



# Connected Health Technology for Cardiovascular Disease Prevention and Management

Shannon Wongvibulsin, PhD<sup>1</sup>

Seth S. Martin, MD, MHS<sup>2</sup>

Steven R. Steinhubl, MD<sup>3</sup>

Evan D. Muse, MD, PhD<sup>3,4,\*</sup>

## Address

<sup>1</sup>Department of Biomedical Engineering, Johns Hopkins University, Johns Hopkins University School of Medicine, Baltimore, MD, USA

<sup>2</sup>Ciccarone Center for the Prevention of Cardiovascular Disease, Division of Cardiology, Department of Medicine, Johns Hopkins University School of Medicine, Baltimore, MD, USA

<sup>3</sup>Scripps Research Translational Institute, 3344 N. Torrey Pines Ct, Suite 300, La Jolla, San Diego, CA, 92037, USA

Email: emuse@scripps.edu

<sup>4</sup>Division of Cardiovascular Disease, Scripps Clinic-Scripps Health, La Jolla, San Diego, CA, USA

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## Abstract

*Purpose of the review* Advances in computing power and wireless technologies have reshaped our approach to patient monitoring. Medical grade sensors and apps that were once restricted to hospitals and specialized clinic are now widely available. Here, we review the current evidence supporting the use of connected health technologies for the prevention and management of cardiovascular disease in an effort to highlight gaps and future opportunities for innovation.

*Recent findings* Initial studies in connected health for cardiovascular disease prevention and management focused primarily on activity tracking and blood pressure monitoring but have since expanded to include a full panoply of novel sensors and pioneering smartphone apps with targeted interventions in diet, lipid management and risk assessment, smoking cessation, cardiac rehabilitation, heart failure, and arrhythmias. While outfitting patients with sensors and devices alone is infrequently a lasting solution, monitoring programs that include personalized insights based on patient-level data are more likely to lead to improved outcomes. Advances in this space have been driven by patients and researchers while healthcare systems remain

slow to fully integrate and adequately adapt these new technologies into their workflows.

*Summary* Cardiovascular disease prevention and management continue to be key focus areas for clinicians and researchers in the connected health space. Exciting progress has been made though studies continue to suffer from small sample size and limited follow-up. Efforts that combine home patient monitoring, engagement, and personalized feedback are the most promising. Ultimately, combining patient-level ambulatory sensor data, electronic health records, and genomics using machine learning analytics will bring precision medicine closer to reality.

## Introduction

Cardiovascular disease (CVD) remains a leading global health concern with an increasingly large economic burden. With approximately one in three deaths attributable to CVD, it is the primary cause of morbidity as well as mortality and is contributing to growing health care costs [1, 2]. The fact that over 90% of the risk for myocardial infarction, a major contributor to CVD morbidity and mortality, is attributable to preventable risk factors [3] offers an enormous potential to improve CVD prevention and management strategies. Despite our understanding that optimizing CVD risk factors, including smoking, obesity, physical inactivity, unhealthy diets, and uncontrolled blood pressure, cholesterol, and diabetes, leads to vast improvements in cardiovascular health outcomes, implementing these modifications remains difficult. Thus, behavioral modification requires innovative tools to support individuals with health behavior changes. The emergence of connected health technology (e.g., mobile phones, smartphones, tablets, wearable devices, smartwatches, and personal health sensors) presents an opportunity to revolutionize disease prevention through personalized, convenient, and easily accessible patient education and behavior change support [4, 5, 6, 7] (Fig. 1).

In addition to supporting personalized health changes, connected health technology also has the potential to enable early disease detection and increase convenience and efficacy of chronic disease management. For instance, personal health devices now enable point-of-care screening for cardiac conditions such as hypertension and arrhythmias. Additionally, real-time, passive, non-obtrusive remote monitoring technologies offer patients with chronic conditions requiring long-term management increased convenience and support for better self-care [4, 5, 6, 7].

With the growing availability of a broad range of connected health devices, there is an enormous potential to transform prevention and management strategies for CVD in order to improve health outcomes and reduce the economic burden of CVD. The goals of connected health technology for CVD range from prevention, disease management, and patient engagement/self-care/education to remote monitoring approaches and tools to augment providers' ability to care for patients. One of the key objectives of this emerging field is to deliver safe, effective, personalized care at all stages, including prevention, early detection, diagnosis, treatment, and management. Here, we provide an overview of connected health technologies that empower patients with CVD prevention and management tools, with particular focus on coronary artery disease (CAD), heart failure (HF), and arrhythmia.

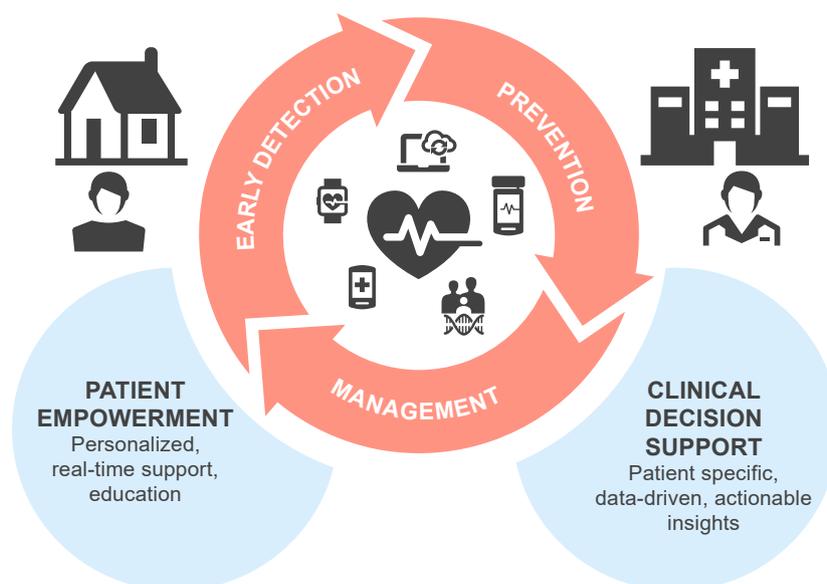
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### Coronary artery disease

Coronary artery disease (CAD) is the most common type of CVD. While there are numerous risk factors for CAD, many of them are modifiable and can be managed through lifestyle changes. Since behavior change is often a complex challenge, a wide range of health technology approaches have been developed to support healthy lifestyle practices, ranging from exercise to medication management.

### Blood pressure management

Hypertension is a known risk factor for adverse cardiovascular outcomes and present in approximately one-third of American adults [1]. The benefits of blood pressure reduction in hypertensive individuals are numerous and include decreased risk for heart failure,



**Figure 1.** Characteristics of connected health technology

myocardial infarction, and stroke. While it has long been demonstrated that lifestyle interventions targeting weight loss, exercise, dietary salt restriction, and minimization of alcohol intake are effective approaches for blood pressure reduction, strategies to effectively support these lifestyle practices are still challenging to implement. The use of connected health technology, which includes a range of tools for patient education, behavior modification support, home self-monitoring of blood pressure, and medication reminders, have generally been shown to be effective at achieving blood pressure reduction [8–12, 13•]. Nevertheless, uncertainty remains regarding the long-term sustainability of these interventions and their long-term clinical effects [9]. Furthermore, it is important to note that although self-monitoring of blood pressure can provide greater insight into the individual's typical blood pressure compared with clinic measurements [14], self-tracking alone is not associated with lower blood pressure or better blood pressure control. Thus, simultaneous interventions, such as systematic medication titration, patient education, or lifestyle counseling, are essential [15, 16•, 17]. As the field moves forward in attempts to optimize interventions for blood pressure control, researchers are increasingly incorporating feedback from patients in order to maximize the potential impact of digital interventions for hypertension management [18]. Self-tracking of blood pressure through watch-based devices, home

blood pressure cuffs, other consumer-facing blood pressure monitors, or the recently developed cuff-less blood pressure monitoring smartphone-based device using the oscillometric finger-pressing method [19] allows easy measurements for understanding night-time versus day-time and stressed versus calm blood pressure readings [14]. The increasing ease at which blood pressure can be self-monitored and health information can be provided offer enormous potential to prevent and manage hypertension at the population level. However, more rigorous clinical validation is still necessary [20].

### Lipid management

In addition to lifestyle modifications conducive to cardiovascular health in general, there is emphasis on lipid-modifying medications as an effective and cost-effective treatment option for improving lipid levels and CVD outcomes. Nevertheless, many patients who meet the indications for statins are never prescribed the medication and those who do receive the prescription have a long-term adherence rate below 50%. As a result, connected health interventions that target both patients and clinicians have been developed [21, 22].

Connected health technology to support lipid management includes provider-facing tools such as electronic health record or mobile/web application-based risk calculators using the American College of Cardiology

Atherosclerotic Cardiovascular Disease Risk Estimator and Statin Intolerance App, guideline support, alerts to support medication prescribing recommendations, as well as patient-facing tools such as mobile/web application-based risk or "heart age" calculators, medication reminders, patient education, connectivity to healthcare providers, and personalized health management support. Despite the availability of these tools, their uptake in clinical practice has not been widespread. As a result, more recent studies have incorporated novel strategies to engage both clinicians and patients. In the visualization of asymptomatic atherosclerotic disease for optimum cardiovascular prevention (VIPVIZA) randomized controlled trial to promote adherence to lifestyle changes and medications for improved clinical outcomes, ultrasound-based pictorial information about subclinical carotid atherosclerosis was provided to the intervention group. At one-year follow-up, the intervention group had a decrease in the Framingham risk score and an increase in use of lipid-lowering treatment, suggesting that providing personalized image-based information likely utilizing connected health devices can be an effective precision medicine tool that improves adherence to preventive guidelines in both patients and providers [22].

Methods from behavioral economics have also been explored in research examining the impact of financial incentives on both physicians and patients for lipid management. Patients and physicians in the incentive group were eligible for financial payments when quarterly low-density lipoprotein cholesterol (LDL-C) goals were achieved. The study employed electronic pill bottles for statin medication adherence tracking along with a web-based platform where clinicians and patients could view monthly LDL-C levels. After 12 months, the study found that financial incentives for both physicians and patients in combination, but not alone, resulted in statistically significant reductions in LDL-C levels (mean decrease of 33.6 mg/dL) [23]. Because the cost-effectiveness of this strategy (i.e., financial incentives combined with electronic pill bottles) was unclear, a recent study used a cardiovascular disease microsimulation model to evaluate the cost-effectiveness of financial incentives to physicians, patients, or both on the reduction of LDL-C and found that shared financial incentives for LDL-C control can be cost-effective. However, the results are dependent upon assumptions concerning the duration of the intervention [21].

Since both genetic and lifestyle factors are associated with susceptibility to coronary artery disease [24], advances in genomic sequencing and analytic technologies offers further opportunity to individualize lipid management strategies. Although not currently in wide clinical use, genetic risk scores, based upon increasing understanding of how certain DNA variants are associated with susceptibility to diseases such as atherosclerotic cardiovascular disease, are an active area of research for assessing individual disease susceptibility and determining personalized strategies prior to disease onset to delay or even prevent the disease from developing altogether [25–27].

### Physical activity

Worldwide, insufficient physical activity is a major public health problem [28]. Increased physical activity is a powerful strategy to prevent and delay the onset of CVD as well as other chronic conditions [29]. To help encourage increased physical activity, options for personalized physical activity interventions through connected health technology are rapidly growing. Features such as automated activity tracking and ongoing adaptive interventions individualized based upon the automatically collected activity data are available [30]. Furthermore, the platforms for physical activity connected health technology range from web-based/social media and smartphone applications to pedometers and other wearables, including fitness bands and smartwatches that capture activity metrics and physiological data [31].

Studies have consistently demonstrated that connected health technology can increase physical activity, at least in the short term [32, 33]. However, long-term, sustainable behavior change and impact on clinical health outcomes remain largely unknown [34•]. Varying degrees of intervention complexity are available, ranging from simple step-tracking using basic built in smartphone accelerometers to sophisticated applications designed based upon behavior change techniques [35, 36]. Many of the same approaches to support behavior change (i.e., self-monitoring, goal-setting, and social support) are employed in a variety of applications and wearable technology, and most of the studies demonstrating the efficacious impact of this technology also employ external behavior change strategies, including social support, financial incentives, and health coaching [37, 38•]. As a result, it is difficult to discern whether the connected health technology alone without additional

support and methods for accountability is capable of sustaining clinically meaningful increases in physical activity. Hence, when considering the use of technology for physical activity promotion, it may be essential to consider theory-driven behavior change strategies that are integrated into the technology design or used as adjunctive tools to support sustainable increases in physical activity. Overall, the most effective interventions are ones that are based on behavior change theory, are personalized to the individual, and offer feedback on the user's performance [31].

The wide availability of connected health technology to promote physical activity is generating enormous amount of activity and physiological data that can be integrated with other data sources within the healthcare setting to generate actionable insights and inform clinical decision-making [39]. Nevertheless, challenges remain regarding how to understand this large volume of data and gain clinical utility from this information. Machine learning approaches are currently being applied to gain insights as well as predict disease onset or progression based upon activity, physiological, and clinical data. Furthermore, incorporating statistical methods and machine learning approaches can allow increased targeting of intervention delivery through Just-In-Time Adaptive Interventions (JITAs) that are triggered based upon the ideal timing and location for physical activity for a particular individual.

## Diet

An unhealthy diet can contribute to many key CVD risk factors including high blood pressure, dyslipidemia, and insulin resistance. Digital tools aim to help individuals improve dietary practices through nutrition education and in-the-moment support for healthy dietary recommendations. Although numerous tools exist to support healthy diets, data remain limited on whether they have clinically meaningful results in the long term. As recognized in the American Heart Association (AHA) Scientific Statement on mobile health for CVD prevention, studies of dietary interventions are often also a part of more complex, multi-modal intervention designs that include physical activity promotion or support from a health coach [40]. For example, participants of the multi-modal SmartLoss program for weight loss targeted both diet and physical activity, and used not only a smartphone application and weight tracking through a linked

scale but also personalized ongoing feedback in an automated, adaptive manner and from trained counselors [41]. Furthermore, many commercial tools to support healthy dietary practices have not been evaluated in high quality clinical studies, and interventions that have been studied clinically are often not commercially available [40]. Nevertheless, numerous diet-related connected health technology tools are in popular use, including MyFitnessPal and LoseIt. These tools enable users to perform diet tracking including caloric tracking through extensive linkage with nutritional databases. Additionally, food tracking is facilitated through automated food identification with barcode scanning. These applications also include features (i.e., calorie-controlled healthy eating, specific goal setting, self-monitoring, personalized feedback, and social support) the AHA Scientific Statement outlined as important for healthcare practitioners to consider when utilizing this technology as a tool to support weight loss [40].

Other applications focus on empowering users to make better informed healthy food choices. Since nutrition labels can often be difficult to understand and also be misleading, smartphone applications such as Foodswith and Eatery aim to provide easy-to-understand nutritional information that can inform in-the-moment dietary decisions. Foodswith allows users to scan food items with barcodes to access a food database with user-friendly nutritional information, three-tiered "traffic light" rating for each food item, and options for healthier alternatives [42]. Eatery employs crowd-sourcing for feedback to inform dietary choices when users share photos of their meals. This crowd-sourcing approach has been demonstrated to correlate well with expert raters' overall assessments of nutritional value [43]. Overall, a number of connected health approaches exist to support improved dietary practices, yet their impact on clinical outcomes have not been well characterized.

Developments in the areas of automated diet tracking and increased personalization of dietary recommendations are rapidly emerging. Although many connected health strategies for dietary modifications involve diet tracking, recording food intake can be a tedious and time-consuming process, resulting in poor user satisfaction and discontinuation of use. As a result, some platforms are incorporating machine learning technology to enable automatic diet tracking through food detection software that can recognize the food and estimate caloric and nutritional content from photos users capture [44]. Another platform that avoids food logging is BagIQ,

which uses passively collected data from grocery stores' customer loyalty programs to provide an overall dietary quality score and personalized feedback on modifications for healthier diets. Approaches for individualized nutrition counseling through connected health platforms are also increasingly available. Furthermore, recent advancements of analytical tools that enable the study of large quantities of metabolic and health data are driving progress in the field of precision nutrition, which integrates data of various types to enable increased understanding of each person's individual dietary needs [45]. With increasing amounts of individual-level data from connected health technology and the advancement of predictive machine learning algorithms, there is growing emphasis on strategies for personalized nutrition based on an individual's physiologic response (such as using continuous glucose monitoring) rather than generalized dietary recommendations and a one-size-fits-all approach [46].

### Smoking cessation

Smoking is not only a major CVD risk factor but also is the number one cause of preventable death in the United States. While cigarette smoking has declined over time, tobacco use remains widespread [1]. As a result, there has been a concerted effort through many connected health approaches, including short message services (SMS), smartphone applications, and social media-based or web-based interventions, for CVD focus on smoking cessation.

SMS-based smoking cessation programs include ones such as the National Cancer Institute's SmokefreeTXT program, the Text2Quit from the American Cancer Society's, Alere Wellbeing's Quit for Life program, and the UK's National Health Service Quitkit's Txt2Stop. Studies of SMS-based smoking cessation interventions have demonstrated proven benefit for improving long-term quit rates [47]. For example, participants with the Text2Quit intervention were two times more likely than the control group to achieve smoking cessation at 6 months post-enrollment [48]. Additionally, the "Happy Quit" randomized controlled trial demonstrated that participants in either the high-frequency or low-frequency text messaging group for smoking cessation were more likely to quit than individuals in the control text message group receiving texts unrelated to quitting [49]. While there are many possible configurations of SMS-based smoking cessation programs,

general features that have been found to be effective are fixed schedule messaging (in comparison with decreasing or variable frequency messaging), messages focused on preparation to quit and how to manage smoking urges, and real-time psychological support [47].

A variety of smartphone applications that employ personalized strategies are also available to support smoking cessation. These include apps that act as adjunctive tools to traditional smoking cessation programs, while others take advantage of social connectivity and behavior change strategies. Efforts to develop smartphone applications for smoking cessation that match with clinical practice guidelines have resulted in applications such as the National Cancer Institute's QuitGuide and QuitStart as well as the Department of Veteran Affairs' Stay Quit Coach. Although smartphone apps have shown effectiveness for smoking cessation, there is room for improvement through tailoring approaches and adaptive messaging personalized to the needs of the user [50]. Considering the individual's socioeconomic status can also be crucial, since text messages alone may not increase quit rate for those who are socioeconomically disadvantaged, but text messages used in combination with proactive telephone counseling (e.g., assistance on coping with withdrawal, maintaining commitment to smoking cessation, and prevention of relapse) can be an effective strategy [51].

The use of financial incentives, social media, and web-based strategies as well as principles from adaptive intervention designs [52, 53] have been explored to further improve the ability of these apps to support smoking cessation efforts. For example, in a pragmatic trial studying electronic cigarettes, free cessation aids (nicotine-replacement therapy or pharmacologic therapy), and financial incentives for smoking cessation, financial incentives with free cessation aids resulted in an increased rate of smoking abstinence than free cessation aids alone [54]. To enhance social connectivity and support for smoking cessation, Crush the Crave includes an open, moderated Facebook group [52]. Additionally, to target and prevent smoking lapses, strategies to manage cue-induced cravings are being developed to deliver "just-in-time" interventions when the user is vulnerable to relapse into smoking. These Just-In-Time Adaptive Interventions (JITAI) are designed to be triggered in a context-dependent manner to target situations where the user may be prone to relapse such as when the user approaches his or her typically smoking break location [53].

## Cardiac rehabilitation

Hospitalization for cardiovascular events and the following recovery process can often be scary, confusing, and challenging for patients. Despite the demonstrated benefits of cardiac rehabilitation, utilization and completion rates remain low due to barriers such as time, cost, and transportation issues [55]. Connected health solutions offer a novel approach to expanding cardiac rehabilitation services, reaching patients in the convenience of their own homes or community, and achieving comparable if not better results than traditional, center-based approaches [56]. As recently reviewed in [57], virtual cardiac rehabilitation programs utilize a variety of technologies, ranging from video conferencing to smartphone applications. For example, a randomized, controlled trial comparing traditional cardiac rehabilitation with a smartphone cardiac rehabilitation application, which provided daily text messages, multimedia education, relaxation audio, and a light-to-moderate physical activity program, found that participants in the smartphone intervention group had significantly higher adherence and completion rates as well as significantly improved 6-min walking test distances and depression scores [56]. Hybrid models, which combine center-based sessions with home-based sessions, have also been explored where the cardiac rehabilitation staff can create a personalized plan for each patient using a dashboard that includes a home exercise prescription, educational videos, and daily medication and vital sign reminders. On the patient-facing side of the platform, the care plan is presented as a daily checklist. As patients complete tasks, their information is updated in the cardiac rehabilitation staff's dashboard, where alerts are presented when there are abnormal vitals or non-adherence with the care plan occurs [58]. Additionally, to provide further support for lifestyle management of risk factors, some programs employ lifestyle health coaching delivered through the telephone or web/smartphone application [59].

Digital technology is also available to help increase patient empowerment at all stages (i.e., hospitalization, discharge, and self-care/recovery). Through a smartphone application, patients who suffered from a myocardial infarction can gain assistance through educational resources for skill building for diet, exercise, and medication habits; connection to their care teams and resources to help with their

recovery; mindfulness techniques to improve patient awareness and emotional strength; and data analytics and biofeedback on steps, heart rate, and blood pressure with smart tools including an Apple watch and Bluetooth blood pressure monitor [60].

Despite the positive results demonstrated in connected health approaches for cardiac rehabilitation, some studies have shown that these interventions do not improve outcomes. For example, the HeartStrong randomized controlled trial examining the effect of electronic reminders, financial incentives, and social support on outcomes following myocardial infarction concluded that the compound intervention did not significantly improve medication adherence or vascular readmission outcomes [61•]. Additionally, the HONOR randomized clinical trial demonstrated that home-based exercise with a wearable activity monitor and telephone coaching did not improve walking performance at 9-month follow-up in peripheral artery disease patients [62]. While connected health strategies that empower patients and increase personalization of cardiac rehabilitation care plans tailored to individual needs are emerging, greater research is necessary to determine which approaches are effective in improving health outcomes and why certain studies have positive results while others demonstrate no improvement through the use of connected health technology. Factors to consider include the individual patient's preferences, quality of the connected health technology, and integration of the technology with clinical care.

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## Heart failure

Heart failure (HF) is a life-threatening progressive disease associated with reduced quality of life, high levels of comorbidity, and high levels of economic burden on the healthcare system [63]. With the major risk factors for HF common to those for CAD and CAD as a risk factor for HF [64], the technology described in the CAD section are also applicable to HF prevention and management. Here, we focus on recent developments specific to HF.

The high re-hospitalization rates for HF exacerbations reflect the challenges associated with long-term management of HF [63, 65]. As a result, connected health technology research in the area of HF has focused on chronic care of the condition through both non-pharmacological (e.g., fluid and dietary sodium restriction, physical activity, and weight loss interventions) and pharmacological management as well as home monitoring using devices such as smart scales, blood

pressure cuffs, and home electrocardiogram (ECG) devices [65–70]. Permanently implantable pressure measurement systems are also available through technology such as the CardioMEMS Champion Heart Failure Monitoring System designed to wirelessly monitor pulmonary artery pressure and heart rate to guide HF management and decrease hospitalization [71]. Since cognitive decline can contribute to poor self-care and non-engagement in HF management strategies, digital games are currently in development to assess cognitive function and have the potential to provide individualized information about the patient's cognitive status which can help inform the development of the patient's personalized care plan [72]. Additionally, various tools have been developed for automated clinical-decision support based upon home monitoring for early detection and prediction of HF deterioration [73•, 74]. Nevertheless, despite some encouraging signals, uncertainty remains regarding the impact of this technology on hospitalization rates, morbidity, and mortality [65, 73•, 75].

### Arrhythmias

With an aging population, the prevalence of arrhythmias is increasing, further heightening the need for methods capable of early detection and ongoing arrhythmia monitoring [65]. Since risk factors for arrhythmia are shared with CAD, and CAD itself is a risk factor for arrhythmia [76], the connected health preventive and management strategies described in the CAD section are also applicable to the prevention and management of arrhythmia. In this section, we focus on technology specific to arrhythmia.

Because of the highly variable and unpredictable nature of arrhythmias, management of the condition within the traditional healthcare model of regular or pre-scheduled appointments is suboptimal [77]. As recently reviewed by McConnell et al. [78] and Kotecha et al. [79] and as described in the International Society for Holter and Noninvasive Electrocardiology (ISHNE) and Heart Rhythm Society (HRS) expert consensus statement [80], connected health technology has the potential to fill this great clinical need. Various connected health methods have been developed for arrhythmia detection and management, ranging from implantable devices with atrial ECG analysis capable of detecting arrhythmias to non-invasive approaches such as smartwatches and mobile applications capable of distinguishing between atrial fibrillation and normal sinus rhythm

[81–84]. Wireless, single-lead real-time ECG smartphone monitoring has been shown to accurately detect baseline intervals, atrial rate, and rhythm, enabling screening in diverse populations [85]. Additionally, AliveCor's KardiaMobile smartphone application [86, 87], Kardia Band paired with an Apple Watch [88], and the Apple Series 4 Watch can record ECGs for automated atrial fibrillation diagnosis. For individuals at increased risk of atrial fibrillation, clinical diagnosis can also be facilitated through the use of a home-based self-applied ECG patch [89•]. For more extensive monitoring, a wireless handheld monitor capable of 12-lead ECG reconstruction for arrhythmia detection has also been developed and tested in patients following an atrial fibrillation ablation procedure. The performance of the wireless device was found to be more sensitive than periodic Holter monitoring in detecting atrial fibrillation and atrial flutter [90]. Automated, real-time analysis of ECGs and messaging to notify designated healthcare professionals when abnormalities are detected are also available through mobile devices such as HeartSaver, which can identify atrial fibrillation, myocardial infarction, and atrioventricular block using automatic detection algorithms [91].

While connected health technology for arrhythmia detection and management carries the potential to offer increased accessibility of the population to disease screening and management, most of these tools have not been integrated into routine clinical use [77, 92]. Questions remain regarding issues of lead placement, electrode contact, and battery drain in cases where indefinite continuous ECG monitoring is required. Furthermore, it is uncertain whether heart rate sensors on watches and fitness bands which employ photoplethysmography (PPG) can be utilized for arrhythmia detection and monitoring [92]. Recently, a novel machine learning algorithm for automated atrial fibrillation detection has been developed using data from a series of clinical studies employing heart rate and step count data from the Apple Watch. Nevertheless, this is a proof-of-concept study that still requires further research [93•]. Of note, the Apple Heart Study is a currently ongoing trial designed to identify atrial fibrillation in up to 500,000 participants with no prior history of the condition [94]. Overall, the field of connected health for arrhythmia detection and management is generating enormous amounts of data that can be leveraged using machine learning technology, with the potential to generate

actionable insights and support clinical decision-making. Recently, the success of machine learning for enabling automated screening has been demonstrated for detecting asymptomatic left ventricular dysfunction from ECGs and atrial fibrillation in PPG pulse waveforms through the use of convolutional neural networks [95, 96]. Although additional

research is necessary to determine the long-term utility of these learning systems in real-world settings and the appropriate management strategies for individuals identified to be at risk for arrhythmias using these tools, rapid progress is under way in the development, validation, and implementation of these technologies.

## Discussion and conclusion

CVD is a growing public health crisis which requires novel methods for prevention and management. Although there is great potential and excitement for CVD connected health technology, the field is still in an early stage and many questions remain unanswered regarding the real-world and long-term impact of these tools. While initial studies have been promising, caveats include small sample sizes, short study durations, and uncertainty about how the technology will perform in real-world settings and integrate with clinical care. Moreover, connected health devices result in enormous amounts of patient-generated data that healthcare providers currently are often unable to use clinically due to concerns about the validity of the data and challenges associated with interpreting this large volume of information in a clinically meaningful and timely manner. Since clinicians are already reporting being overworked and overwhelmed, it is necessary for connected health to help clinicians be more efficient and improve quality of care rather than adding unnecessary burden. Furthermore, safety and privacy as well as general lack of regulation of this connected health technology are other issues.

One of the biggest opportunities in digital medicine is sensor/data integration. An enormous amount of information regarding health and wellness can be learned by combining multiple signals [97]. Currently, an individual with type 2 diabetes and hypertension would likely have a continuous glucose monitor, an activity monitor, and a blood pressure monitor. Each of these would require a separate device and software application and strikingly there is a lack of an integrated dashboard where the rich data stream from each of these devices come together to provide meaningful insight to the user. Importantly, much of this information is not relayed to the electronic health record. Rather than having a single device solely measuring an individual physiologic or biologic parameter, the goal would be to utilize a single device that provides comprehensive monitoring. Although the initial growth phase for digital health technologies concentrated on the development, clinical validation, and implementation of single sensors, the field is seeing rapid growth in multi-sensor technologies. We are surely to see more efforts like the recently reported ECG and PPG sensors in neonates providing advanced, intensive care unit (ICU) level physiologic monitoring [98]. These innovations will be driven not only by continued miniaturization of powerful sensors but also by optimizing sensor delivery within soft, form-fitting, and skin-like materials [99, 100]. As efforts in material science advance with sensor platforms becoming smaller, unobtrusive, and integrated into

common wearables, we are likely to see less reliance on implantable devices which risk a host of complications.

Currently, the most available sensors are for physiologic parameters such as heart rate, blood pressure, ECG, activity, and SpO<sub>2</sub>. However, there has been a tremendous activity in the development of wearable biosensors for the detection metabolites, proteins, bacteria, DNA, and hormones in biofluids (tears, sweat, saliva, and interstitial fluid) [100]. These novel sensors harness electrochemistry, near-infrared spectroscopy, fluorescence, and radio frequency for non-invasive and continuous detection in the form of temporary tattoos, wristbands, patches, and even embedded into textiles. For a patient with congestive heart failure on diuretics, a reliable at-home continuous measurement of serum sodium, potassium, or NT-proBNP may have enormous clinical implications.

Overall, while further research is necessary, revolutionizing CVD prevention and management through connected health technology is well underway. A wide range of connected health tools, from those that enable population-level disease screening to those that support self-care and patient education, have been developed and offer the potential to reduce healthcare costs and increase the efficacy and personalization of care at all stages of a patient's journey, from early diagnosis to chronic disease management. The simultaneous advancements in sensor, mobile, wearable, and computing technology as well as data analytics and machine learning algorithms make it an opportune time for connected health technology to improve health outcomes.

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## Compliance with Ethical Standards

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### Conflict of Interest

Shannon Wongvibulsin, Steven R. Steinhubl, and Evan D. Muse each declare no potential conflicts of interest. Seth S. Martin serves on the scientific advisory boards of Amgen, Sanofi, Regeneron, Esperion, Novo Nordisk, Quest Diagnostics, and Akcea Therapeutics and reports grants from Apple, Google, iHealth, Nokia, Maryland Innovation Initiative, American Heart Association, Aetna Foundation, P J Schafer Memorial Fund, and David and June Trone Family Foundation. Dr. Martin reports a patent pending filed by Johns Hopkins as a co-inventor for a method of LDL-C estimation. Dr. Martin is a founder of and holds equity in Corrie Health, which intends to further develop the platform. This arrangement has been reviewed and approved by the Johns Hopkins University in accordance with its conflict of interest policies.

### Human and Animal Rights and Informed Consent

This article does not contain any studies with human or animal subjects performed by any of the authors.

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- Of importance
- Of major importance

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