week.[19] A systematic review of studies investigating the effect of personalised mobile health interventions in older adults showed the potential to improve step count and sedentary time, although none achieved statistical significance.[20]

Hypertension

Hypertension is the leading preventable cause of death worldwide.[21] Manufacturers have sought to incorporate blood pressure measurements into commercially available wearable devices. Several sensor modalities have been assessed and developed in preclinical and clinical stages (table). Devices are now available to the public with the purpose of providing validated measurements of blood pressure from the wrist. The Omron HeartGuide, the first clinically validated wristwatch blood pressure device, uses an inflation cuff within the strap to measure blood pressure (Omron Healthcare, Kyoto, Japan).[22] It compared well with office-based sphygmomanometer measurements (difference in systolic blood pressure <5mm Hg [SD 8]), but less well against simultaneous ambulatory blood pressure monitoring outside the office (3·2 mm Hg [SD 17]).[23] More recently, Huawei have released an inflatable cuff-based blood pressure wristwatch that has also shown sufficient accuracy to meet the Association for the Advancement of Medical Instrumentation, European Society of Hypertension, and International Organization for Standardization universal standards (differences between test and reference systolic and diastolic blood pressure –1·4 mm Hg [SD 6·47] and –0·2 mm Hg [SD 5·85], respectively);[24] however, the manufacturer states that the data obtained by the device should not be used for medical research, diagnostic, or treatment purposes and are for reference use only. Both products are listed as validated blood pressure devices by Science and Technology for Regional Innovation and Development in Europe, an international organisation associated with the European Society of Hypertension, International Society of Hypertension and World Hypertension League that aims to improve the accuracy of hypertension assessment, diagnosis, and management by providing guidance and practice tools along with the latest scientific and validation evidence.[25] The Aktiia bracelet (Aktiia, Neuchâtel, Switzerland) is a cuffless blood pressure device that derives measurements from an optical photoplethysmography sensor. It requires an initial calibration step against a separate sphygmomanometer device, and this must be repeated intermittently. Given that there are currently no guidelines for the validation of cuffless blood pressure devices, the Aktiia bracelet was validated against an adapted international standard (difference between test and reference systolic and diastolic blood pressure 0·46 mm Hg [SD 7·75] and 0·39 mm Hg [SD 6·86], respectively).[26]

These developments highlight the willingness of the commercial sector to generate and make available validation data in response to calls for better regulation.[27] Although these wearable devices might be more comfortable and practical for home use, and are likely to avoid white coat hypertension due to the stress of the clinical environment, they do present new challenges for validation; body position (particularly the position of the wrist and arm relative to the heart) and activity have been shown to influence the blood pressure measurement.[23,28] Because of this, and the fact that these devices are validated against traditional office-based measurements, the instructions for use advise only recording blood pressure while in an upright, seated, relaxed position. This is an important point for physicians to consider when interpreting blood pressure recordings from wearable devices. As the use of these devices expands it might be beneficial for international organisations to develop and adapt standards to consider validation of wearable sensors in the ambulant patient.

Arrhythmia

Prolonged ECG monitoring devices such as Holter monitors are cumbersome, can only be worn for short

periods, and might miss paroxysmal arrhythmias. Furthermore, implantable devices (loop recorders) are invasive and require specialist training to insert and analyse. Wearable technology can be advantageous for arrhythmia detection; several modern smartwatches use photoplethysmography sensors, and more recently ECG technology, to detect heart rate and rhythm. Photoplethysmography sensors can detect atrial fibrillation, the most common significant arrhythmia, with a sensitivity and specificity of 91–100% in comparison with ECG.[29,30] The Apple Heart study investigated the use of smartwatch-based arrhythmia detection in 419 297 participants (Apple, Cupertino, CA, USA).[31] Through the watch's photoplethysmography sensor, if an irregular cardiac rhythm was detected, a notification advised a telemedicine consultation and to wear an ECG recording patch for 7 days. Within a median monitoring period of 117 days, 2 161 participants received an irregular pulse notification (0·52%). After exclusions, 450 participants returned usable ECG data, 34% of which were confirmed to have atrial fibrillation. Although undergoing simultaneous ECG monitoring, the positive predictive value of subsequent irregular pulse notifications was 84%. In a similar study performed across China, 246 541 people downloaded a mobile atrial fibrillation app that used data from a photoplethysmography wristband or watch. Of these, 187 912 people used the app via their smartphone and 0·23% received a notification of a suspected atrial fibrillation. After follow-up, the positive predictive value of the photoplethysmography detected signal was 91·6%.[32] These studies were the first demonstration of a general population-wide approach to arrhythmia screening using a commercially available wearable device with telemedicine. Given that atrial fibrillation was diagnosed in asymptomatic participants, future research should consider whether major sequelae such as the incidence of stroke can be reduced by this approach in adequately powered prospective controlled trials.

Heart rate-sensing wearable technology has also been applied to multiple types of apparel, leading to a variety of potential arrhythmia detection modalities. The smart shirt design Cardioskin (BioSerenity, Paris, France) can record a 15 lead ECG continuously with quality comparable to Holter monitors.[33] ECG vests or chest straps worn for 28 days were investigated in the assessment of 146 patients with a diagnosis of cryptogenic stroke.[34] Atrial fibrillation was detected in 21·9% of patients, with the number needed to screen to detect one incidence of atrial fibrillation being 4·8 patients. Smart eyewear might also provide additional opportunities. A smartphone camera-based program can detect atrial fibrillation through facial photoplethysmography using variations detected in skin colour, with a sensitivity of 95% and specificity of 96% in discriminating atrial fibrillation from sinus rhythm.[35] This introduces the potential for facial photoplethysmography to be developed for eyeglasses.[8] Miniaturisation of photoplethysmography has led to a heart rate monitoring ring (Oura Health, Oulu, Finland), but it has only been tested in sinus rhythm to date.[7] A variety of wearable designs might soon become available for consumer-driven arrhythmia monitoring, allowing device selection that best suits patient preference and comfort.

Heart failure

In the management of congestive heart failure (CHF), reduced activity levels are predictive of worse outcomes, including mortality.[36] Wearable actigraphy devices have been validated against patient diaries and physical activity during cardiac rehabilitation.[37] Wrist-based actigraphy enabled the dichotomisation of 50 patients with CHF into higher and lower physical activity groups, with the lower physical activity group having a five times higher rate of hospital admission.[38] A systematic review of wearable actigraphy monitoring in patients with CHF revealed reduced physical activity was associated with poor clinical outcomes, mortality, and morbidity.[39] The AWAKE-HF study, which assessed the effect of combination sacubitril and valsartan versus enalapril on quality of life in patients with heart failure with reduced ejection fraction, used wearable actigraphy to detect physical activity. The study showed no significant difference in activity between either treatment group, despite an improvement in patient-reported quality of life in the group who received sacubitril and valsartan, suggesting a divergence between objectively gathered patient data and subjective outcomes.[40] A band electrode design integrated in shirts or vests can measure and detect changes in intrathoracic impedance which correlates with weight reduction secondary to diuresis (figure 4). Monitoring this parameter might predict hospital admission more reliably than change in weight alone.[41,42] One study investigated heart failure patients wearing such a vest for only 5 min a day after discharge from hospital, with data transmitted via Bluetooth and mobile phone.[43] For 106 participants, there were 64 heart failure events (18 readmissions and 46 up-titrations of diuretic medication). An algorithm analysing intrathoracic impedance was consequently developed, which showed 87% sensitivity and 70% specificity in identifying patients with recurrent admissions due to decompensated heart failure. Remote dielectric sensing (ReDS) uses electromagnetic signals emitted across the chest. It correlates well with pulmonary congestion and has been developed for home monitoring and wearable apps.[44,45] Daily ReDS monitoring in 50 patients with CHF for 90 days, with appropriate medication changes, resulted in an 87% reduction in admissions compared with the pre-monitoring period, and 79% reduction compared with the post-monitoring period.[46] Retrospective studies corroborate these findings.[47,48]

Ischaemic heart disease

Despite the evidence supporting physical activity and cardiac rehabilitation after acute coronary syndrome (ACS) and revascularisation, studies using activity-monitoring

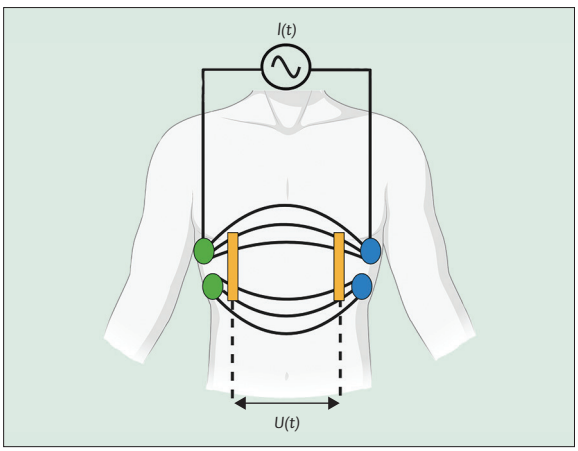

Figure 4: **Intrathoracic impedance measurement technique**
Electrodes on both sides of the chest (green and blue) pass a constant current across the chest, *I*(*t*), with an impedance detection circuit (yellow) measuring the voltage drop caused by intrathoracic blood volume *U*(*t*).

devices report daytime sedentary periods in excess of 9 h within the first month of recovery.[49,50] A prospective study of 72 patients with stable ischaemic heart disease taking optimal medical therapy demonstrated an improvement in exercise time following a 6-week cardiac rehabilitation programme over a 12 month follow-up period; however, the proportion of patients who met guideline recommendations of physical activity targets did not change significantly and sedentary time remained high throughout.[51] Patients with the lowest level of sedentary time made the most improvement in physical activity, with the reverse also being true. A study of 330 patients who provided wristwatch-based accelerometer data following discharge after an ACS revealed that only 16% conformed to exercise guidelines.[52] Simply wearing an activity monitor might encourage physical activity. Small randomised controlled studies of patients attending cardiac rehabilitation demonstrate that wearable pedometers improved adherence with physical activity advice, with improvements in psychosocial health and self-reported function;[53,54] however, these studies also included support from specialist staff which might have contributed to the results. The UP-STEP ACS study utilising the Fitbit Charge 2 (Fitbit, San Francisco, CA, USA) will be the first to assess the effect of wearable physical activity monitoring in improving exercise capacity and modifying cardiovascular risk factors in a randomised setting in recovering patients with ACS.[55]

Pulmonary hypertension

Pulmonary hypertension is a debilitating condition with significant morbidity and mortality, and high levels of fatigue and reduced physical activity. Accelerometer-based sensors detected reduced daily step counts, distance walked, and time spent in moderate to vigorous physical activity, with good correlations with established clinical parameters of physical activity (eg, 6 min walk test and quality-of-life questionnaires).[56–58] This does not always correlate with right heart catheter measurements and echocardiographic changes, suggesting that fatigue and reduced physical activity might be the result of a complex multi-system response.[59] The FIT-PH study aims to evaluate the correlation of Fitbit wristband activity data with implanted pulmonary artery pressure monitoring devices and their relationship to the patient's clinical condition and quality of life (NCT04078243). When used to monitor response to a physical training intervention, a study using wrist-based accelerometers showed an increase in physical activity in the intervention group, along with an improvement in 6 min walk distance (6MWD).[60] Using armband accelerometers, inspiratory muscle training failed to show an increase in daily physical activity levels, 6MWD, or questionnaire responses against controls.[61] Drug and device trials in pulmonary hypertension have incorporated activity monitoring as outcomes. Inhaled nitric oxide therapy was assessed in a randomised, double-blind, placebo-controlled trial.[62] Using armband accelerometers, 23% of the people in the treatment group showed a significant improvement in physical activity following an 8 week treatment period, whereas no improvement was observed in the placebo group; 71% of people in the placebo group had a significant decrease in physical activity versus 39% in the treatment group.[62] The TROPHY1 feasibility study, investigating the use of pulmonary artery denervation, showed an improvement in physical activity monitored through wearable accelerometery alongside conventional metrics.[63] Other recent trials in pulmonary hypertension such as VENTASTEP,[64] which investigated inhaled iloprost, and TRACE,[65] which investigated selective prostacyclin receptor therapy, used wearable technology to measure parameters of daily physical activity as primary outcome measures.[64,65]

Aortic valve disease

Data from wearable devices are surprisingly sparse in aortic valve disease, considering their potential to track progression and optimally time intervention. In a study of 52 patients with severe aortic stenosis, there was little correlation between wrist-based accelerometer measurements of daytime physical activity and conventional performance assessments and self-reported activity questionnaires.[66] Wrist-mounted accelerometer-based daily activity monitoring in 25 patients undergoing transcatheter aortic valve implantation showed a recovery to pre-transcatheter aortic valve implantation levels of physical activity by 5 weeks.[67] Further studies are required to explore the relationship between activity level and other physiological biomarkers with prognosis and intervention.

Computational and predictive modelling

By combining the various sources of information from wearable technology into personal representations,

computer modelling could substantially enhance the information that can be extracted from such data.[68] Modern medicine is guided by randomised controlled trials, which report relatively small overall effect sizes in large, heterogeneous patient groups. The results are then applied, often by extrapolation, as a generic remedy. Even if an individual patient in the clinic would have met the inclusion criteria of the key randomised control trial, would they have been one of the few positive responders? The individual's personal circumstances, comorbidities, socioeconomic status, genetics, activity levels, ethnicity, age, frailty, and other factors might be relevant. Computational modelling can analyse complex datasets to determine relevant factors and associations, offering the goal of tailored, or personalised care, rather than a one-size-fits-all approach.[69] Wearable technology has the potential to obtain patient-specific data to tune these models in an individualised manner. Continuous assimilation of physiological data over prolonged periods will allow computational models to develop and age with the patient; the so called digital twin.[70] It is anticipated that such models will incorporate artificial intelligence technology to characterise and delineate patient-specific physiological relationships that will be used to predict the likelihood of a new diagnosis, disease decompensation, or response to an intervention.[71] In the All of Us research programme, which includes more than 400 000 participants, data from wearable devices are combined with surveys, electronic health records, and clinical and laboratory samples to advance precision diagnosis on a large scale.[72]

Handling data from wearable technology in the clinic

Incorporating data from wearable devices into clinical decision making appears intuitive, plausible, and attractive. Patients are already presenting to their doctors with data from their wearable device as a new, patient-driven initiative. The collection of relevant health data before the first clinical consultation has the potential to revolutionise the traditional doctor–patient interaction (figure 5). Patients might be anxious about what they consider abnormal data, even without symptoms, and might (paradoxically) curtail their exercise as a result. At this early stage, doctors should ensure that data have been obtained within the manufacturer's stated intended use and do not exceed its evidence base or breach its regulatory approval. Off-label use might transfer responsibility from the manufacturer to the end user.

Challenges and future perspectives

The ubiquity of wearable devices risks that they will be used in clinical decision making, irrespective of validation. Despite a wide range of studies, they have not yet been shown to improve defined medical outcomes, necessitating studies to identify risks and benefits to the patient and health-care systems. Medical training will need to address these risks and benefits as the evidence base grows, as well as navigate the difficulties posed by volumes of disparate device data. Cardiologists, who are familiar with assessing traditional cardiovascular symptoms such as chest pain, palpitations, and shortness of breath, based on a patient's subjective description, will need to assimilate these new data sources and, in time,

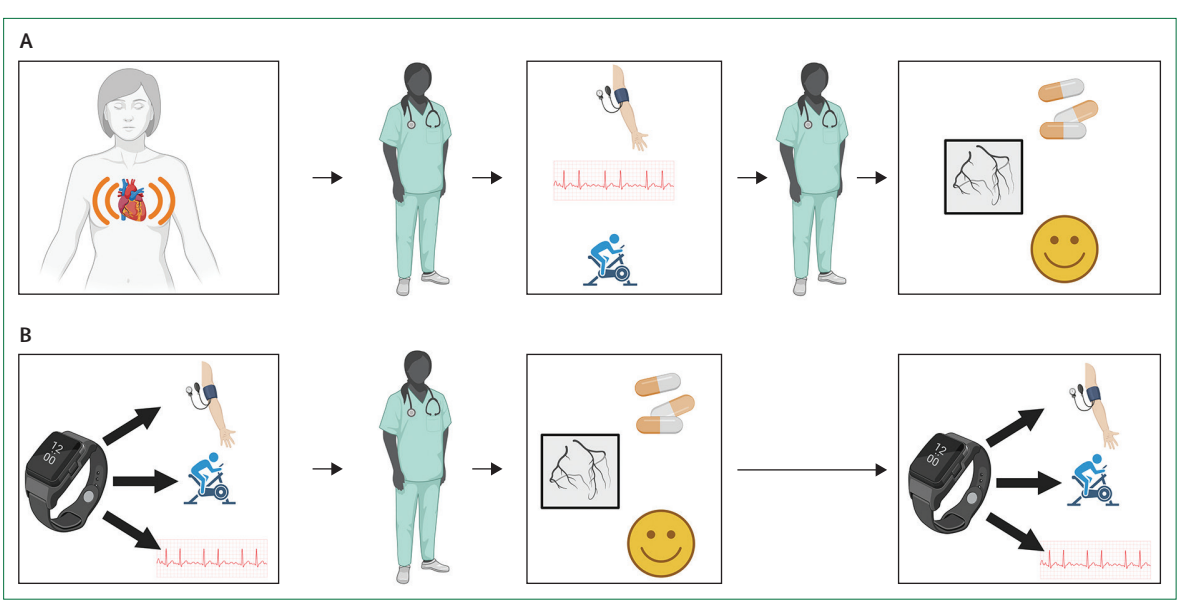

Figure 5: **How wearable devices can disrupt the traditional doctor–patient interaction**
(A) The traditional model of healthcare is initiated by symptoms, leading to a patient–clinician consultation. The clinician then requests investigations that document objective cardiovascular parameters under resting and stress conditions that leads to reassurance or diagnosis and treatment. (B) Patients present to their doctor with objective cardiovascular measurements under resting and physical exercise conditions, as measured and alerted by their wearable device. This process might lead to earlier initiation of treatment or reassurance and might facilitate monitoring the response to treatment.

Search strategy and selection criteria

The Web of Science and PubMed databases were used to search for relevant journal articles, including clinical trials, meta-analyses, and randomised controlled trials. The search terms used were "wearable", "sensors", "cardiovascular", "blood pressure", "cuffless", "heart disease", and "physical activity". Publications accessible from the database inception up to Nov 1, 2022 were considered for inclusion based on their relevance to consumer-led wearable devices in cardiovascular medicine. Articles were not included or excluded according to language.

use them to monitor the response to treatment. Parallel developments in machine learning and artificial intelligence might also be applied to data from wearable devices to identify novel associations in terms of diagnosis, risk prediction, and treatment choices.[71] It is also likely that sensor technology will advance beyond traditional methods such as photoplethysmography with the emergence of smart fabrics. These incorporate novel sensing methods, including soft magnetoelastic generators and hierarchical in situ filling porous piezoresistive sensors capable of transducing pressure displacement. Such fabrics provide new ways of integrating biomedical sensing technology into clothing and wearable devices.[73,74] The regulatory landscape for digital health care will need to develop rapidly. Public trust and acceptance will also be required. One hope is that wearables might help to reduce inequalities in health care, provided they are inexpensive, and do not discriminate against individuals who may struggle to engage with the technology (eg, due to a lack of familiarity with electronic devices or health conditions which may make using small devices challenging). The combination of wearables with telemedicine might also lead to a revolution in community care, as well as a reduction in both acute hospital admission and health spending.

Conclusion

Wearable technology has the potential to elevate the routine clinical consultation from a subjective discussion based on patient recollection to a standardised series of objective parameters of both health and quality of life gathered over months or years. Wearable devices have shown some potential application in many cardiovascular diseases, either through disease screening or monitoring; however, the evidence base and the integration of wearable data into clinical cardiology is still in its infancy. Such data could soon help personalise and improve the management of cardiovascular diseases on multiple levels, ultimately resulting in better outcomes on both an individual and a population-wide scale.

Contributors

PDM, GJW, JPG, TJAC, and DRH conceived the idea for this Review. PDM, GJW, and JPG contributed to the original manuscript draft. PDM and GJW designed the figures used. All authors contributed to subsequent drafting and editing of the manuscript.

Declaration of interests

EAA is an advisor to Apple and has received funding from Apple, Google, and Samsung. AL receives research support from Apple. PDM has received speaker's honoraria from Abbot. All other authors declare no competing interests.

Acknowledgments

All figures created with Biorender.com. This work was supported by the National Institute for Health and Care Research (NIHR) Sheffield Biomedical Research Centre (BRC). The views expressed are those of the authors and not necessarily those of the NIHR or the Department of Health and Social Care. PDM was funded by the Wellcome Trust (grant number 214567/Z/18/Z). GJW was funded by the Engineering and Physical Sciences Research Council (scholarship number 199860907). AA-B was supported by King Saud bin Abdulaziz University for Health Sciences via the Saudi Cultural Bureau. AL was supported by the British Heart Foundation (grant number FS/18/52/33808). AR was funded by the Wellcome Trust (grant number 206632/Z/17/z), MRC Experimental Medicine Award (grant number MR/W026279/1), Medtronic External Research Program, Abbott Investigator Sponsor Studies Award, Endotronix, Novartis, and Janssen. MRW was supported by the British Heart Foundation (grant number RE/18/4/34215) and the National Institute for Health and Care Research. TJAC was supported by the Engineering and Physical Sciences Research Council. None of the funding sources had any role in the writing of the manuscript, and none of the authors have been paid to write this manuscript.

References

1 International Organization for Standardisation. ISO 81060-2:2018. Non-invasive sphygmomanometers—Part 2: Clinical investigation of intermittent automated measurement type. Geneva: International Organization for Standardisation, 2018.

2 Rohani DA, Faurholt-Jepsen M, Kessing LV, Bardram JE. Correlations between objective behavioral features collected from mobile and wearable devices and depressive mood symptoms in patients with affective disorders: systematic review. *JMIR Mhealth Uhealth* 2018; **6:** e165.

3 Bot BM, Suver C, Neto EC, et al. The mPower study, Parkinson disease mobile data collected using ResearchKit. *Sci Data* 2016; **3:** 160011.

4 Hershman SG, Bot BM, Shcherbina A, et al. Physical activity, sleep and cardiovascular health data for 50,000 individuals from the MyHeart Counts Study. *Sci Data* 2019; **6:** 24.

5 Jensen MT. Resting heart rate and relation to disease and longevity: past, present and future. *Scand J Clin Lab Invest* 2019; **79:** 108–16.

6 Shcherbina A, Mattsson CM, Waggott D, et al. Accuracy in wrist-worn, sensor-based measurements of heart rate and energy expenditure in a diverse cohort. *J Pers Med* 2017; **7:** 3.

7 Kinnunen HO, Koskimäki H. 0312 The HRV Of The Ring - comparison of nocturnal HR and HRV between a commercially available wearable ring and ECG. *Sleep* 2018; **41** (suppl 1)**:** A120.

8 Howell TA, Chao D, Thomas CD, Day RG, Tong PP. Eyeglasses with a heart rate monitor. US Patent No. 7677723B2. Washington DC: US Patent and Trademark Office, 2010.

9 Han D, Bashar SK, Lázaro J, et al. A real-time PPG peak detection method for accurate determination of heart rate during sinus rhythm and cardiac arrhythmia. *Biosensors* 2022; **12:** 82.

10 Apple Support. Taking an ECG with the ECG app on the Apple Watch. Sept 12, 2022. https://support.apple.com/en-us/HT208955 (accessed Sept 15, 2022).

11 Ouyang H, Tian J, Sun G, et al. Self-powered pulse sensor for antidiastole of cardiovascular disease. *Adv Mater* 2017; **29:** 1703456.

12 Aliverti A. Wearable technology: role in respiratory health and disease. *Breathe* 2017; **13:** e27–36.

13 Takahashi S, Nakazawa E, Ichinohe S, Akabayashi A, Akabayashi A. Wearable technology for monitoring respiratory rate and spo_2 of covid-19 patients: a systematic review. *Diagnostics* 2022; **12:** 2563.

14 Wang C, Li X, Hu H, et al. Monitoring of the central blood pressure waveform via a conformal ultrasonic device. *Nat Biomed Eng* 2018; **2:** 687–95.

15 Kenny JS, Clarke G, Myers M, et al. A wireless wearable doppler ultrasound detects changing stroke volume: proof-of-principle comparison with trans-esophageal echocardiography during coronary bypass surgery. *Bioengineering* 2021; **8:** 203.

16 WHO. Global health risks: mortality and burden of disease attributable to selected major risks. Geneva: World Health Organization, 2009.

17 Winzer EB, Woitek F, Linke A. Physical activity in the prevention and treatment of coronary artery disease. *J Am Heart Assoc* 2018; **7:** e007725.

18 Ciravegna F, Gao J, Ireson N, Copeland R, Walsh J, Lanfranchi V. Active 10: Brisk walking to support regular physical activity. In: PervasiveHealth. *Proceedings of 13th EAI International Conference on Pervasive Computing Technologies for Healthcare* 2019; 11–20.

19 Nes BN, Gutvik CR, Lavie CL, Nauman J, Wisløff U. Personalized activity intelligence (PAI) for prevention of cardiovascular disease and promotion of physical activity. *Am J Med* 2017; **130:** 328–36.

20 Broers ER, Kop WJ, Denollet J, et al. A personalized ehealth intervention for lifestyle changes in patients with cardiovascular disease: randomized controlled trial. *J Med Internet Res* 2020; **22:** e14570.

21 Forouzanfar MH, Afshin A, Alexander LT, et al. Global, regional, and national comparative risk assessment of 79 behavioural, environmental and occupational, and metabolic risks or clusters of risks, 1990–2015: a systematic analysis for the Global Burden of Disease Study 2015. *Lancet* 2016; **388:** 1659–724.

22 Kuwabara M, Harada K, Hishiki Y, Kario K. Validation of two watch-type wearable blood pressure monitors according to the ANSI/AAMI/ISO81060-2:2013 guidelines: Omron HEM-6410T-ZM and HEM-6410T-ZL. *J Clin Hypertens* 2019; **21:** 853–58.

23 Kario K, Shimbo D, Tomitani N, Kanegae H, Schwartz JE, Williams B. The first study comparing a wearable watch-type blood pressure monitor with a conventional ambulatory blood pressure monitor on in-office and out-of-office settings. *J Clin Hypertens* 2020; **22:** 135–41.

24 Zhang W, Zhou YN, Zhou Y, Wang JG. Validation of the watch-type HUAWEI WATCH D oscillometric wrist blood pressure monitor in adult Chinese. *Blood Press Monit* 2022; **27:** 353–56.

25 STRIDE BP. Joint Initiative with ESH (European Society of Hypertension), International Society of Hypertension and World Hypertension League: validated blood pressure monitors. https://www.stridebp.org/bp-monitors (accessed Nov 20, 2022).

26 Vybornova A, Polychronopoulou E, Wurzner-Ghajarzadeh A, Fallet S, Sola J, Wuerzner G. Blood pressure from the optical Aktiia Bracelet: a 1-month validation study using an extended ISO81060-2 protocol adapted for a cuffless wrist device. *Blood Press Monit* 2021; **26:** 305–11.

27 Campbell NR, Gelfer M, Stergiou GS, et al. A call to regulate manufacture and marketing of blood pressure devices and cuffs: a position statement from the world hypertension league, international society of hypertension and supporting hypertension organizations. *J Clin Hypertens* 2016; **18:** 378–80.

28 Sola J, Vybornova A, Fallet S, Polychronopoulou E, Wurzner-Ghajarzadeh A, Wuerzner G. Validation of the optical Aktiia bracelet in different body positions for the persistent monitoring of blood pressure. *Sci Rep* 2021; **11:** 20644.

29 Tison GH, Sanchez JM, Ballinger B, et al. Passive detection of atrial fibrillation using a commercially available smartwatch. *JAMA Cardiol* 2018; **3:** 409–16.

30 Bonomi AG, Schipper F, Eerikäinen LM, et al. Atrial fibrillation detection using a novel cardiac ambulatory monitor based on photoplethysmography at the wrist. *J Am Heart Assoc* 2018; **7:** e009351.

31 Perez MV, Mahaffey KW, Hedlin H, et al. Large-scale assessment of a smartwatch to identify atrial fibrillation. *N Engl J Med* 2019; **381:** 1909–17.

32 Guo Y, Wang H, Zhang H, et al. Mobile photoplethysmographic technology to detect atrial fibrillation. *J Am Coll Cardiol* 2019; **74:** 2365–75.

33 Fouassier D, Roy X, Blanchard A, Hulot J-S. Assessment of signal quality measured with a smart 12-lead ECG acquisition T-shirt. *Ann Noninvasive Electrocardiol* 2020; **25:** e12682.

34 Pagola J, Juega J, Francisco-Pascual J, et al. Yield of atrial fibrillation detection with textile wearable holter from the acute phase of stroke: pilot study of Crypto-AF registry. *Int J Cardiol* 2018; **251:** 45–50.

35 Yan BP, Lai WHS, Chan CKY, et al. Contact-free screening of atrial fibrillation by a smartphone using facial pulsatile photoplethysmographic signals. *J Am Heart Assoc* 2018; **7:** e008585.

36 Walsh JT, Charlesworth A, Andrews R, Hawkins M, Cowley AJ. Relation of daily activity levels in patients with chronic heart failure to long-term prognosis. *Am J Cardiol* 1997; **79:** 1364–69.

37 Deka P, Pozehl B, Norman JF, Khazanchi D. Feasibility of using the Fitbit® Charge HR in validating self-reported exercise diaries in a community setting in patients with heart failure. *Eur J Cardiovasc Nurs* 2018; **17:** 605–11.

38 Waring T, Gross K, Soucier R, ZuWallack R. Measured physical activity and 30-day rehospitalization in heart failure patients. *J Cardiopulm Rehabil Prev* 2017; **37:** 124–29.

39 Tan MKH, Wong JKL, Bakrania K, et al. Can activity monitors predict outcomes in patients with heart failure? A systematic review. *Eur Heart J Qual Care Clin Outcomes* 2019; **5:** 11–21.

40 Khandwalla RM, Grant D, Birkeland K, et al. The AWAKE-HF study: sacubitril/valsartan impact on daily physical activity and sleep in heart failure. *Am J Cardiovasc Drugs* 2021; **21:** 241–54.

41 Cuba-Gyllensten I, Gastelurrutia P, Riistama J, et al. A novel wearable vest for tracking pulmonary congestion in acutely decompensated heart failure. *Int J Cardiol* 2014; **177:** 199–201

42 Cuba Gyllensten I, Bonomi AG, Goode KM, et al. Early indication of decompensated heart failure in patients on home-telemonitoring: a comparison of prediction algorithms based on daily weight and noninvasive transthoracic bio-impedance. *JMIR Med Inform* 2016; **4:** e3.

43 Darling CE, Dovancescu S, Saczynski JS, et al. Bioimpedance-based heart failure deterioration prediction using a prototype fluid accumulation vest-mobile phone dyad: an observational study. *JMIR Cardio* 2017; **1:** e1.

44 Amir O, Rappaport D, Zafrir B, Abraham WT. A novel approach to monitoring pulmonary congestion in heart failure: initial animal and clinical experiences using remote dielectric sensing technology. *Congest Heart Fail* 2013; **19:** 149–55.

45 Amir O, Azzam ZS, Gaspar T, et al. Validation of remote dielectric sensing (ReDS™) technology for quantification of lung fluid status: comparison to high resolution chest computed tomography in patients with and without acute heart failure. *Int J Cardiol* 2016; **221:** 841–46.

46 Amir O, Ben-Gal T, Weinstein JM, et al. Evaluation of remote dielectric sensing (ReDS) technology-guided therapy for decreasing heart failure re-hospitalizations. *Int J Cardiol* 2017; **240:** 279–84.

47 Roy S, Zafar A, Vazquez CE, et al. Noninvasive remote dielectric sensing vest significantly reduces readmission rate of patients with heart failure. *J Card Fail* 2018; **24:** S92.

48 Opsha Y, Zhuge P, Guevarra J, Lundberg M, Rogal G. Retrospective evaluation of remote dielectric sensing (ReDS) vest technology and its impact on heart failure readmission rates and diuretics therapy. *J Card Fail* 2019; **25** (suppl)**:** S147–48.

49 Freene N, Borg S, McManus M, et al. Comparison of device-based physical activity and sedentary behaviour following percutaneous coronary intervention in a cohort from Sweden and Australia: a harmonised, exploratory study. *BMC Sports Sci Med Rehabil* 2020; **12:** 1–8.

50 Duran AT, Ewing Garber C, Cornelius T, Schwartz JE, Diaz KM. Patterns of sedentary behavior in the first month after acute coronary syndrome. *J Am Heart Assoc* 2019; **8:** e011585.

51 Freene N, McManus M, Mair T, Tan R, Davey R. High sedentary behaviour and low physical activity levels at 12 months after cardiac rehabilitation: a prospective cohort study. *Ann Phys Rehabil Med* 2020; **63:** 53–58.

52 Kronish IM, Diaz KM, Goldsmith J, Moise N, Schwartz JE. Objectively measured adherence to physical activity guidelines after acute coronary syndrome. *J Am Coll Cardiol* 2017; **69:** 1205–07.

53 Butler L, Furber S, Phongsavan P, Mark A, Bauman A. Effects of a pedometer-based intervention on physical activity levels after cardiac rehabilitation: a randomized controlled trial. *J Cardiopulm Rehabil Prev* 2009; **29:** 105–14.

54 Houle J, Doyon O, Vadeboncoeur N, Turbide G, Diaz A, Poirier P. Effectiveness of a pedometer-based program using a socio-cognitive intervention on physical activity and quality of life in a setting of cardiac rehabilitation. *Can J Cardiol* 2012; **28:** 27–32.

55 Nogic J, Thein PM, Cameron J, Mirzaee S, Ihdayhid A, Nasis A. The utility of personal activity trackers (Fitbit Charge 2) on exercise capacity in patients post acute coronary syndrome [UP-STEP ACS Trial]: a randomised controlled trial protocol. *BMC Cardiovasc Disord* 2017; **17:** 1–9.

56 González-Saiz L, Santos-Lozano A, Fiuza-Luces C, et al. Physical activity levels are low in patients with pulmonary hypertension. *Ann Transl Med* 2018; **6:** 205.

57 Cascino TM, McLaughlin VV, Richardson CR, et al. Physical activity and quality of life in patients with pulmonary hypertension. *Eur Respir J* 2019; **53:** 1900028.

58 Sehgal S, Chowdhury A, Rabih F, et al. Counting steps: a new way to monitor patients with pulmonary arterial hypertension. *Lung* 2019; **197:** 501–08.

59 Saxer S, Lichtblau M, Berlier C, Hasler ED, Schwarz EI, Ulrich S. Physical activity in incident patients with pulmonary arterial and chronic thromboembolic hypertension. *Lung* 2019; **197:** 617–25.

60 González-Saiz L, Fiuza-Luces C, Sanchis-Gomar F, et al. Benefits of skeletal-muscle exercise training in pulmonary arterial hypertension: The WHOLEi+12 trial. *Int J Cardiol* 2017; **231:** 277–83.

61 Aslan GK, Akıncı B, Yeldan I, Okumus G. A randomized controlled trial on inspiratory muscle training in pulmonary hypertension: effects on respiratory functions, functional exercise capacity, physical activity, and quality of life. *Heart Lung* 2020; **49:** 381–87.

62 Nathan SD, Flaherty KR, Glassberg MK, et al. A randomized, double-blind, placebo-controlled study of pulsed, inhaled nitric oxide in subjects at risk of pulmonary hypertension associated with pulmonary fibrosis. *Chest* 2020; **158:** 637–45.

63 Rothman AMK, Vachiery J-L, Howard LS, et al. Intravascular ultrasound pulmonary artery denervation to treat pulmonary arterial hypertension (TROPHY1): multicenter, early feasibility study. *JACC Cardiovasc Interv* 2020; **13:** 989–99.

64 Mueller C, Stollfuss B, Roitenberg A, Harder J, Richter MJ. Evaluation of clinical outcomes and simultaneous digital tracking of daily physical activity, heart rate, and inhalation behavior in patients with pulmonary arterial hypertension treated with inhaled iloprost: protocol for the observational VENTASTEP study. *JMIR Res Protoc* 2019; **8:** e12144.

65 Howard LS, Rosenkranz S, Frantz RP, et al. Assessing daily life physical activity by actigraphy in pulmonary arterial hypertension: insights from the randomized controlled study with selexipag (TRACE). *Chest* 2023; **163**: 407–18.

66 Tang Y, Green P, Maurer M, et al. Relationship between accelerometer-measured activity and self-reported or performance-based function in older adults with severe aortic stenosis. *Curr Geriatr Rep* 2015; **4:** 377–84.

67 Green P, Woglom A, Maurer M, et al. Accelerometer-measured physical activity recovery in the first month after transcatheter aortic valve replacement. *J Am Coll Cardiol* 2012; **59** (suppl)**:** E1964 (abstract).

68 King RC, Villeneuve E, White RJ, Sherratt RS, Holderbaum W, Harwin WS. Application of data fusion techniques and technologies for wearable health monitoring. *Med Eng Phys* 2017; **42:** 1–12.

69 Hose DR, Lawford PV, Huberts W, Hellevik LR, Omholt SW, van de Vosse FN. Cardiovascular models for personalised medicine: where now and where next? *Med Eng Phys* 2019; **72:** 38–48.

70 de Lepper AGW, Buck CMA, van 't Veer M, Huberts W, van de Vosse FN, Dekker LRC. From evidence-based medicine to digital twin technology for predicting ventricular tachycardia in ischaemic cardiomyopathy. *J R Soc Interface* 2022; **19:** 20220317.

71 Krittanawong C, Rogers AJ, Johnson KW, et al. Integration of novel monitoring devices with machine learning technology for scalable cardiovascular management. *Nat Rev Cardiol* 2021; **18:** 75–91.

72 Ramirez AH, Gebo KA, Harris PA. Progress with the ALL of US research program: opening access for researchers. *JAMA* 2021; **325:** 2441–42.

73 Zhou Y, Zhao X, Xu J, et al. Giant magnetoelastic effect in soft systems for bioelectronics. *Nat Mater* 2021; **20:** 1670–76.

74 Xu J, Li H, Yin Y, et al. High sensitivity and broad linearity range pressure sensor based on hierarchical in-situ filling porous structure. *npj Flex Electron* 2022; **6:** 62.

Copyright © 2023 The Author(s). Published by Elsevier Ltd. This is an Open Access article under the CC BY 4.0 license.