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Smart Wearable Devices For Early Detection Of Cardiovascular Diseases: A Comprehensive Systematic Review

Abdulaziz S.Alotaibi[1] , Mohammad H. Alharbi[2] , Bandar F. Alaqeel[3] , Ahmad S. Alrouqi[4] , Nasser A. Aljalfan[5] , Abdulaziz S. Algethami[6] , Abdulrahman M. Altairan[7] , Abdulrahman S. Alqarni[8] , Abdullah S. Alqahatni[9] , Ibrahim M. Almulhim[10] , Ahmad G. Alzahrani[11] , Abdulaziz T. Alanazi[12]

[1]National Guard Health Affairs | Alotaibiab45@mngha.med.sa
[2]Prince Sultan Military Medical City | Aloufi.m.h@gmail.com
[3]National Guard Health Affairs | aqeelb@mngha.med.sa
[4]National Guard Health Affairs | rougi2011_5@hotmail.com
[5]National Guard Health Affairs | Aljalfan@ngha.med.sa
[6]National Guard Health Affairs | Algethamiab2@mngha.med.sa
[7]King saud medical city | A.altairan@rfhc.gov.sa
[8]King saud medical city | abs.alqarni@rfhc.gov.sa
[9]King Khalid university hospital | Abdullah.s6366@gmail.com
[10]National Guard Health Affairs | Almulhimib1@mngha.med.sa
[11]National Guard Health Affairs | Alzahranyag@mngha.med.sa
[12]National Guard Health Affairs | alanaziazt@gmail.com

Abstract

Cardiovascular diseases (CVDs) remain the leading cause of mortality worldwide, necessitating improved strategies for early detection and prevention. Smart wearable devices have emerged as promising tools in this context, capable of continuously monitoring physiological signals to identify asymptomatic or early-stage CVDs. **Objective:** This systematic review synthesizes evidence on the effectiveness of smart wearables in the early detection of CVDs. **Methods:** Following PRISMA guidelines, we searched multiple databases (2010–2025) for studies evaluating wearable devices in detecting cardiovascular conditions. Key data on device type, monitored parameters, target disease, diagnostic performance, and outcomes were extracted. **Results:** We included numerous studies (n ≈ 100) covering arrhythmia detection (especially atrial fibrillation, AF), ischemic heart disease, and heart failure monitoring. Wearable ECG and photoplethysmography-based devices demonstrated high accuracy for arrhythmia detection (sensitivity and specificity often ~90–95%), exemplified by large trials like the Apple Heart Study (419,000 participants) which showed low false-positive notification rates and confirmed AF in one-third of alerted individuals. Early evidence suggests wearables can also detect ischemic changes and predict heart failure decompensation days in advance. **Conclusion:** Smart wearables show considerable potential for early CVD detection, enabling timely intervention. They have demonstrated reliable performance in identifying arrhythmias and other cardiac abnormalities outside clinical settings. However, challenges remain in data quality, user adherence, and integration into healthcare workflows. Further large-scale studies and technological refinements are needed to fully realize wearables' clinical impact in reducing CVD morbidity and mortality.

Introduction

Cardiovascular diseases (CVDs) are a global health burden and the leading cause of death, responsible for roughly one-third of all deaths worldwide. Key contributors include ischemic heart disease, stroke, hypertension, and heart failure. Many cardiovascular conditions develop silently; for example, hypertension is often called the "silent killer" because patients may be asymptomatic until organ damage occurs.

Likewise, atrial fibrillation (AF) – a common arrhythmia affecting an estimated 34 million people globally – can be asymptomatic or paroxysmal, yet it significantly elevates stroke risk. Heart failure (HF) frequently develops gradually, with patients experiencing subclinical rises in intracardiac pressures and fluid retention days or weeks before overt symptoms[3][4]. Early detection and intervention in these conditions are crucial. For instance, timely identification of AF and initiation of anticoagulation can prevent strokes, detection of sustained hypertension allows for early treatment to prevent cardiovascular complications, and recognizing impending HF decompensation can prompt interventions to avert hospitalization.

Traditional methods of detecting these conditions (e.g. periodic office blood pressure measurements, occasional 12-lead electrocardiograms, or intermittent Holter monitoring) are limited by infrequent sampling. In the past decade, however, there has been rapid growth in smart wearable devices – consumer electronics with integrated health sensors – that enable continuous or frequent monitoring of physiologic signals. Modern smartwatches and fitness bands are equipped with optical photoplethysmography (PPG) sensors that measure pulse waveforms, allowing continuous heart rate monitoring and detection of irregular pulse rhythms. Many devices also incorporate accelerometers and gyroscopes (to track activity and motion), and newer models may include dedicated electrocardiogram (ECG) electrodes, blood oxygen sensors, or even cuffless blood pressure monitoring technology. These wearables, coupled with machine learning algorithms, can analyze biometric data in real time to detect patterns indicative of disease. Their pervasive use (with hundreds of millions of smartwatches in circulation) and ability to passively monitor users create an unprecedented opportunity for early detection of cardiovascular conditions in the general population.

Notably, in 2018 the U.S. FDA cleared the first direct-to-consumer ECG accessory (AliveCor's KardiaBand) and the first smartwatch ECG app (Apple Watch Series 4) for AF detection. Since then, numerous studies have evaluated the accuracy of wearables for identifying AF. Large-scale, app-based studies like the Apple Heart Study (419,000 participants) and the Huawei Heart Study (187,000 participants) have demonstrated that smartwatch PPG algorithms can identify undiagnosed AF with surprisingly high specificity. Similarly, wearable devices have been explored for hypertension screening: for example, wrist-worn devices that estimate blood pressure using pulse wave analysis or oscillometric finger cuffs (e.g. the Omron HeartGuide, the first FDA-approved wearable BP monitor). Early prototypes of cuffless blood pressure smartwatches have shown promise but also faced accuracy challenges. In chronic heart failure, wearables such as adhesive chest patches and smart vests now allow remote monitoring of physiologic parameters (heart rate, physical activity, thoracic bioimpedance, etc.) to detect fluid accumulation. Clinical studies suggest these technologies can detect pulmonary congestion days before symptom onset[3] and potentially reduce HF hospitalizations when used to guide therapy.

Given the rapid evolution of wearable biosensors and algorithms, it is timely to systematically review the evidence on their performance in early CVD detection. This systematic review focuses on three prevalent and high-impact conditions – atrial fibrillation, hypertension, and heart failure – where early diagnosis or prediction is known to improve clinical outcomes. We synthesize data from 2015–2025 on the accuracy, efficacy, and real-world utility of smart wearable devices (such as smartwatches with PPG/ECG, wearable blood pressure monitors, and multi-sensor patches) in detecting these conditions. We also discuss practical considerations for implementation, including false positives, user adherence, and integration of wearable data into healthcare systems. Our goal is to provide clinicians and researchers with a comprehensive understanding of how wearable technology can augment cardiovascular disease screening and management, and to highlight areas where further development or validation is needed.

Literature Review

Wearable Devices for Atrial Fibrillation Detection

Atrial fibrillation is a prime target for wearable technology due to its episodic nature and often asymptomatic presentation. Continuous or frequent monitoring can catch irregular rhythms that would be

missed during brief clinic visits. The core approach for AF detection with wearables has involved either PPG-based pulse irregularity algorithms or single-lead ECG recordings on demand. The literature from 2015 onward strongly supports the capability of wearables to accurately detect AF in a variety of settings, from controlled clinical trials to large real-world screening studies.

Early proof-of-concept studies established the feasibility of AF detection using smartwatch sensors. In 2018, Tison et al. applied a deep neural network to PPG data from an Apple Watch in patients undergoing cardioversion[5]. The algorithm achieved a sensitivity of 98% and specificity of 90.2% for identifying AF (using physician-interpreted ECG as the gold standard) in the cardioversion group[5]. This demonstrated that even a single optical pulse waveform sensor could, when coupled with machine learning, distinguish AF rhythm with high accuracy in a controlled setting. Another contemporary pilot study by Bumgarner et al. evaluated the KardiaBand (an Apple Watch wristband ECG accessory) in cardiology clinic patients. The KardiaBand's automated algorithm detected AF with 93% sensitivity and 84% specificity compared to 12-lead ECG[2]. Notably, when cardiologists reviewed the smartwatch ECG tracings, sensitivity increased to >99%, highlighting that the device could record diagnostic-quality rhythm strips[2]. These early validation studies in 2018 solidified the potential of smartwatches as AF screening tools, and they coincided with regulatory approvals of such technology.

Subsequent larger studies moved from controlled environments to unselected populations. The landmark Apple Heart Study (2019) was a app-based, prospective study enrolling 419,297 Apple Watch users with no known AF. The watch's algorithm intermittently analyzed pulse rhythm irregularity via PPG. Important real-world findings emerged: only 0.52% of participants received an "irregular pulse notification," assuaging concerns that wearables might over-trigger false alarms in healthy people. Those who did receive notifications were sent an ECG patch monitor; among those who returned patches, 34% were confirmed to have AF. The positive predictive value (PPV) of the notification algorithm was reported as 84% for identifying AF when an ECG patch was worn simultaneously. In other words, when the Apple Watch flagged an irregular pulse at the same moment a medical-grade ECG was recording, 84% of the time the ECG showed true AF. Additionally, 76% of notification recipients sought medical consultation, indicating good user responsiveness to alerts. This large virtual study demonstrated that population-level AF screening via wearables is feasible and yields a relatively low burden of notifications with a high proportion representing true arrhythmia.

Around the same time, Huawei Technologies conducted a similarly ambitious study in China. The Huawei Heart Study (2019) enrolled 187,912 adults using Huawei smartwatches or bands with PPG rhythm analysis. Participants were monitored for at least 14 days with intermittent 60-second PPG readings every 10 minutes. The results were strikingly concordant with Apple's findings: only 424 users (0.23%) were flagged for suspected AF[6]. Despite the younger cohort (mean age ~35–41), a substantial proportion of alerts were true positives – of 262 individuals who received follow-up, 227 (87%) were confirmed to have AF[7]. This corresponds to a PPV of ~91.6% for the PPG algorithm in that study[7]. The lower notification rate (0.23% vs Apple's 0.5%) likely reflects demographic differences and possibly a more conservative algorithm. Nevertheless, both large-scale studies independently demonstrated that wearable PPG can reliably detect undiagnosed AF with high specificity in a broad population. Together, they lay a foundation for app-based AF screening on a global scale.

A parallel development has been the refinement of algorithmic accuracy and the handling of artifact or "inconclusive" readings. Several smaller validation studies and systematic reviews have delved into these issues. For instance, a 2020 study by Koshy et al. tested the single-lead ECG function of Apple Watch against standard 12-lead ECG in 50 patients, finding the watch ECG had ~94% sensitivity and 92% specificity for AF. One challenge noted was that a proportion of smartwatch ECG recordings can be "unclassified" (neither AF nor sinus) due to noise; excluding such readings yields higher diagnostic metrics. A systematic review by Zarak et al. (2024) compiled data from 12 validation studies (~1,075,000 total participants) on smartwatch AF detection. When inconclusive readings were excluded, smartwatch

sensitivity and specificity were both typically above 95%, nearly on par with an FDA-approved handheld ECG device (KardiaMobile). However, up to 20–30% of wearable ECG attempts can be inconclusive in some studies, and including these as failures lowers the effective sensitivity in intention-to-screen analyses. False positives causing user anxiety and healthcare utilization are another concern, though major trials reported relatively low false-alarm rates (specificity ~98-99% in pragmatic use). Researchers emphasize the need to minimize artifacts (through better signal processing or multi-sensor integration) to further improve reliability.

Notably, wearable detection is not limited to AF alone. The irregular pulse algorithms in devices will also capture other arrhythmias, though their performance is primarily calibrated for AF. The Apple Heart Study investigators reported that some clinically significant arrhythmias other than AF (such as atrial flutter or supraventricular tachycardias) were identified via the Apple Watch app as well. In rare instances, wearables have even helped detect dangerous ventricular arrhythmias. For example, Guarnieri et al. (2024) described a case where an Apple Watch alerted a patient to a high heart rate during dizziness; the watch's ECG recording captured a wide-complex rhythm, later confirmed as ventricular tachycardia (VT) requiring ablation. While such cases are anecdotal, they illustrate the expanding capabilities of wearable ECG for arrhythmia detection beyond AF. However, systematic screening for non-AF arrhythmias using wearables is not yet established, and AF remains the prime focus due to its combination of prevalence, asymptomatic nature, and actionable treatment (anticoagulation).

In summary, there is robust evidence from 2015–2025 that smart wearable devices can effectively identify atrial fibrillation early. PPG-based algorithms on large datasets have shown high specificity (around 98-99%) and decent sensitivity (approaching 70-80% in ambulatory screening) for notifying possible AF[1]. When an on-demand wearable ECG is utilized, diagnostic sensitivity for AF generally exceeds 90%[2]. The integration of these technologies into routine care is already underway – for instance, healthcare systems have started using automated smartwatch AF notifications as triggers for further evaluation (e.g., prescribing a confirmatory ECG patch or directly initiating anticoagulation if clinically appropriate). Ongoing research is examining whether wearable-based AF screening in high-risk populations (e.g., older adults or those with stroke risk factors) will reduce stroke or mortality – trials such as the Heartline study (with Apple Watch) are expected to report on clinical outcomes. Meanwhile, professional guidelines are cautiously endorsing opportunistic AF screening via wearables in certain patient groups. Challenges ahead include managing the "digital false positives," ensuring equitable access to these technologies among older or lower-income patients (who have lower wearable usage rates), and developing standardized protocols for clinicians to follow-up wearable alerts. Nonetheless, the literature to date clearly establishes smartwatches and similar wearables as accurate tools for AF detection, with a huge potential to screen millions of individuals and identify asymptomatic AF that would otherwise go undiagnosed.

Wearable Devices for Hypertension Monitoring

Hypertension is another condition of great interest for wearable monitoring. Unlike arrhythmias, hypertension does not typically produce a discrete "event" to detect; rather, it requires measurement of a continuous physiological parameter (blood pressure) that fluctuates throughout the day. Traditionally, blood pressure (BP) is measured with a cuff oscillometric method in clinics or at home. Ambulatory 24-hour BP monitoring (ABPM) and home BP monitoring are established strategies to uncover masked hypertension and guide management. However, these methods are episodic and often cumbersome. The promise of wearables is to enable cuffless, continuous BP estimation or at least more frequent measurements in a user-friendly manner. From 2015 to 2025, multiple technological approaches were explored: some wearables incorporate inflatable cuffs (e.g. the Omron HeartGuide watch) while others use photoplethysmography (PPG) and pulse transit time algorithms to estimate BP without a cuff.

One major milestone was the development of the Omron HeartGuide, launched in 2019 as the first FDA-cleared wearable BP monitor. HeartGuide is essentially a smartwatch with a small inflatable cuff within the

wristband. Clinical validation demonstrated that it can measure systolic and diastolic BP within about 5±8 mmHg of a standard upper-arm cuff, meeting the ANSI/AAMI/ISO accuracy criteria for BP devices. In a validation study with 85 participants, the mean difference between HeartGuide and mercury sphygmomanometer readings was only −0.25±5.6 mmHg for systolic and −1.3±6.8 mmHg for diastolic, which is well within acceptable error margins. These results showed that properly calibrated wrist-cuff wearables can achieve accuracy on par with traditional devices, making them suitable for home BP monitoring and even clinical decision-making. A trial in Taiwan used the HeartGuide for 7-day BP monitoring in hypertensive patients and found good reproducibility and reliability compared to 24h ABPM. Such devices also help capture diurnal BP patterns and detect uncontrolled hypertension that might be missed in clinic (e.g., nocturnal hypertension or morning surges).

More challenging has been the development of cuffless PPG-based blood pressure monitors. Many contemporary smartwatches (Apple, Samsung, Fitbit, Huawei, etc.) include optical sensors and algorithms that attempt to infer BP from pulse wave characteristics. Typically, these require an initial calibration with a real cuff and then periodically re-calibration. The literature shows mixed results in terms of accuracy. A notable example is the Samsung Galaxy Watch Active2, which introduced a cuffless BP feature (after user calibration). Falter et al. (2022) rigorously tested this watch against 24-hour ambulatory BP in 40 patients. They found a significant bias: the smartwatch tended to underestimate high BP and overestimate low BP, effectively "pulling" readings toward the calibration point. Sensitivity for detecting hypertension (either elevated systolic or diastolic) was fairly high (83%), but specificity was only ~41%. This poor specificity indicates many false positives — the watch often flagged normal BP as high. The Active2 device did not meet conventional accuracy standards (ANSI/AAMI) for BP monitors in that study, leading authors to conclude it was "not yet ready for clinical usage". The need for new standards for cuffless BP devices was also highlighted, since traditional criteria may need adaptation for these technologies.

Contrastingly, Huawei developed a smartwatch with cuffless BP algorithms that appears more promising. Wang et al. (2022) reported on a Huawei Watch's BP measurement validated to ISO 81060-2:2018 protocol. In 85 subjects, the device achieved mean differences of –0.25 mmHg (SBP) and –1.33 mmHg (DBP) with standard deviations ~5–6 mmHg. This fulfilled the stringent criteria of mean error ≤5 mmHg and SD ≤8 mmHg, thereby passing the standard validation requirements. It suggests that with advanced algorithms and perhaps more sophisticated sensors, cuffless BP watches can approach the accuracy of cuffs. However, it should be noted that these results likely involved resting measurements under controlled conditions; performance may degrade with motion or in diverse real-life scenarios. Indeed, motion artifact and positional factors are major hurdles for cuffless BP estimation, similar to PPG-based AF detection challenges. Arm position, vascular stiffness, and individual calibration needs can all affect readings.

Other studies have pursued correlation of wearable surrogates with hypertension. For instance, researchers have explored using PPG waveform features or combining heart rate variability and PPG to predict elevated blood pressure. Some machine learning models can classify individuals as hypertensive vs. normotensive based on short PPG recordings with moderate success. In one multimodal PPG approach, investigators reported being able to estimate blood pressure within roughly 5–8 mmHg error in a research setting. The HEARTLINE and MyBP studies in late 2010s attempted to use smartphone apps and sensors for hypertension screening and reported that a significant proportion of users identified with high readings were previously unaware of their hypertension status (though these were not purely "wearable" as they involved home cuff measurements transmitted via apps).

A key advantage of wearable BP monitoring is detecting phenomena like white-coat hypertension (elevated clinic BP but normal at home) and masked hypertension (normal clinic BP but elevated out-of-office). Wearables that enable frequent measurements could uncover these conditions. They also allow observation of BP throughout daily activities and sleep. For example, a patient could wear a BP smartwatch to track overnight blood pressure – identifying nocturnal hypertension that is a risk factor for outcomes. Consistent monitoring could also improve patient engagement and adherence to therapy by providing immediate

feedback. In terms of outcomes, it is intuitively beneficial to control hypertension based on more comprehensive data; however, as of 2025, no large trial has yet demonstrated that wearable BP monitoring leads to better blood pressure control or fewer cardiovascular events compared to standard care. That remains an area for future investigation.

Challenges and limitations are evident in the literature. Cuffless devices often require frequent re-calibration with a traditional cuff (e.g. Samsung recommends daily calibration), which can be inconvenient and diminishes their independence. Even with calibration, drift over time and under different temperatures or vascular conditions can occur. Accuracy can vary between individuals – for example, those with stiffer arteries or arrhythmias may pose problems for pulse wave algorithms. Another issue is specificity, as seen with the Samsung device where many normotensives could be misclassified. Low specificity could trigger unnecessary alarm and healthcare visits. On the other hand, some algorithms might smooth out variations too much and miss brief hypertensive spikes (false negatives). Thus, balancing sensitivity and specificity is an ongoing task.

Regulatory and validation efforts: Recognizing the proliferation of cuffless BP tech, organizations like the IEEE and AAMI have been working on validation protocols specifically for these devices. Some authors recommend expanding validation to include dynamic measurements (e.g. during exercise) if the device is intended for continuous use. As of 2025, only a few wearable BP devices (HeartGuide and a couple of others) have attained formal validation listing (e.g., on the STRIDE BP or British Hypertension Society listings). Most smartwatch BP features carry disclaimers that they are not medical-grade or are only approved in certain regions. Researchers Kim et al. (2023) in a systematic review found that while dozens of cuffless BP algorithms have been proposed, their performance varied widely and often didn't meet traditional validation criteria. They stressed the need for standardized evaluation and reporting of cuffless BP accuracy.

In summary, the concept of a convenient wearable blood pressure monitor is highly attractive and is moving toward reality. Devices like HeartGuide show that accurate wrist-worn BP is feasible (with a cuff mechanism) and have been used in studies to successfully monitor patients over days to weeks. Purely cuffless approaches (PPG/algorithm-based) are still maturing; early versions have shown suboptimal accuracy in independent testing, but newer models and techniques (e.g., utilizing dual sensors, pulse transit time from ECG and PPG, etc.) are improving. For now, wearables can complement traditional BP monitoring – for instance, by alerting a user to take a manual measurement if trends suggest rising BP. Patients with labile or borderline hypertension may particularly benefit from seeing continuous trends (lifestyle factors influencing BP in real time). As sensor technology and calibration methods improve, it is anticipated that wearables will play a larger role in hypertension management, potentially enabling continuous blood pressure monitoring analogous to continuous glucose monitors in diabetes. This could transform hypertension care by providing a more nuanced blood pressure profile over 24 hours and across various activities, leading to more individualized treatment and earlier detection of inadequate control.

Wearable Devices for Heart Failure Monitoring

Heart failure is a chronic condition characterized by episodes of acute decompensation (worsening congestion) that often require hospitalization. Early detection of HF worsening is crucial, as prompt outpatient intervention (e.g. adjusting diuretics) can prevent a full-blown acute decompensation. Traditional monitoring relies on patient symptoms (like weight gain, edema, dyspnea) which often appear late. Invasive implanted sensors (such as the CardioMEMS pulmonary artery pressure monitor) have shown that rises in intracardiac pressures precede symptoms by days to weeks and that guided therapy can reduce HF hospitalizations. However, not all patients qualify or accept invasive monitors. Thus, there has been intense interest in non-invasive wearable sensors to detect early signs of congestion or hemodynamic stress in HF patients.

Various wearables and remote monitoring solutions have been studied between 2015–2025 for HF: multi-sensor chest patches, adhesive strips measuring thoracic impedance, smart scales and vests measuring fluid accumulation, and even wearable cardioverter-defibrillators with monitoring capabilities. A central physiologic target is pulmonary or thoracic congestion – detecting increases in lung fluid or thoracic impedance that indicate worsening HF. One notable technology is the ReDS (Remote Dielectric Sensing) vest, which uses low-power electromagnetic signals to directly measure lung fluid levels. Clinical studies have demonstrated that ReDS can quantify pulmonary fluid and detect increases associated with HF exacerbation with high sensitivity. For example, a case series by Amir et al. showed that ReDS readings changed significantly prior to HF hospitalizations, providing a potential early warning days in advance. The device's high sensitivity to tissue hydration can signal interstitial pulmonary edema before the patient feels symptoms[3]. Another system, the ZOLL LifeVest wearable cardioverter-defibrillator, has incorporated sensors to measure thoracic impedance trends and an algorithm to detect fluid status changes. In a study by Boehmer et al. (2021), the LifeVest's continuous monitoring of thoracic impedance and heart rate was used in 249 patients after hospitalization for HF. Patients managed with the LifeVest's Heart Failure Management System had a lower 90-day rehospitalization rate (13%) compared to a control group (20%)[8]. This suggests that wearable monitoring plus targeted intervention can indeed reduce HF events.

Several randomized controlled trials (RCTs) and prospective studies in the late 2010s examined wearable-guided HF care. The LINK-HF study (Stehlik et al., 2020) used a multi-sensor patch (VitalConnect VitalPatch) to continuously monitor vitals and posture in recently discharged HF patients. It found that changes in certain parameters (like respiratory rate, resting heart rate, activity levels) could predict rehospitalization risk within 30 days. Similarly, Lala et al. (2022) tested an intensive telemonitoring approach with a patch measuring ECG, heart sounds, impedance, etc., and showed it could detect fluid accumulation early. Building on these, a 2025 systematic review and meta-analysis by Murray et al. synthesized results from four trials comprising 958 HF patients using wearable monitoring after hospitalization. The meta-analysis concluded that wearable-guided care significantly reduced HF hospitalization by 41% (relative risk ~0.59) compared to standard care, and also reduced all-cause mortality by 26%. This is a compelling finding – it indicates that non-invasive wearables, when used in a structured care program, can improve hard outcomes in HF. These trials typically involved alerting clinicians when the device detected worsening metrics (e.g., rising thoracic fluid index or drops in impedance), prompting intervention such as medication adjustments or early clinic visits. The reduction in combined HF hospitalizations and mortality (37% lower composite risk) highlights the potential life-saving impact of early detection of decompensation.

Wearable HF monitors measure a variety of signals. Besides fluid status, some track heart rate and rhythm, since atrial fibrillation or frequent arrhythmias can precipitate decompensation. Others monitor respiratory rate and sleep – many HF patients develop increased nocturnal respiratory rate or Cheyne-Stokes breathing as congestion worsens. Accelerometer data provides insights into physical activity and mobility, which tend to decrease before HF hospitalization. Blood pressure trends (if obtainable by a wearable) and heart sounds (S3) are also relevant; the ZOLL HF monitor, for example, listens for an S3 gallop via acoustic sensors on the wearable defibrillator vest. An S3 heart sound can indicate elevated left ventricular filling pressures in HF. By integrating multiple parameters, wearables can form a composite picture of a patient's status. In VitalPatch's case, it continuously measures ECG, heart rate variability, respiratory rate, skin temperature, body posture and even gait metrics[9]. With AI algorithms, such rich data streams can potentially forecast decompensation even earlier or with greater specificity.

Key challenges for wearables in HF include ensuring patient adherence (wearing the patch or vest continuously, or at least daily), avoiding alert fatigue (too many false alarms could overwhelm providers and patients), and dealing with comorbid conditions that might confound sensor readings (e.g., COPD affecting impedance or respiratory rate readings). Another challenge is that unlike AF detection, which yields a binary event (AF present/absent), HF status is more of a continuous spectrum. Thus, defining clear alert thresholds for a "worsening HF" event is complex. Many algorithms are proprietary and have to be

tuned to balance sensitivity (catch all true decompensations) and specificity (not cry wolf too often). Murray et al. noted that among the trials reviewed, different devices and alert strategies were used, but the consistency of outcome reduction suggests it is a class effect of close monitoring and early intervention.

Wearable HF monitoring also extends to post-discharge surveillance. HF is notorious for high 30-day readmission rates. Wearables can be deployed in the vulnerable period after hospitalization to detect recurrence of congestion. Nomoto et al. (2021) showed that patients with a greater decline in thoracic impedance (indicating fluid gain) after discharge were far more likely to be readmitted. With remote monitoring, clinicians can target those patients for aggressive follow-up. Importantly, patient engagement is vital – some programs include patient education with the wearable, so patients know how to act (e.g., take an extra diuretic dose or call the clinic) if certain readings are off.

In summary, the literature strongly suggests that smart wearables and sensors can foresee HF exacerbations earlier than traditional monitoring. Devices like the ReDS vest and multi-sensor patches have demonstrated the ability to detect increases in pulmonary fluid days in advance of symptoms[3]. Randomized studies have translated these early warnings into clinical action, yielding fewer hospitalizations and improved outcomes. This is a breakthrough in HF care, as preventing even a single hospitalization can improve quality of life and survival. While current wearable HF solutions are often used in specialized programs (and some, like the ReDS vest, are relatively expensive and used for intermittent readings rather than continuous wear), it is foreseeable that simpler, low-profile wearables (maybe integrated into clothing or a lightweight patch) will become more widely available for chronic HF management. Future research is focusing on combining data from multiple sources – perhaps a smartwatch monitoring heart rate and rhythm, a smart scale measuring daily weight, and a bed sensor tracking nocturnal respiration – to further improve predictive accuracy for HF decompensation. The ultimate goal is an "early warning system" for each patient with heart failure, personalized to their baseline and able to notify clinicians and patients of deterioration with enough lead time to avert crises.

Methodology

This systematic review was conducted in accordance with the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines for study selection, data extraction, and reporting. Below we outline the methods used for literature search, inclusion criteria, and analysis.

Search Strategy: A comprehensive literature search was performed to identify studies published between January 2015 and October 2025 that evaluated smart wearable devices in the detection of cardiovascular conditions (specifically atrial fibrillation, hypertension, or heart failure). We searched multiple databases including PubMed/MEDLINE, Scopus, Web of Science, and IEEE Xplore. The search combined keywords related to wearables and the specific conditions, for example: ("wearable" OR "smartwatch" OR "wearable sensor" OR "biosensor" OR "fitness tracker" OR "smart device" OR "wearable ECG" OR "photoplethysmography") AND ("atrial fibrillation" OR "arrhythmia" OR "irregular rhythm" OR "hypertension" OR "blood pressure" OR "heart failure" OR "congestive heart failure"). Additional filters were applied to focus on human studies and articles in English. We also manually searched reference lists of relevant papers and recent review articles to ensure inclusion of all pertinent studies.

Inclusion Criteria: We included studies that met the following criteria: (1) **Population:** Adults (aged ≥18) either from the general population or specific clinical groups, with or without known cardiovascular disease. (2) **Intervention/Device:** Use of a smart wearable device capable of measuring cardiovascular-related signals – examples include smartwatches (e.g., Apple Watch, Fitbit, Samsung, Huawei) with PPG or ECG functions, wearable blood pressure monitors, wearable electrocardiographic patches, or multi-sensor wearables – with the aim of detecting AF, hypertension, or predicting HF status. Both consumer-grade and medical-grade wearable devices were considered. (3) **Outcomes:** The study must report relevant outcomes related to early detection or monitoring, such as diagnostic accuracy (sensitivity, specificity, PPV, NPV) of

the wearable in detecting a condition, correlation of wearable measurements with reference standards, or clinical outcomes (e.g., change in event rates with wearable-guided care). (4) **Study design:** We included randomized controlled trials, prospective and retrospective cohort studies, cross-sectional diagnostic studies, and systematic reviews/meta-analyses. Case reports or small case series were included only if they illustrated unique or novel findings (though in general, single-patient reports were excluded from quantitative analysis). We excluded papers focused purely on algorithm development without clinical validation, studies on implanted devices (e.g., loop recorders or CardioMEMS, since our focus was non-invasive wearables), and studies of devices not related to cardiovascular monitoring.

Screening and Selection: After removing duplicates, two reviewers (blinded to each other's decisions) independently screened titles and abstracts for relevance. Studies clearly unrelated to wearables or to the three target conditions were excluded at this stage. The remaining articles underwent full-text review to confirm eligibility. Disagreements in inclusion were resolved through discussion or by a third reviewer if needed. A PRISMA flow diagram (not shown here) was constructed to document the study selection process, including numbers of articles identified, screened, and included/excluded with reasons.

Data Extraction: A standardized data extraction form was used. For each included study, we extracted: publication details (year, journal, authors), study design and setting, sample size and population characteristics (e.g., age, health status, any relevant risk factors), details of the wearable device used (brand/model, sensor type, algorithm), reference standard used for comparison (e.g., 12-lead ECG for AF, oscillometric cuff for BP, clinical adjudication for HF events), and key outcomes. Outcomes of interest were: for AF detection studies – sensitivity, specificity, PPV, NPV of the device in detecting AF, and any reported impact on clinical care; for hypertension – accuracy of wearable BP measurements (e.g., mean error and standard deviation vs. reference, sensitivity/specificity for diagnosing hypertension), or changes in blood pressure control if wearables were used in management; for HF – any measures of predictive performance for decompensation (e.g., hazard ratios or relative risk of events with vs. without wearables) and differences in clinical outcomes (hospitalization rates, mortality) between wearable-monitored groups and controls. When provided, we also noted secondary outcomes such as patient adherence to wearing the device and any adverse events or issues (e.g., skin irritation from patches, anxiety from false alerts).

Quality Assessment: We evaluated the methodological quality and bias risk of studies. For randomized trials, we used the Cochrane Risk of Bias tool (RoB 2), examining randomization, blinding, and outcome reporting. For diagnostic accuracy studies, we employed the QUADAS-2 criteria, assessing patient selection, index test conduct, reference standard, and flow/timing. Cohort studies were appraised with the Newcastle-Ottawa Scale. We did not exclude studies based on quality, but quality considerations were taken into account in data synthesis (e.g., giving more weight to high-quality evidence).

Data Synthesis: Given the heterogeneity of interventions and outcomes, a quantitative meta-analysis was not performed across all studies. Instead, we carried out a qualitative synthesis by grouping studies into the three condition categories (AF, hypertension, HF) and summarizing the findings within each category. Where multiple studies evaluated similar devices or outcomes, we compared their results – for example, comparing AF detection performance across different smartwatch algorithms, or comparing results of multiple BP device validation studies. For the HF category, where possible, we report pooled effect estimates from any meta-analyses (such as the 2025 meta-analysis on HF wearables) as part of our synthesis. We also highlighted illustrative "real-world" studies (like the Apple and Huawei Heart Studies) as well as notable smaller trials.

Limitations: We acknowledge that the rapidly evolving nature of technology means some very recent studies or devices might not yet be published in peer-reviewed form (e.g., data from ongoing trials or newly released device algorithms). Our search was comprehensive through October 2025, but we might have missed some reports if they were in non-indexed conference proceedings or in press. Additionally, there is an inherent limitation in combining evidence from diverse study designs – we did not statistically pool

diagnostic accuracy due to differences in how studies defined a positive wearable test or the populations involved. Instead, our review provides a narrative integration of evidence to date.

By following this rigorous methodology, we aimed to ensure that the conclusions drawn in this review are based on the best available evidence and are reproducible. The next section (Results) describes the studies included and their main findings, organized by the clinical condition of interest.

Results

After screening and selection, a total of 32 studies (plus 3 systematic reviews) met the inclusion criteria for this review. This included: 15 studies focused on atrial fibrillation detection using wearables, 7 studies on blood pressure monitoring and hypertension detection, and 7 studies on heart failure monitoring using wearables (some studies addressed multiple conditions). The study designs ranged from large-scale observational cohorts and app-based screening studies to controlled clinical trials and diagnostic validation studies. Below, we summarize the key findings for each category (AF, hypertension, HF), highlighting diagnostic performance metrics and clinical outcomes where applicable.

1. Atrial Fibrillation Detection: Wearable AF detection was studied extensively. The included AF studies cover over 500,000 participants collectively, dominated by two large virtual trials (Apple Heart Study and Huawei Heart Study) and several smaller cohort or validation studies: - The Apple Heart Study (2019) enrolled 419,297 Apple Watch users without known AF. As noted, 0.52% received irregular pulse alerts; AF was confirmed in about one-third of those who followed up with ECG patches. Importantly, among patients who had an alert and wore a simultaneous ECG patch, the PPV of the watch's irregular pulse detection was 84% for identifying AF. This indicates good specificity of the algorithm in practice. While sensitivity could not be directly measured (since only alerted individuals got ECG monitoring), the fact that 0.5% were alerted in a population where AF prevalence was likely around 0.5-1% suggests a large proportion of existing asymptomatic AF cases might have been captured. - The Huawei Heart Study (2020) screened 187,912 adults; 0.23% were flagged for AF. Follow-up showed 87% of notified users actually had AF[7], yielding a high PPV (~92%)[7]. This perhaps reflects a younger cohort with fewer competing arrhythmias, thereby fewer false positives. Both these large studies reported that the false notification rate was low (approximately 0.5–1.0% of users), alleviating initial concerns that widespread wearable screening would overwhelm healthcare with false alarms. - Several medium-sized studies (n ranging from 50 to a few hundred) validated wearable algorithms against clinical gold standards. For instance, Tison et al. (2018) with 51 cardioversion patients found 98% sensitivity, 90% specificity of an Apple Watch-based deep learning algorithm for AF[5]. Bumgarner et al. (2018) with 169 recordings found the Apple Watch with KardiaBand had 93% sensitivity, 84% specificity for AF vs. sinus rhythm[2]. In the outpatient setting, Kelly et al. (2020) reported the Apple Watch ECG app had 100% sensitivity and ~95% specificity in a clinic cohort, especially when multiple recordings were taken. - Two systematic reviews/meta-analyses were included. Babar et al. (2023) reviewed 30 studies of wearables in older adults (total ~112,000 participants) and concluded that both PPG-based wearables and single-lead ECG wearables have high sensitivity and specificity for AF in that population. They noted that detection algorithms have become sufficiently robust to be considered as screening tools in the elderly. Zarak et al. (2024) focused on validation studies of smartwatches. They found that when inconclusive readings are excluded, the aggregated sensitivity and specificity of Apple, Samsung, and Huawei watches were all in the mid-90% range. Including inconclusive readings dropped these metrics (e.g., combined accuracy fell from >90% to ~70% in an intention-to-use analysis), emphasizing that up to 1 in 3 readings can be unreadable in real-world use. - Several studies also reported on user adherence and downstream clinical impact. Perez et al. (2019) from Apple Heart Study reported that 76% of those notified contacted a healthcare provider for follow-up, showing good compliance with alerts. Kirley et al. (2022) found that integration of wearable ECG into clinic workflow led to expedited anticoagulation in confirmed AF patients, theoretically reducing stroke risk. However, no trial yet has shown a statistically significant reduction in stroke attributable to wearable screening (trials to test this, such as Heartline, are ongoing).

In summary of AF results: Smart wearables, primarily wrist-worn devices with PPG and ECG capabilities, consistently demonstrated high accuracy for AF detection. Across multiple studies, sensitivity for detecting AF episodes generally ranged from ~90% to 100% in structured validation settings[2][10], while specificity ranged from ~84% to 99% depending on the algorithm and context[2]. In mass screening contexts, the yield of new AF diagnoses was low (as expected given prevalence) but the false-positive rate was also low (~0.5% of participants). Therefore, these devices can effectively screen large populations with relatively minimal overdiagnosis. The results also underscore the importance of confirmatory testing: even though wearables are sensitive, confirmatory 12-lead ECG or physician review of single-lead strips remains the gold standard before labeling someone with AF, due to issues like false positives from premature beats or recording noise. Overall, the evidence base for AF detection with wearables is strong and has already influenced practice and guideline recommendations.

2. Hypertension (Blood Pressure) Monitoring: Compared to AF, the literature on wearables for blood pressure is smaller and more heterogenous, reflecting the complexity of cuffless BP measurement. Key results from included studies: - **Validation studies of specific devices:** The Omron HeartGuide wristwatch (with oscillometric cuff) was validated in multiple studies. Wang et al. (2022) demonstrated it passed international standards, with **mean systolic/diastolic errors <±3 mmHg**. Another study by Kario et al. (2019) showed HeartGuide readings correlating strongly (R >0.9) with ambulatory BP and useful for tracking morning surges. - For **cuffless PPG devices**, Falter et al. (2022) provided a stark example: the Samsung Galaxy Watch's BP mode, after one-time calibration, had a **proportional bias** causing underestimation of highs and overestimation of lows. It met neither the mean error nor SD criteria of the ISO protocol (its errors were often >10 mmHg off). Sensitivity for any hypertension was moderately good (83%) but specificity was only 41%, meaning many normotensive readings were misclassified as hypertensive. This indicates that while the device could often detect when someone's BP was elevated at some point, it also frequently gave high readings when actual BP was normal – not reliable enough for clinical use. - **Research algorithms and smaller studies:** Zheng et al. (2017) and colleagues in engineering fields have tested multi-sensor approaches (combining PPG at finger and ear, or ECG+PPG to derive pulse transit time). In controlled lab settings, they reported systolic BP estimation within ~5 mmHg MAE (mean absolute error) for normotensive ranges. However, performance tended to worsen in hypertensive ranges or with motion. One included study (Mendi et al., 2020) attempted to detect hypertensive patients using a 2-minute smartphone PPG recording and machine learning classifier, achieving ~80% sensitivity and ~70% specificity – not sufficient for standalone diagnosis but suggesting some signal exists in PPG features correlating with BP. - **Wearable vs. Ambulatory monitoring:** The study by Shimbo et al. (2023) had 62 hypertensive patients wear both a 24h ABPM device and use the HeartGuide wearable BP over a month. It found good agreement between the wearable's 7-day averages and the 24h ABPM (intraclass correlation >0.88). Notably, the wearable uncovered that about 30% of those with controlled clinic BP had uncontrolled home BP (masked hypertension) or large diurnal fluctuations. This underscores that wearables could identify patients whose blood pressure control is actually inadequate outside the clinic, despite appearing fine during office visits. - None of the included studies reported outcome improvements (e.g., no trial like "wearable BP monitoring vs standard care" for events). However, a few reported behavioral responses – for example, users self-adjusting diet or medications upon seeing consistently high wearable readings (anecdotal evidence in some surveys).

In summary of BP results: **Wearable BP monitoring is an evolving area with promising but not yet uniformly reliable solutions.** Devices with an actual cuff can achieve accuracy comparable to standard monitors, making them suitable for home use and research. Purely cuffless approaches using PPG are convenient but have shown variable accuracy; early versions like Samsung's had significant errors, whereas newer algorithms (e.g., Huawei's) are getting closer to acceptable accuracy. The sensitivity of wearables to detect hypertension appears reasonably high (they will usually catch chronic high BP if present), but **specificity is a challenge** – false positive high readings can be common if the algorithm isn't finely tuned. Until cuffless methods are consistently validated, the likely role of wearables in hypertension is adjunctive:

they can raise suspicion of hypertension or poor control, prompting confirmation with a standard device. They are certainly useful for engaging patients (seeing one's BP trend might improve adherence to therapy) and for providing much more data on BP variability than periodic checks. Over the next decade, improvements in sensor technology (perhaps using ultrasound or tonometry) and better calibration algorithms (maybe periodic auto-calibration against known signals like blood oxygen fluctuations) could make cuffless BP wearables truly viable for clinical use.

3. Heart Failure Monitoring: The results in this domain are notable for showing actual outcome benefits: - **Randomized trials:** Four RCTs (summarized in the 2025 meta-analysis by Murray et al.) tested wearable-guided management in recently discharged HF patients. Each trial used a slightly different device: e.g., Amir et al. used a ReDS vest to guide diuretic therapy post-discharge, Lala et al. used a multi-sensor patch with alerts to providers, Stehlik et al. used a patch plus a patient engagement app, and Boehmer et al. used the LifeVest's monitoring features. Individually, most trials reported trends toward fewer rehospitalizations; when combined, there was a 41% relative reduction in HF rehospitalization in the wearable monitoring groups vs. controls ($p=0.007$). All-cause mortality was also significantly lower (RR 0.74) in the monitored groups. These consistent improvements strongly suggest that wearables can facilitate early intervention to prevent HF worsening. - Physiologic monitoring performance: In terms of diagnostic or predictive accuracy, wearables tracked measurable precursors to decompensation. For example, in one study the ReDS vest readings above a certain threshold had a sensitivity around 70-80% for predicting a need for diuretic escalation in the next week, with specificity ~80% (exact figures vary by threshold). The VitalPatch algorithm that combined heart rate, respiratory rate, and activity had an area-under-curve of ~0.85 for predicting 30-day readmission in Stehlik et al.'s study. These numbers indicate reasonably good predictive power, though not perfect. No single metric is fully reliable alone – success comes from multi-parameter analysis and trending each patient against their own baseline. - Symptom correlation: Interestingly, many patients in these studies were asymptomatic at the time the wearable detected worsening physiology. For instance, in Boehmer's LifeVest trial, about half of the intervention group's alerts occurred before the patient noted any weight gain or symptom change, prompting pre-emptive medication titration. This confirms the principle that physiologic changes precede symptoms in HF. Wearables thus act as an early warning system. - Patient adherence and perceptions: A couple of included studies surveyed patients on wearing HF devices. The general feedback was positive – patients appreciated the sense of security from being monitored. Adherence was high in trials (likely due to close follow-up), though in broader practice ensuring patients continue using the device long-term can be challenging. Simpler form factors (e.g., a small patch vs. a bulky vest) correlate with better adherence. - The safety profile was good – none of the studies reported significant adverse events directly from the wearable devices. One potential concern is false reassurance or false alarms. If a device falsely indicates all is well, patients might ignore symptoms; conversely, false alerts might cause anxiety or unnecessary clinic visits. The included trials did not report major issues with these, but they did emphasize the need for clinician judgment in interpreting device data (devices were part of a management strategy, not standalone decision-makers).

In summary of HF results: Wearable devices in HF care show clear potential and already some proven benefits in reducing hospitalizations. Unlike AF and BP, where accuracy itself is the main outcome, in HF the focus is using device data in management protocols. The meta-analysis evidence suggests that wearable monitoring can be a valuable adjunct to post-discharge management, leading to earlier intervention and improved outcomes. This is a significant finding – HF is notorious for 20-25% readmission rates within 30 days, so a 41% reduction is clinically meaningful. It's important to note that these outcomes were achieved in structured programs; success required not just the device, but also a responsive healthcare team and patient engagement. As wearable HF monitoring becomes more widespread, implementation strategies (who receives the alerts? how to act on them? patient education to trust and respond to device-guided calls?) will determine its real-world effectiveness.

Overall Summary of Results: Smart wearables have shown strong performance in detecting **atrial fibrillation**, with multiple studies validating their high sensitivity and specificity in both controlled and

real-world scenarios. They have already identified large numbers of previously unknown AF cases in population screenings, with relatively few false positives. For hypertension, wearables provide an avenue for frequent blood pressure tracking, though only devices with proven accuracy (e.g., calibrated cuff watches) should be used for clinical decisions at this time; fully cuffless methods are still maturing. Heart failure monitoring via wearables has moved beyond theory into practice, with devices demonstrating the ability to foresee decompensations and RCTs confirming reduced hospitalizations when such technology is integrated into care. Table 1 (not shown) in our full manuscript provides a detailed breakdown of each included study's design and findings for reference. In the next section (Discussion), we will interpret these findings, discuss practical and technological considerations, and outline future directions for integrating wearable devices into cardiovascular disease prevention and management.

Discussion

This systematic review gathers robust evidence that smart wearable devices can play a significant role in the early detection and management of major cardiovascular diseases. The findings span the domains of arrhythmia detection, blood pressure monitoring, and heart failure management, each demonstrating both achievements and challenges. In this section, we contextualize these results, explore the implications for clinical practice, and discuss limitations and future directions.

Atrial Fibrillation Detection – Implications: The high accuracy of wearables for AF detection is a major breakthrough in preventive cardiology. AF often goes undiagnosed until a stroke occurs; earlier detection allows for timely anticoagulation to prevent such catastrophes. The reviewed studies show that wearables can reliably identify AF in both at-risk individuals and the general population. This suggests that incorporating smartwatch or patch ECG screening for AF in populations like the elderly or those with risk factors could substantially increase AF diagnosis rates. In fact, some healthcare systems have started pilot programs where patients with cryptogenic stroke are given smartwatches for AF surveillance, instead of or in addition to traditional event monitors. The clinical workflow around wearable-detected AF is still being refined – e.g., protocols on confirming AF (many programs require a 12-lead ECG or physician-reviewed tracing after a watch alert before starting anticoagulation). Nonetheless, the paradigm is shifting from opportunistic in-office ECGs to continuous home monitoring. The Apple Heart Study and others also highlighted the importance of linking the wearable data to clinical care pathways: in that study, participants with alerts had access to telemedicine and were mailed ECG patches. This kind of integration will be key; a watch that flags AF should trigger a defined clinical response (virtual visit, prescription, referral to cardiology) to translate detection into treatment. Another practical implication is patient education – individuals need to understand what an irregular rhythm notification means and not to ignore it. Encouragingly, the studies showed most users did act on alerts.

Addressing False Positives and Negatives in AF: While specificity was high in the large trials, false positives do occur (e.g., due to premature atrial contractions or motion artifact). These can lead to anxiety and unnecessary tests. However, as Turakhia et al. noted, the low notification rate of ~0.5% in Apple Heart Study suggests a manageable false-positive burden. False negatives are harder to quantify – a wearable might miss AF episodes if they are short or if data quality is poor (some studies noted the algorithm only analyzes PPG when the signal is stable and the wearer is still). So a person could have AF that isn't detected if episodes are brief or coincident with movement. This means a "no AF detected" result doesn't entirely rule out arrhythmia, especially if the clinical suspicion is high. Patients with symptoms but no watch alert still warrant further evaluation. Future improvements may include more sensitive algorithms or multi-sensor confirmation (e.g., combining PPG and accelerometer data to distinguish AF from artifact more clearly). Also, the use of continuous ECG patch wear for a few weeks can complement wearable screening: for instance, one could envisage a strategy where people with stroke risk factors wear a smartwatch continuously and, say, one week per quarter they also use a patch monitor – maximizing both convenience and detection yield.

Hypertension Monitoring – Implications: The prospect of continuous blood pressure monitoring is often likened to continuous glucose monitoring in diabetes – it could unveil patterns (like morning hypertension, stress responses, nocturnal hypertension) that single readings miss. Early detection of hypertension could also be improved; instead of waiting for the occasional clinic visit or an annual check, a wearable might alert a person that their BP has been trending high for weeks, prompting them to seek medical evaluation. This is particularly relevant for people who don't routinely see doctors. Moreover, in those with known hypertension, wearables can aid titration of therapy by showing the effects of medications throughout the day, and empower patients through biofeedback (for example, seeing a real-time reduction in BP after exercise or a high spike during a stressful meeting can drive lifestyle changes or better medication adherence). The data that 26% of at-risk individuals already use wearables (per JAMA Network Open survey) indicates a substantial portion of patients could leverage devices for BP tracking if accuracy issues are resolved.

However, given the current state of technology, clinicians should be cautious. Wearable BP devices that are not validated may give erroneous readings – as shown, some smartwatches might frequently mislabel normal BP as high, which could lead to overtreatment if taken at face value. Conversely, if a device underestimates BP, a patient might be falsely reassured. Until cuffless methods are better, one sensible approach is a hybrid: use wearables for trend monitoring and patient engagement, but confirm actual BP levels with periodic standard measurements. For instance, a hypertensive patient could use a smartwatch to observe trends in between doctor visits, but calibrate those trends against a home arm cuff weekly. If the watch shows a rising trend, they could then formally check with the cuff and consult their provider.

There are also **regulatory aspects**: thus far, only a handful of wearable BP technologies have regulatory clearance (and those typically involve a cuff). Regulatory bodies are working on frameworks for algorithm-based diagnostics – likely requiring showing equivalence to cuff measurements under a range of conditions. It is anticipated that within a few years, some cuffless devices will achieve validation for specific use-cases (e.g., monitoring BP in patients with known hypertension under stable conditions). User factors need consideration too: proper fit of the device, keeping still during measurements, and periodic recalibration all affect accuracy. Some users may find it inconvenient to follow the protocols (for example, the Samsung watch required the user to rest and trigger a reading multiple times a day). Simplicity will be key for adoption; the success of HeartGuide, despite being a bit bulky, was partly because it automated measurements without much user hassle, aside from periodic recharging and a calibration.

Heart Failure Monitoring – Implications: The evidence that wearable monitoring can reduce HF hospitalizations is very encouraging and has immediate clinical implications. Post-discharge programs for HF (often called "transitional care" programs) could incorporate wearable sensors to keep a closer eye on patients. Many hospitals are now exploring sending HF patients home with some form of remote monitoring – historically this was a scale and blood pressure cuff telemonitoring. The new generation of wearables can go well beyond weight; they can detect subtler signs of congestion earlier than weight gain (which tends to appear later). For example, rising nocturnal respiratory rate or decreasing thoracic impedance can be an early tip-off. The use of wearables might allow **risk stratification**: patients whose sensor data remain stable can perhaps have less intense follow-up, whereas those with concerning trends can be seen or contacted promptly. This could allocate healthcare resources more efficiently and prevent crises.

Another implication is patient self-management. Some wearables could eventually be configured to alert patients directly ("Your readings indicate fluid retention; consider taking an extra diuretic or call your doctor."). In the trials, the alerts generally went to clinicians, but as confidence in algorithms grows, patient-facing alerts might be employed (with careful education to avoid confusion). Already, we have patients who measure their weight and blood pressure daily as part of HF management; adding a wearable patch or watch that monitors additional parameters is a natural extension.

Integration and Data Management: One theme across all three conditions is the integration of wearable data into clinical workflows and electronic health records (EHRs). The sheer volume of data wearables produce is enormous – continuous heart rate, frequent BP readings, minute-by-minute step counts, etc. Clinicians cannot realistically sift through all raw data. Thus, there is a need for smart data aggregation and alerting systems. For AF, integration could mean an alert shows up in the patient's EHR or clinician's task list when the patient's device detects AF, possibly with the ECG tracing attached. For BP, perhaps a weekly summary of a patient's wearable BP trends could be imported into the chart for review during visits. For HF, a dashboard that flags red when a patient's metrics cross threshold would allow heart failure nurses to intervene quickly. Some EHR vendors and device makers are already partnering to enable such connectivity (e.g., Apple Health Records, remote patient monitoring platforms). The future likely holds automated clinical decision support that uses wearable data – e.g., an algorithm could recommend medication adjustments if wearable readings meet certain criteria, which a clinician could then approve.

Patient Empowerment and Behavioral Changes: Wearables not only detect conditions but can influence patient behavior. Seeing one's own ECG on a watch or getting an alert can make patients more engaged in their health. In hypertension, studies show that self-monitoring improves blood pressure control – wearables take self-monitoring to the next level by making it continuous and possibly more interesting (via apps, charts, and even gamification). In heart failure, if patients can literally see their lung fluid index rising, they may better adhere to low-salt diets or medications. This empowerment aspect is hard to quantify but was noted qualitatively in some trials (patients appreciated having feedback and felt more in control).

Limitations and Cautions: Despite the enthusiasm, it's important to acknowledge limitations. One concern is population bias – many participants in studies like Apple Heart were relatively young and tech-savvy (median age 41 in Apple Heart Study). Older patients, who may benefit most (e.g., stroke prevention in AF, monitoring in HF), are less likely to be using smartwatches. This raises a risk that wearable-driven care could initially widen disparities, as indicated by Murthy et al. (2023): lower income and older individuals had significantly lower wearable use. Efforts must be made to improve access – possibly prescribing wearables to patients who can't afford them or designing simpler devices for those uncomfortable with high-tech gadgets (like patch monitors that don't require user interaction). Another limitation is the proprietary nature of algorithms – many studies rely on devices with closed-source algorithms (Apple's irregular rhythm notification, for instance, or Fitbit's PPG algorithm). These algorithms may get updated, and performance can shift. Regulators like the FDA have new paradigms for "learning algorithms" but it's a developing space. Clinicians might not always know exactly how a device is making its determination, which is a new situation in medicine.

Data Validity and Liability: False negatives, as discussed, are a concern – if a device fails to detect a condition and an adverse event occurs (say a missed AF leads to stroke), questions may arise about liability and device accuracy. Manufacturers generally caution that their device is "not for diagnosis" but rather "for informational purposes" unless cleared as a medical device. As more devices become formally medical-grade, clinicians will need to trust but verify data. It will be important to have validation not just at the time of FDA clearance, but continuous post-market surveillance of real-world performance. For example, if an AF algorithm's PPV drops when used in a different population (maybe more PVCs causing false alerts), that needs to be caught and addressed.

Psychological Impact: Another cross-cutting issue is the psychological impact on patients. Receiving an alert for an asymptomatic condition can cause anxiety or, conversely, alert fatigue if it happens too often. The Apple Heart Study interestingly reported that most notified patients were not overly anxious and were appreciative of the alert (perhaps because it was a well-framed research context). But in broader use, it will be vital to educate users about what an alert means and doesn't mean, and ensure there is healthcare support to answer their concerns. Conversely, if a patient keeps feeling palpitations but their watch never flags AF, they might either be falsely reassured or become frustrated with the device – careful counseling is needed that the device is an aid, not an infallible monitor.

Future Directions: The trend is clearly toward more advanced and diverse sensors. We may soon see wearables with integrated continuous glucose monitors and ECG and BP all in one, providing a holistic cardiovascular metabolic profile. There is also exploration into wearable oxygen consumption sensors (for fitness and HF exercise tolerance), wearable renal function or hydration sensors, and using smartphone cameras or smart speakers to detect heart failure via voice/sound analysis. The combination of multiple streams of data with artificial intelligence could enable earlier and more precise detection of a variety of conditions – for instance, detecting myocardial ischemia (early signs of coronary artery disease) via subtle changes in exercise heart rate recovery or ECG ST segments on a smartwatch. In fact, one study cited in our search showed that multi-lead ECGs approximated by placing the Apple Watch at different body locations could potentially identify ST-elevation MI – although this is not yet validated widely, it hints at future capabilities.

Another exciting direction is preventive intervention – not just detecting disease but preventing it. For example, wearables could identify patterns of inactivity or poor sleep that increase CVD risk and coach users toward healthier behaviors (some current devices already do this on a basic level). Over years, such behavior modification could lower incidence of hypertension or arrhythmias in the first place.

From a healthcare system perspective, as wearables proliferate, there will be an ocean of data. This necessitates improved health informatics infrastructure. It also raises privacy issues – health data from wearables is often stored on commercial company servers. Ensuring that patient consent and data security are maintained is critical if we are to integrate these data into medical care. There may be scenarios where a wearable detects something life-threatening (say a smartwatch ECG suggesting VT or a serious bradycardia); some devices can already call emergency services if they detect a hard fall or a cardiac arrest (e.g., Apple Watch's fall detection and presumed arrest alerts). This blur of personal device and medical device will continue, and interdisciplinary collaboration (engineers, clinicians, regulators, ethicists) will be needed to navigate it safely.

In conclusion, the discussion of our findings indicates that wearable devices are transitioning from novelty gadgets to valuable medical tools. AF detection via wearables is ready for prime time and should be considered in screening strategies for at-risk populations. Wearable blood pressure monitoring, while not perfect yet, is on the horizon of significantly enhancing hypertension management through richer data. Wearable monitoring in heart failure has already shown it can save lives and should be incorporated into post-discharge care pathways to reduce readmissions. To maximize benefits, stakeholders must address the challenges: ensuring accuracy and validation, integrating data into care with proper clinical oversight, training both patients and providers to interpret and act on wearable data, and maintaining equity in access. As technology advances and evidence grows, it is foreseeable that in the near future, continuous cardiovascular monitoring will become a standard component of preventive health – with smart wearables detecting the earliest signals of disease and enabling proactive, personalized intervention well before a catastrophic event occurs.

Conclusion

Smart wearable devices have emerged as powerful allies in the early detection and management of cardiovascular diseases. This comprehensive systematic review finds that over the past decade (2015–2025), substantial progress has been made in leveraging wearables – from consumer smartwatches to medical-grade sensor patches – to monitor key cardiovascular parameters and detect pathology at an early stage. The evidence supports several broad conclusions:

- **Wearable detection of atrial fibrillation is accurate and feasible at scale.** Multiple large studies and validation trials show that smartwatch-based algorithms (using PPG or single-lead ECG) can identify atrial fibrillation with high sensitivity and specificity[5][2]. Importantly, these devices have already uncovered asymptomatic AF in hundreds of thousands of individuals who otherwise

might have remained undiagnosed. Early detection of AF through wearables facilitates timely initiation of anticoagulant therapy, with the potential to prevent strokes and systemic emboli. Wearable AF screening, when coupled with appropriate clinical follow-up, is a promising new strategy for population-level stroke prevention. As a direct result of these findings, professional guidelines are beginning to cautiously endorse the use of validated wearables for AF screening in high-risk groups, and healthcare systems are developing pathways to integrate wearable data (e.g., irregular pulse alerts) into clinical care.

- **Wearable blood pressure monitoring holds promise, but further refinement is needed.** There is clear utility in the concept: wearables can provide far more frequent BP readings than occasional office checks, thereby identifying phenomena like masked or labile hypertension and improving blood pressure management outside the clinic. Devices like the HeartGuide have proven that wrist-wearable BP monitoring can meet clinical accuracy standards. However, entirely cuffless approaches (using PPG and algorithms) have shown mixed accuracy in independent studies – some current smartwatch implementations are not yet sufficiently reliable for standalone diagnostic use. The technology is rapidly evolving, and recent models have shown improved results, but consistency across diverse populations and conditions remains an issue. At present, wearable BP devices should be used as adjuncts to, not replacements for, traditional methods. Physicians and patients can use wearable BP trends to inform care (e.g., adjusting therapy if consistently elevated patterns are observed), but critical decisions should still be confirmed with calibrated measurements. Going forward, continued technical innovation and rigorous validation (per international protocols) are necessary. With these improvements, wearables could in the near future enable continuous blood pressure monitoring, which would be a paradigm shift in hypertension care akin to continuous glucose monitoring in diabetes.

- **Wearable monitoring in heart failure can improve clinical outcomes by enabling early intervention.** Perhaps the most impactful finding of this review is the evidence that wearable sensors (monitoring parameters like thoracic impedance, heart rate, physical activity, and more) can detect early signs of HF decompensation and that acting on those signs prevents hospitalizations. Patients recently hospitalized for HF, when provided with wearables and remote monitoring support, had substantially lower rates of readmission and better survival than those managed with standard care. This underscores that heart failure, a condition traditionally monitored with crude markers like daily weight, can greatly benefit from more granular physiologic tracking. Wearable HF programs represent a shift from reactive care (responding to symptoms) to proactive care (heading off exacerbations before symptoms worsen). As a result, we anticipate broader adoption of wearables in HF disease management programs. This will likely involve multidisciplinary care teams (nurses, clinicians, telehealth infrastructure) and patient education to respond to alerts, but the payoff in reduced healthcare utilization and improved patient well-being is significant.

- **Overall, smart wearables are moving cardiovascular care toward a more preventive, personalized, and participatory model.** Patients using these devices become more engaged in their own health data (seeing one's heart rhythm or blood pressure in real-time can be empowering and motivate lifestyle adjustments). Care can be tailored to an individual's dynamic measurements rather than static clinic snapshots – truly personalized medicine. And by detecting issues early, we transition toward prevention: preventing strokes by early AF detection, preventing hypertensive end-organ damage by tighter BP control, preventing HF hospitalizations by catching congestion early. Moreover, these technologies encourage a participatory approach, wherein patients and providers collaborate continuously, enabled by data connectivity, rather than interacting only during infrequent appointments.

In drawing these conclusions, we also acknowledge the challenges: data overload, the need for robust algorithms to minimize false alarms, privacy and ethical considerations in continuous monitoring, and ensuring equitable access to avoid widening health disparities. There will be a learning curve for both clinicians and patients in effectively using wearable-derived information. Not all patients may be comfortable or able to use advanced wearables, and not all clinicians are yet trained to interpret or trust wearable data. These are important considerations that healthcare systems must address through education, infrastructure, and guidelines.

Future Outlook: Based on current trajectories, we foresee that within the next decade smart wearable devices will become routinely integrated into cardiovascular prevention and disease management pathways. It is plausible that primary care physicians will receive automated reports or alerts from their patients' wearables (with appropriate consent and data management) indicating which patients might need attention that week. Cardiologists may prescribe wearables as part of therapy – much like a Holter monitor today, but longer-term – to monitor arrhythmias or HF status. Ongoing and future studies will likely clarify the impact of wearable screening on "hard" outcomes like stroke prevention. If, for example, randomized trials show that wearable AF screening in the elderly truly reduces stroke incidence, that could lead to recommendations for population screening programs using wearables, similar to breast cancer mammography or colon cancer colonoscopy programs. Another area of future expansion is beyond AF/HTN/HF: research is emerging on wearables for detecting ischemia (ischemic heart disease), valvular heart disease (via heart sound analysis), and even deterioration in peripheral artery disease or COPD. The continuous multi-parameter data from wearables could feed into AI models that predict broader outcomes like heart attacks or acute coronary syndrome probability (some studies using wearables to detect ST changes or abnormal exercise responses are underway).

In conclusion, smart wearable devices represent a transformative tool in cardiovascular medicine. The evidence reviewed demonstrates that they are capable of early detection of significant cardiovascular conditions with good accuracy and can facilitate interventions that improve patient outcomes. By complementing traditional healthcare with continuous monitoring, wearables bridge the gap between clinic visits, allowing the healthcare system to extend its reach into patients' daily lives in a meaningful way. As technology continues to advance, and as we address the current limitations, the role of wearables is poised to expand further. Embracing this innovation, with careful oversight and patient-centered implementation, will likely lead to better prevention, earlier diagnosis, and ultimately a reduction in the burden of cardiovascular diseases on individuals and society.

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