International Journal of Innovative Technologies in Social Science

e-ISSN: 2544-9435

Operating Publisher
SciFormat Publishing Inc.
ISNI: 0000 0005 1449 8214

2734 17 Avenue SW,
Calgary, Alberta, T3E0A7,
Canada
+15878858911
editorial-office@sciformat.ca

ARTICLE TITLE	WEARABLE TECHNOLOGIES FOR ATRIAL FIBRILLATION: A NARRATIVE REVIEW OF DIAGNOSTIC ACCURACY, CLINICAL INTEGRATION, AND THE MANAGEMENT OF SILENT ARRHYTHMIAS
DOI	https://doi.org/10.31435/ijitss.1(49).2026.5512
RECEIVED	06 January 2026
ACCEPTED	17 March 2026
PUBLISHED	27 March 2026
LICENSE	The article is licensed under a **Creative Commons Attribution 4.0 International License.**

WEARABLE TECHNOLOGIES FOR ATRIAL FIBRILLATION: A NARRATIVE REVIEW OF DIAGNOSTIC ACCURACY, CLINICAL INTEGRATION, AND THE MANAGEMENT OF SILENT ARRHYTHMIAS

Szymon Janczarski *(Corresponding Author, Email: smjanczarski@gmail.com)*
Medical University of Silesia in Katowice, Poland
ORCID ID: 0009-0004-0881-1083

Aleksandra Banaś
Medical University of Silesia in Katowice, Poland
ORCID ID: 0009-0009-5584-5944

Dominika Sarna
Medical University of Silesia in Katowice, Poland
ORCID ID: 0009-0001-4849-8093

Piotr Widera
Medical University of Silesia in Katowice, Poland
ORCID ID: 0009-0008-7518-2482

Maciej Michalik
Medical University of Silesia in Katowice, Poland
ORCID ID: 0009-0007-9778-8736

Klaudia Kwolek
Medical University of Silesia in Katowice, Poland
ORCID ID: 0009-0003-2145-7528

Marcel Pilarek
Medical University of Silesia in Katowice, Poland
ORCID ID: 0009-0004-4114-5078

Wiktoria Laskowska
Medical University of Silesia in Katowice, Poland
ORCID ID: 0009-0000-8116-0038

Filip Basta
Medical University of Silesia in Katowice, Poland
ORCID ID: 0009-0008-4685-7778

Hubert Dacyl
Medical University of Silesia in Katowice, Poland
ORCID ID: 0009-0002-6417-6382

ABSTRACT

Atrial fibrillation (AF) is the most common sustained cardiac arrhythmia worldwide and represents a major contributor to stroke, heart failure, and cardiovascular mortality. A significant proportion of AF cases remain asymptomatic, often referred to as "silent AF," which delays diagnosis and increases the risk of severe thromboembolic complications. Conventional diagnostic methods, including standard electrocardiography (ECG) and short-term Holter monitoring, are limited by their episodic nature and reliance on clinical settings, frequently failing to capture intermittent arrhythmic events. In recent years, consumer wearable technologies - particularly smartwatches equipped with photoplethysmography (PPG) sensors and single-lead ECG capabilities - have emerged as promising tools for continuous cardiac rhythm monitoring.

This narrative review synthesizes contemporary evidence on the diagnostic accuracy, clinical integration, and behavioral implications of wearable technologies for AF detection. Literature published between 2018 and 2025 was identified through searches of PubMed/MEDLINE, Scopus, and Google Scholar. Studies evaluating sensing technologies, algorithmic approaches, large-scale population trials, and digital health behavior were included.

Current evidence demonstrates that wearable devices can achieve high concordance with traditional ECG-based diagnostic methods, with many studies reporting sensitivities and specificities exceeding 90%. Passive PPG monitoring combined with user-initiated ECG confirmation enables scalable detection of previously undiagnosed AF in real-world settings. However, challenges remain, including signal artifacts, false-positive alerts, user adherence, and socioeconomic disparities in device access.

Overall, wearable technologies represent a valuable adjunct for early AF detection and long-term rhythm monitoring. Their optimal clinical role lies within hybrid diagnostic pathways that integrate patient-generated data with physician validation and established cardiovascular care frameworks.

KEYWORDS

Atrial Fibrillation, Wearable Devices, Remote Patient Monitoring, Single-Lead ECG, Photoplethysmography, Socio-Technical Barriers

CITATION

Szymon Janczarski, Aleksandra Banaś, Dominika Sarna, Piotr Widera, Maciej Michalik, Klaudia Kwolek, Marcel Pilarek, Wiktoria Laskowska, Filip Basta, Hubert Dacyl. (2026) Wearable Technologies for Atrial Fibrillation: a Narrative Review of Diagnostic Accuracy, Clinical Integration, and the Management of Silent Arrhythmias. *International Journal of Innovative Technologies in Social Science*. 1(49). doi: 10.31435/ijitss.1(49).2026.5512

1. Introduction

Atrial fibrillation (AF) represents one of the most common and clinically significant cardiac arrhythmias worldwide, imposing an escalating epidemiological and economic burden on global healthcare systems. In the United States alone, the prevalence of AF is projected to more than double, reaching an estimated 12.1 million cases by 2030, with the overall lifetime risk approaching 30% to 40% (Joglar et al., 2023). Characterized by disorganized atrial electrical activity and subsequent mechanical dysfunction, AF serves as a primary catalyst for profound cardiovascular morbidity and mortality. The arrhythmia is associated with a 1.5- to 2-fold increased risk of death, a 5-fold increased risk of incident heart failure, and a 2.4-fold increased risk of stroke (Joglar et al., 2023). The pathophysiology driving these outcomes is rooted in the stasis of blood within the fibrillating atria, particularly the left atrial appendage, which creates a highly thrombogenic environment (Hindricks et al., 2021). Despite the life-threatening severity of these sequelae, a substantial proportion of the AF population - estimated at up to one-third of all patients - remains entirely asymptomatic, experiencing what is clinically defined as "silent" AF (Joglar et al., 2023). This subclinical presentation profoundly complicates the clinical landscape, as it obscures the true prevalence of the disease and allows prothrombotic cascades and structural atrial remodeling to progress unchecked. Frequently, a catastrophic thromboembolic event serves as the first and only clinical manifestation of previously undetected silent AF (Joglar et al., 2023).

The insidious and asymptomatic nature of AF underscores a critical "window of opportunity" in the clinical management of the arrhythmia, wherein early detection fundamentally alters the therapeutic trajectory.

The time elapsed from the actual pathophysiological onset of AF to its formal electrocardiographic diagnosis dictates the viability of specific treatment paradigms. When AF is identified in its early, paroxysmal stages - prior to the onset of irreversible atrial fibrosis and extensive electrophysiological remodeling - clinicians can successfully pursue a proactive rhythm control strategy. As conclusively demonstrated by the landmark EAST-AFNET 4 trial, implementing interventions such as cardioversion or catheter ablation within this early window significantly improves long-term cardiovascular outcomes and reduces the risk of severe complications compared to usual care (Kirchhof et al., 2020). Conversely, a delayed diagnosis typically confronts clinicians with persistent or permanent AF, characterized by advanced structural remodeling that renders rhythm control interventions largely futile. In such late-stage scenarios, clinical management is heavily restricted to a conservative rate control strategy combined with lifelong anticoagulation, which may mitigate symptoms and stroke risk but fundamentally fails to arrest the underlying progression of the cardiac disease (Hindricks et al., 2021). Consequently, the timely and accurate diagnosis of subclinical AF constitutes a major, unmet clinical need. Establishing scalable diagnostic pathways to detect silent AF before structural irreversibility occurs is essential for transitioning global cardiovascular care from the reactive management of severe complications to proactive disease modification.

Despite the advantages of early diagnosis to prevent catastrophic sequelae, the conventional modalities utilized for AF detection are fundamentally constrained by their episodic nature and their strict reliance on clinical infrastructure. Currently, the diagnostic gold standard requires the formal electrocardiographic documentation of the arrhythmia via a standard 12-lead electrocardiogram (ECG) or a 24-hour ambulatory Holter monitor (Joglar et al., 2023). However, these traditional methodologies are intrinsically "medical-led," necessitating specialized healthcare personnel, formal clinical appointments, and expert physician interpretation. Consequently, they are inherently ill-suited for the proactive surveillance of broad, asymptomatic populations. Furthermore, these time-limited assessments suffer from a critical "intermittency gap." Because paroxysmal AF is highly episodic, meaning a brief 12-lead ECG snapshot or even a continuous 24-hour Holter recording frequently fails to capture transient arrhythmic events, yielding false-negative reassurance while the underlying thromboembolic risk persists undetected (Lubitz et al., 2022; Perez et al., 2019) While implantable loop recorders successfully overcome this intermittency by providing continuous long-term telemetry, their invasive surgical nature and substantial costs restrict their application strictly to highly selected, high-risk patient cohorts, precluding their use as a generalized screening tool.

To bridge this profound diagnostic gap, there is a compelling clinical rationale for transitioning toward decentralized, "patient-led" monitoring strategies facilitated by everyday consumer technology. Wearable devices, particularly smartwatches and fitness trackers equipped with photoplethysmography (PPG) and single-lead ECG capabilities, offer a major opportunity for improving early detection as well as management of atrial fibrillation. By enabling continuous, real-world physiological surveillance outside the traditional clinical environment, these ubiquitous devices empower individuals to independently capture cardiac anomalies at the exact moment of their manifestation, without the immediate presence of a physician (Lubitz et al., 2022). The diagnostic viability and unprecedented scalability of this approach have been conclusively validated by landmark, large-scale pragmatic trials, most notably the Fitbit Heart Study (Lubitz et al., 2022) and the Apple Heart Study (Perez et al., 2019). This continuous, longitudinal monitoring aims to effectively neutralize the intermittency gap inherent to conventional Holters, operating seamlessly in the background of a patient's daily life. Ultimately, leveraging consumer wearables as a scalable screening tool represents the logical next step in clinical cardiology; it provides a critical, accessible early warning system capable of detecting subclinical AF at its absolute onset, thereby prompting timely medical evaluation long before irreversible structural remodeling or severe embolic complications can occur (Perez et al., 2019).

2. Methodology

2.1. Study Design

The present study utilizes a comprehensive narrative review methodology to synthesize the interdisciplinary landscape of digital AF management and wearable technology. Given the rapid technological evolution of consumer health electronics and the convergence of clinical cardiology, biomedical engineering, and digital health behavior, a narrative design is uniquely appropriate. Unlike a systematic review constrained by rigid quantitative aggregation, this narrative approach facilitates an integrative socio-technical synthesis of heterogeneous evidence. It enables a holistic evaluation of how clinical diagnostic capabilities interact with structural patient behaviors, technological accessibility, and real-world implementation.

2.2. Search Strategy and Data Sources

To construct a robust evidentiary corpus, a comprehensive literature search was conducted across three primary academic databases: PubMed/MEDLINE, Scopus, and Google Scholar. To ensure the findings remain contemporary and accurately reflect the accelerated proliferation of modern smartwatch and digital diagnostic technologies, the primary search was restricted to literature published between 2018 and 2025. However, select foundational studies and epidemiological data published prior to this period were included to provide essential clinical and pathophysiological context.

The search syntax utilized a combination of Boolean operators (AND/OR) to capture the intersection of clinical arrhythmia management and consumer innovation, encompassing the following predefined keyword clusters:

- **Core Clinical Terms:** *Atrial fibrillation*, *Stroke prevention*, *Early rhythm control*.
- **Technology and Device Terms:** *Wearable devices*, *Consumer health technology*, *Smartwatches*.
- **Signal and Detection Methods:** *Photoplethysmography (PPG)*, *Single-lead electrocardiography (ECG)*, *Heart rhythm monitoring*.
- **Clinical Integration and Outcomes:** *Clinical decision support*, *Remote patient monitoring*, *Early detection*, *Diagnostic accuracy*.

2.3. Inclusion and Exclusion Criteria

The literature selection process was guided by specific inclusion and exclusion criteria designed to maintain high academic rigor while addressing the systemic dimensions of digital health. Included materials were strictly limited to peer-reviewed original research, large-scale pragmatic trials (e.g., Apple Heart Study, Fitbit Heart Study), algorithmic validation studies, and comprehensive clinical guidelines published in the English language. Crucially, the review explicitly included studies focusing on the "human variable" within the diagnostic chain, prioritizing literature that examined digital health behavior, sustained adherence, the psychological impact of false-positive alerts, and the socio-economic factors dictating device access. Exclusion criteria encompassed non-peer-reviewed grey literature, editorials lacking empirical data, and studies focusing exclusively on traditional, hospital-bound Holter monitoring without an ambulatory digital health or consumer wearable component.

2.4. Data Extraction and Thematic Synthesis

Due to the methodological heterogeneity of the selected corpus - which spans large-scale consumer trials, clinical benchmarking, and behavioral health observations - a thematic synthesis approach was employed. Data were extracted and categorized into core thematic pillars: sensing technologies (optical PPG and biopotential ECG), diagnostic accuracy and hardware constraints (e.g., kinematic interference), user engagement dynamics (the "behavioral gap"), and clinical integration (early rhythm control pathways and socio-economic equity). This interpretative framework allows for a multi-layered evaluation, ensuring that the clinical efficacy of wearable AF detection is critically contextualized against the behavioral, ethical, and socio-technical realities of sustained device engagement in real-world settings.

3. Results

3.1. Sensing Technologies and Algorithmic Approaches for AF Detection

To bridge the diagnostic gap created by silent arrhythmias, wearable technologies leverage two distinct but complementary sensing modalities integrated into consumer hardware. The first, photoplethysmography, utilizes optical sensors to detect volumetric blood flow changes, enabling continuous, non-invasive rhythm screening at a population scale. The second, single-lead ECG, provides electrical tracings by completing a circuit across the device, offering a clinical-grade "Lead I" equivalent for definitive verification.

Current clinical paradigms are shifting toward a sequential monitoring architecture, or a "passive-to-active" workflow. In this model, background PPG surveillance operates persistently to identify irregularities, which then trigger a user-initiated ECG recording for diagnostic confirmation. This hierarchical approach intends to optimize the balance between the broad reach of optical screening and the high specificity of biopotential sensing, effectively neutralizing the "intermittency gap" of traditional tools while maintaining clinical rigor within a decentralized, patient-led framework.

3.2. Photoplethysmography (PPG): Optical Signal Acquisition and Irregularity Detection

The biophysical mechanism of photoplethysmography (PPG) within wearable architectures relies on the optical measurement of blood volume fluctuations in the microvascular tissue bed. As light is emitted from a light-emitting diode (LED), typically in the green spectrum, commonly centered around 530 nm, to minimize motion-induced signal degradation, it is either transmitted through or reflected by the skin and absorbed by hemoglobin (Tamura et al., 2019). The resulting intensity changes recorded by the photodetector allow for the quantification of peripheral pulse waves, where atrial fibrillation (AF) is characterized by the absence of discrete P-waves and a high degree of pulse-wave irregularity (Tamura, 2019; Pereira et al., 2020).

Algorithmic identification of AF from these signals utilizes both statistical time-domain metrics and non-linear analysis of beat-to-beat (RR or peak-to-peak) intervals. Reported metrics include the root mean square of successive differences (RMSSD), the coefficient of variation, and sample entropy, which serve to differentiate the chaotic pulse patterns of AF from normal sinus rhythm (Bashar et al., 2019; Kwon et al., 2019). Deep learning architectures, including convolutional neural networks (CNNs) and recurrent neural networks (RNNs/LSTM), have been implemented to automate feature extraction from raw PPG waveforms, effectively managing the influence of premature atrial contractions (PACs) which frequently confound traditional detection methods (Kwon et al., 2019; Peimankar & Puthusserypady, 2020). Across multiple investigations, these automated systems achieved sensitivity ranges of 93.4% to 98.2% and specificity ranges of 91.0% to 99.0% (Ding et al., 2024; Kwon et al., 2019).

3.3. Single-Lead ECG: Device Architecture and Diagnostic Agreement

Integrated electrocardiogram functionality in consumer wearables employs a single-lead configuration to record the heart's electrical potentials, effectively creating a "Lead I" equivalent. In smartwatch-based systems, this is achieved by completing an electrical circuit through contact with the wrist-facing electrode and a second electrode most often located on the digital crown or bezel, which is engaged by a finger from the opposite hand (Francisco et al., 2025; Smith & Maisrikrod, 2025). Adhesive patch-based monitors utilize a similar Lead I-like orientation on the upper chest, providing full-disclosure recording for extended periods of up to 14 days (Nault et al., 2019). In a two-phase clinical validation, the Cardiostat™ patch demonstrated 99% sensitivity for atrial fibrillation and atrial flutter detection compared to standard 12-lead ECGs (Nault et al., 2019).

The evolution of electrode technology facilitates the shift from clinical settings to long-term home monitoring. While traditional silver/silver-chloride (Ag/AgCl) "wet" electrodes remain a benchmark, material science innovations have introduced "dry" electrodes composed of conductive polymers, carbon-based nanomaterials, and metal-nanowire composites (Kim et al., 2022). These dry sensors enable high-fidelity signal acquisition without the use of conductive gels, thereby reducing skin irritation and maintaining signal quality during prolonged wear (Kim et al., 2022). Validation of integrated ECG sensors in smartwatches has reported high diagnostic agreement with traditional clinical tools, with one study documenting an accuracy of 99.06% (Guo et al., 2019).

3.4. Passive vs. Active Monitoring Architectures

Modern wearable monitoring is defined by the architectural distinction between passive background surveillance and active user-initiated recordings. Passive monitoring utilizing PPG technology allows for continuous, "always-on" heart rhythm assessment during periods of rest or inactivity (Francisco et al., 2025, Turakhia et al., 2019). Large-scale population-based data underscore the clinical utility of this approach: the Apple Heart Study (n = 419,297) utilized periodic tachograms to identify irregular pulse patterns, while the Fitbit Heart Study (n = 455,664) required 11 consecutive irregular tachograms within a 24-hour window to trigger an "Irregular Heart Rhythm Notification" (Lubitz et al., 2022, Turakhia et al., 2019;). These passive protocols reported positive predictive values (PPVs) of 84% in the Apple study and 98.2% in the Fitbit study (Lubitz et al., 2022; Turakhia et al., 2019).

Current diagnostic workflows increasingly favor a sequential verification model, wherein a passive PPG alert triggers an active ECG recording to confirm the arrhythmia (Choi et al., 2025). This hierarchical approach leverages the persistent nature of PPG sensing to identify potential episodes and the higher-fidelity ECG sensor to provide definitive rhythm classification, effectively mitigating false positives caused by motion artifacts or benign arrhythmias (Blok et al., 2025; Saarinen et al., 2023). In the Huawei Heart Study, which enrolled 187,912 participants, the implementation of this sequential diagnostic protocol resulted in a PPV of 91.6% for AF detection (Guo et al., 2020). This architectural shift toward background monitoring paired with spot-check verification represents the current standard for identifying silent arrhythmias in ambulatory populations (Choi et al., 2025; Francisco et al., 2025).

3.5. Diagnostic Accuracy and Validation Evidence

Several studies benchmarked the classification accuracy of smartwatches against clinical ground-truth reference systems, including multi-channel 12-lead electrocardiograms, 24-hour Holter monitors, and telemetry ECG hardware (Iqhrammullah et al., 2025; Luo et al., 2025). Across the literature, hardware validation studies consistently demonstrated that single-channel biopotential and optical photoplethysmography sensing modalities integrated into smartwatches show high concordance with reference standards for identifying atrial fibrillation patterns (Inocian et al., 2024; Shahid et al., 2025).

3.5.1. Sensor Modality Performance Metrics

The reviewed studies provided quantitative data on the sensitivity, specificity, and predictive values of smartwatch sensors under both controlled and unconstrained real-world operating conditions:

Optical Sensing (PPG): A Luo et al 2025 meta-analysis reported that PPG-based smartwatches achieved a pooled sensitivity of 97.4% and a pooled specificity of 96.6%. A real-world ambulatory study utilizing a Garmin smartwatch for continuous optical monitoring against a simultaneous Holter reference reported 97.3% sensitivity, 88.6% specificity, and a 91.6% positive predictive value for atrial fibrillation feature extraction at the user level (Chang et al., 2022).

Biopotential Sensing (ECG): The automated classification accuracy of onboard ECG firmware varied. One meta-analysis reported a pooled sensitivity of 83% and a specificity of 88.4% for single-lead ECG smartwatches (Luo et al., 2025). Another systematic review found that automated algorithmic extraction yielded a sensitivity of 86% and a specificity of 94%, with a PPV of 93% and a negative predictive value (NPV) of 86% (Iqhrammullah et al., 2025).

Human-in-the-Loop Validation: When raw ECG time-series data were exported and subjected to expert visual analysis rather than proprietary onboard classifiers, the system metrics improved significantly, optimizing to a sensitivity of 96%, a specificity of 95%, a PPV of 95%, and an NPV of 94% (Iqhrammullah et al., 2025).

3.5.2. Hardware and Algorithmic Benchmarking by Manufacturer

A comparison of major commercial architectures demonstrated variations in both algorithmic output and raw signal quality when tested directly against 12-lead ECG or Holter ground truths:

Apple Watch: A meta-analysis comparing the Apple Watch's biopotential sensor directly to a 12-lead ECG reference demonstrated a pooled sensitivity of 94.8% and a specificity of 95% (Shahid et al., 2025). In a direct comparative study, the onboard automated classifier achieved 87% sensitivity and 86% specificity; introducing human-in-the-loop expert validation improved sensitivity to 94% (Abu-Alrub et al., 2022). Furthermore, a pragmatic study testing the device against a 24-hour Holter revealed distinct operational mode disparities: the passive background optical sampling ("irregular rhythm notification") exhibited a highly limited sensitivity of 21.4% (with 100% specificity), whereas active, user-initiated 30-second ECG biopotential sampling matched the Holter system with 100% sensitivity and 99.1% specificity (Inocian et al., 2024).

Huawei: Validation of the Huawei Watch GT2 Pro provided robust objective data for its single-channel ECG algorithm. Tested simultaneously against a 12-lead ECG reference, the algorithmic classifier achieved a 96.7% recall (sensitivity), 96.9% precision, and an F1 score of 96.8% (Niu et al., 2023).

Garmin: Validated against a continuous Holter monitor, the Garmin device's continuous optical sensing algorithm effectively extracted AF features in unconstrained environments, achieving 97.3% sensitivity and 88.6% specificity (Chang et al., 2022).

Samsung & Withings: The Samsung Galaxy Watch's automated algorithm yielded an 88% sensitivity and 81% specificity, while the Withings hardware showed an automated sensitivity of 78% and specificity of 80% (Abu-Alrub et al., 2022). Upon human expert evaluation of the raw data, the Withings system's accuracy improved to 96% sensitivity and 86% specificity (Abu-Alrub et al., 2022).

3.5.3. Signal Degradation and Hardware Constraints

While wearable electronics show promise, the literature highlighted severe reliability gaps due to technological constraints. System performance frequently declines in ambulatory settings due to signal-to-noise ratio (SNR) degradation:

Data Loss and Inconclusive Output: Unlike a 12-lead ECG, which offers a multi-vector spatial resolution of the heart's electrical activity, single-channel wearable sensors are highly susceptible to data corruption. The Samsung Galaxy Watch generated raw ECG signals that experts found difficult to interpret in 20% of cases and completely uninterpretable in 15% of cases (Abu-Alrub et al., 2022). Applying an "intention-to-diagnose" methodology (where unclassified/noisy epochs are treated as failures) heavily impacts system reliability

metrics; for instance, filtering out unclassified data artificially inflated the automated sensitivity of the Apple Watch from 87% to 99% (Abu-Alrub et al., 2022).

Optical Interference: Optical PPG sensors face hardware limitations irrelevant to traditional biopotential ECGs. Signal quality relies on photon reflection/absorption and is heavily degraded by poor peripheral skin perfusion, melanin density variations (skin tones), subdermal ink (tattoos), and ambient light leakage, triggering false positive/negative classifications (Luo et al., 2025; Zarak et al., 2024).

Kinematic Interference (Motion): Kinematic artifacts severely distort both PPG and ECG waveforms. In one ambulatory study, the continuous rhythm classification algorithm failed to process data for 44% ± 16% of the recording epoch exclusively due to motion-induced signal degradation (Bonomi et al., 2018).

3.5.4. Algorithmic Edge Cases: Ectopic Beat Classification

Distinguishing AF from other irregular rhythms is a primary algorithmic challenge. Premature atrial and ventricular contractions (PACs and PVCs) introduce variance in cardiac cycles that mimic AF, serving as the main source of false-positive outputs in algorithms relying on simple peak-to-peak (R-R interval) regularity heuristics (Chang et al., 2022; Niu et al., 2023). However, advanced algorithms processing morphological features in single-lead ECGs show potential. Benchmarked against a 12-lead ECG, the Huawei Watch GT2 Pro classifier demonstrated a recall of 90.5% and a precision of 89.4% for PAC detection, alongside an 86.1% recall and 89.6% precision for PVCs (Niu et al., 2023).

3.5.5. Noise Rejection Architecture and Inter-Rater Reliability

Despite SNR challenges, studies report high inter-rater reliability when the raw single-channel trace maintains sufficient integrity for expert visual analysis. Electrophysiologists exhibited high agreement in evaluating exported data, yielding Cohen's Kappa coefficients of 0.96 for Apple, 0.92 for Samsung, and 0.94 for Withings (Abu-Alrub et al., 2022). A meta-analysis assessing global ECG interpretability reported a Cohen's Kappa of 0.83, noting that only 3% of combined outputs were strictly unreadable (Iqhrammullah et al., 2025). To optimize data integrity, manufacturers integrate onboard accelerometers to gate data acquisition; algorithms actively discard PPG or ECG epochs when kinematic vectors exceed predefined noise thresholds (Chang et al., 2022; Niu et al., 2023).

3.5.6. System Deployment at Scale and False Alarm Rates

The large-scale deployment of wearable smartwatch (WSW) screening systems yields high data volumes but introduces systemic efficiency challenges. WSW diagnostic validity is comparable to the FDA-cleared KardiaBand hardware (Zarak et al., 2024). A review of 1,075,088 end-users highlighted that while WSWs reliably extract AF features, high false-positive alert rates remain a critical system flaw that can overload downstream diagnostic infrastructure (Zarak et al., 2024). Conversely, advanced statistical modeling can mitigate this; a study deploying a wrist-based PPG Markov model optimized to process inter-pulse interval sequences reduced the estimated false-positive detection rate to less than 0.2% in healthy control groups under typical operating conditions (Bonomi et al., 2018). Ultimately, the system area under the curve (sAUC) remains robust against reference standards, reaching 0.96 for automated firmware processing and up to 0.98 utilizing human-in-the-loop interpretation (Iqhrammullah et al., 2025; Shahid et al., 2025). Collectively, while the diagnostic performance of these devices shows strong concordance with clinical reference systems, mitigating hardware constraints and managing high false alarm rates remains a critical prerequisite for their unassisted deployment in clinical pathways.

3.6. Digital Health Behavior: Adherence and User Engagement

3.6.1. Adherence: Do patients sustain long-term device use, or does “gadget fatigue” emerge?

Sustained engagement with wearable health technologies - understood as consistent device use over extended periods in real-world settings - is a critical determinant of their clinical value in both physiological surveillance and decision support. Evidence from structured clinical studies indicates that participants may maintain high levels of adherence, with median wear times during six-month follow-up exceeding 80% of the intended monitoring duration (Frodi et al., 2024). These findings suggest that, under controlled research conditions, prolonged device utilization is achievable.

Nevertheless, adherence patterns in routine practice appear less stable. Observational data from consumer markets demonstrate that approximately half of users discontinue regular use of wearable devices such as Fitbit within six months of acquisition, highlighting a decline in engagement frequently described as "gadget fatigue" (Frodi et al., 2024).

Multiple behavioral and psychosocial factors contribute to this attenuation in use, including diminished perceived utility, inconvenience associated with daily wear, insufficient personalization, and the absence of

integration with formal healthcare systems. Early discontinuation results in fragmented longitudinal datasets, thereby limiting the reliability and clinical interpretability of wearable-derived metrics in chronic cardiovascular conditions such as atrial fibrillation (Goevaerts et al., 2025).

Furthermore, comparative interpretation across studies is complicated by inconsistencies in how adherence is defined and quantified. Metrics vary widely - ranging from hours of daily wear to app login frequency or proportion of analyzable recording days - introducing methodological heterogeneity that restricts generalizability and synthesis of findings (Albergoni et al., 2019).

Collectively, while short-term adherence appears promising within research environments, maintaining sustained engagement in everyday clinical contexts remains a significant barrier to the scalable implementation of wearable-based AF screening and management strategies.

3.6.2. The "Alert-to-Action" Pathway: Behavioral and Psychological Responses to Notifications

Wearable technologies commonly employ automated alerts to prompt user responses, forming a behavioral sequence that can be conceptualized as an "alert-to-action" pathway. Empirical research in digital health indicates that notifications can temporarily enhance user interaction and health-related behaviors. However, their capacity to produce durable behavioral change and long-term retention remains uncertain (Bell et al., 2023). Findings from microrandomized trials demonstrate measurable short-term engagement effects, yet consistent long-term adherence benefits have not been definitively established.

Within the AF detection context, alerts signaling possible rhythm irregularities may initiate a spectrum of responses. For certain individuals, notifications appropriately motivate confirmatory diagnostic testing and professional medical consultation, potentially enabling earlier recognition of previously undiagnosed AF. Conversely, alerts may also generate unintended psychological consequences, including heightened anxiety, excessive self-monitoring, or increased - sometimes unnecessary - healthcare utilization.

The dual nature of continuous cardiac monitoring therefore warrants careful consideration. While the capacity to identify silent AF represents a meaningful preventive opportunity, inadequately contextualized alerts may contribute to stress amplification or medical overuse. Accordingly, there is increasing support for notification systems that are adaptive, personalized, and embedded within structured clinical workflows to balance early detection benefits against potential psychological harms (Gaffey et al., 2025).

3.6.3. Demographic Barriers: Engagement levels in most affected elderly populations vs. tech-savvy youth.

Evidence suggests that elderly populations, who are often at highest risk for atrial fibrillation, face unique challenges in engaging with wearable ECG technologies. As previously presented, wearable devices may prove as a significant diagnostic tool in detecting AF episodes in older adults. However, these devices require prolonged wear, daily charging, and device management that can reduce usability for seniors, whereas younger, tech-savvy individuals may find these requirements easier to accommodate (Avanu et al., 2025;Machino et al., 2023). Importantly, while most paroxysmal AF episodes are captured early during monitoring, user experience factors - such as comfort, simplicity, and tolerability - strongly influence engagement and the likelihood of completing extended monitoring periods. These findings highlight a demographic trade-off: older adults may benefit most from continuous AF detection but may require additional support, training, and simplified device designs to maintain adherence, whereas younger users often tolerate technical complexity more readily.

3.6.4. Goal: Address the "human" variable in the diagnostic chain - the device only works if it's worn.

The effectiveness of wearable technologies for atrial fibrillation depends not only on device accuracy but fundamentally on patient behavior. Even the most advanced sensors cannot provide meaningful diagnostic information if devices are not consistently worn (Albergoni et al., 2019; Frodi et al., 2024; Goevaerts et al., 2025). Therefore, clinical strategies should focus on the human element - designing educational interventions, engagement plans, and user-centered protocols that motivate sustained use. Emphasizing routine device wear, integrating devices seamlessly into daily life, and addressing behavioral barriers can translate technological precision into reliable, actionable clinical data. By explicitly targeting adherence and engagement, healthcare teams can maximize the diagnostic value of wearables and support the early detection of silent AF (Bell et al., 2023).

4. Discussion

4.1. Clinical Implications and Integration into Healthcare

4.1.1. Implications for Diagnostic Timelines and Early Rhythm Control

The clinical utility of wearable-detected atrial fibrillation is fundamentally tied to the "treatment-time" effect, where the window for effective intervention is significantly narrower than previously assumed. As synthesized by Kim et al. (2022), AF-related electrical and structural atrial remodeling begins within just "a few weeks" of the arrhythmia's onset, contributing to its progressive and self-sustaining nature. This rapid pathophysiology underscores the necessity of wearables as high-sensitivity surveillance tools capable of triggering medical evaluation long before symptoms typically manifest.

The evidence for early intervention is anchored in the landmark EAST-AFNET 4 trial, which demonstrated that rhythm control initiated shortly after diagnosis (median 36 days) reduced the risk of a composite of cardiovascular death, stroke, and heart failure hospitalization by 21% over a 5.1-year follow-up. Specifically, early rhythm control (ERC) was associated with a 28% reduction in cardiovascular death and a 35% reduction in stroke (Kim et al., 2022). Wearables facilitate these superior outcomes by identifying asymptomatic "early AF" (defined as ≤ 1 year from onset), allowing patients to be transitioned into ERC pathways - utilizing antiarrhythmic medications or ablation - while the disease is still in its most plastic and treatable stage.

The importance of this diagnostic "speed" is further quantified by a sub-analysis of the EAST-AFNET 4 data (Eckardt et al., 2022), which revealed that attaining and maintaining sinus rhythm within the first 12 months of diagnosis explained 81% of the observed treatment benefit. This finding establishes sinus rhythm as the primary mediator of improved survival and stroke prevention. Wearables effectively "open" this critical therapeutic window for asymptomatic patients who would otherwise remain undiagnosed until the arrhythmia has progressed to a persistent or permanent state. By the time such patients are identified through traditional episodic care, structural remodeling has often advanced to a point where rhythm control becomes largely futile, leaving conservative rate control as the only viable, yet less effective, management strategy.

4.1.2. Long-Term Monitoring and Post-Interventional Follow-Up

Beyond screening, wearables have important implications for longitudinal rhythm monitoring. Continuous or extended ECG recording increases AF detection compared with intermittent strategies in elderly populations, highlighting the value of prolonged monitoring windows (Fredriksson et al., 2020).

Advanced wearable textile ECG systems have demonstrated superior detection of post-ablation AF recurrence compared with conventional 24-hour Holter monitoring, suggesting an expanded role in post-treatment surveillance (Avanu et al. 2025; Machino et al.2023).

These data indicate that wearable technologies may not only detect incident AF but also enhance post-therapeutic rhythm assessment, thereby extending their clinical utility across the disease continuum.

4.1.3. Patient-Generated Data, Algorithms, and Clinical Governance

Wearable-detected AF must be interpreted within a structured clinical framework. Expert reviews emphasize that smartwatch-detected arrhythmias require confirmatory ECG documentation and professional interpretation before therapeutic decisions are made (Hindricks et al. 2021).

Comparative analyses demonstrate improved diagnostic performance when clinician oversight is incorporated into smartwatch ECG interpretation, reinforcing the concept that wearable systems augment - but do not replace - clinical expertise (Abu-Alrub et al 2022).

This interaction between patient-generated data, algorithmic processing, and clinician adjudication defines a hybrid diagnostic ecosystem essential for safe integration into cardiovascular care.

4.2. Challenges, Risks, and Ethical Considerations: Why Wearables Have Not Replaced Holter Monitoring

The preceding sections demonstrate that wearable technologies have achieved impressive diagnostic concordance with reference ECG systems, offer scalable passive monitoring, and meaningfully expand opportunities for early AF detection. However, translating technical validity into safe, equitable, and sustainable clinical implementation exposes structural limitations. The persistence of Holter monitoring as a clinical reference tool is not simply technological conservatism; it reflects unresolved clinical, behavioral, ethical, and socio-economic challenges.

4.2.1. The "Anxious Well": False Positives, Low Prevalence Screening, and Systemic Burden

Large-scale trials such as the Apple Heart Study and Fitbit Heart Study confirmed the feasibility of population-level AF screening using consumer wearables (Lubitz et al., 2022; Perez et al., 2019; Turakhia et al., 2019). Yet these cohorts were predominantly younger, digitally engaged individuals with relatively low baseline AF prevalence. In low-prevalence populations, even high-specificity algorithms inevitably generate a non-trivial absolute number of false-positive alerts. As shown in large validation syntheses (Iqhrammullah et al., 2025; Luo et al., 2025; Zarak et al., 2024), device-level sensitivity and specificity remain strong, but predictive value is prevalence-dependent.

Diagnostic Accuracy and Validation Evidence paragraph demonstrated that motion artifacts, signal dropout, and unclassified epochs materially affect real-world accuracy (Abu-Alrub et al., 2022; Bonomi et al., 2018). When intention-to-diagnose methodologies are applied, performance metrics decline compared to filtered datasets. In real-life ambulatory environments, algorithms may fail to process substantial recording periods due to kinematic interference (Bonomi et al., 2018). Although sequential PPG-to-ECG verification architectures reduce false positives (Choi et al., 2025; Guo et al., 2020), they do not eliminate them.

The clinical consequence is the emergence of the "anxious well" - low-risk individuals who receive irregular rhythm notifications and subsequently seek urgent evaluation. Evidence suggests that wearable alerts can increase healthcare utilization and psychological distress (Gaffey et al., 2025; Rosman et al., 2024). Notifications may amplify health anxiety, particularly when alerts are not contextualized within absolute risk (Bell et al., 2023).

Guidelines from ESC and ACC/AHA/HRS explicitly require confirmatory ECG documentation prior to diagnosis or anticoagulation decisions (Hindricks et al., 2021; Joglar et al., 2023). Thus, wearables create a two-step pathway: detection followed by medical validation. This pathway, while protective against overtreatment, shifts workload toward outpatient cardiology services. In systems already managing a substantial number of patients with AF, indiscriminate screening of low-risk populations risks diluting specialist resources away from higher-risk patients.

Holter monitoring, by contrast, is physician-directed, time-bounded, and embedded within clinical triage frameworks. Its deployment is selective rather than consumer-triggered, reducing unnecessary cascade testing. Until wearable alerts are risk-stratified and embedded within structured referral algorithms, replacing Holter systems would risk overwhelming downstream diagnostic infrastructure.

4.2.2. Data Privacy and Ownership: Clinical Records vs. Corporate Ecosystems

Wearable AF detection operates within corporate digital ecosystems. Trials such as Apple and Fitbit illustrate that rhythm data are captured, processed, and stored within proprietary platforms before clinical engagement occurs (Lubitz et al., 2022; Perez et al., 2019). This architecture contrasts sharply with Holter systems, where data are generated, stored, and interpreted within regulated medical infrastructures.

Unresolved questions remain: Who owns longitudinal rhythm data—the patient, the technology provider, or the healthcare institution? What governs secondary data use, algorithm retraining, or commercial analytics? Smith and Maisrikrod (2025) question whether wearable ECG technology creates medico-legal ambiguity when clinicians are asked to interpret externally generated data. Francisco et al. (2025) similarly highlight concerns regarding transparency, algorithm explainability, and accountability in AI-enabled detection systems.

Advanced deep learning models applied to PPG and ECG signals (Kwon et al., 2019; Peimankar & Puthusserypady, 2020) further complicate interpretability. Proprietary algorithm updates may alter performance characteristics without clinician visibility. In contrast, Holter monitoring systems undergo standardized validation, regulatory oversight, and stable technical specifications.

Until interoperable standards, transparent algorithm governance, and clear data ownership frameworks are established, wearable systems cannot fully assume the medico-legal role of clinical diagnostic tools. Holter monitoring remains embedded in established regulatory and documentation pathways that protect both patients and clinicians.

4.2.3. Socio-Economic Equity and the Digital Divide

AF prevalence increases sharply with age and comorbidity burden. Yet consumer wearable adoption skews toward younger, wealthier, and technologically literate populations (Lubitz et al., 2022; Perez et al., 2019). This demographic asymmetry creates a structural inequity: those most capable of purchasing and operating wearables are not those at highest stroke risk.

Digital Health Behavior: Adherence and User Engagement paragraph demonstrated that sustained engagement is inconsistent outside research environments (Frodi et al., 2024; Goevaerts et al., 2025). Adherence declines over time, and older adults - despite greater diagnostic need - face usability and comfort

challenges (Avanu & Dodi, 2025; Fredriksson et al., 2020; Machino et al., 2023). Behavioral barriers, device charging requirements, and digital literacy constraints limit continuous use in elderly populations.

Population-wide screening models (Guo et al., 2020) suggest that targeted strategies improve diagnostic yield. However, if early AF detection becomes predominantly consumer-driven, healthcare systems risk creating a two-tier model: digitally connected individuals receive earlier rhythm control opportunities (Kirchhof et al., 2020), while socio-economically disadvantaged populations remain dependent on symptom-driven or opportunistic detection.

Holter monitoring, though episodic, is accessible through publicly funded healthcare systems and does not require personal device ownership. In this sense, traditional ambulatory ECG monitoring may paradoxically remain more equitable than consumer-led digital screening unless reimbursement models and public health strategies explicitly address digital access disparities.

4.2.4. The Human Variable: Device Accuracy Is Irrelevant Without Wear Time

In results we emphasized a critical principle: diagnostic potential depends on sustained adherence. Wearables promise continuous monitoring, but real-world engagement often declines within months (Frodi et al., 2024). Behavioral fatigue, diminished perceived benefit, and alert burden undermine longitudinal data continuity (Albergoni et al., 2019; Bell et al., 2023).

Holter monitoring, while limited to 24-48 hours (or extended patch durations), guarantees uninterrupted recording during the prescribed interval. It is not dependent on long-term motivation or lifestyle integration. In contrast, wearable-derived datasets are vulnerable to intermittent wear, charging lapses, and user disengagement, leading to fragmented rhythm histories and potential false reassurance.

Therefore, while wearable technologies neutralize the “intermittency gap” theoretically, they introduce a “behavioral gap.” Continuous monitoring exists only if the device remains worn, charged, and properly positioned. Until adherence stabilization strategies are standardized and scalable, wearables should not fully supplant clinician-directed ambulatory ECG systems.

4.2.5. Synthesis: Complement, Not Replacement

Wearable technologies represent a transformative adjunct in AF detection. They expand surveillance beyond clinical walls, identify silent arrhythmias, and potentially enable earlier rhythm control intervention (Kirchhof et al., 2020). However, replacement of Holter monitoring is constrained by a number of aforementioned obstacles.

The persistence of Holter monitoring is therefore not a reflection of technological inferiority but of systemic integration. Holter systems remain standardized, equitable, physician-directed, and embedded in clinical governance structures.

The future likely lies in hybrid models: risk-stratified wearable screening, sequential ECG confirmation pathways, integration into guideline-directed workflows, and equity-focused public health strategies. Only through addressing behavioral, ethical, and structural constraints can wearable AF detection evolve from an adjunctive screening tool into a true replacement for traditional ambulatory ECG monitoring.

At present, wearable technologies enhance cardiology - but they have not yet redefined it.

5. Conclusions

The integration of wearable technologies into atrial fibrillation management represents a fundamental shift from reactive, clinic-centric cardiology to a proactive, decentralized model of continuous surveillance. This review has synthesized a body of evidence demonstrating that consumer-grade wearables - leveraging both optical PPG and single-lead ECG - have reached a level of technical maturity characterized by high concordance with clinical gold standards. With pooled sensitivities often exceeding 94%, these devices effectively bridge the "intermittency gap" inherent in traditional 24-hour Holter monitoring. By facilitating the detection of "silent" or subclinical AF, wearables provide a critical window of opportunity for stroke prevention, potentially altering the natural history of the disease before irreversible structural remodeling occurs.

The clinical imperative for this technology is rooted in the "treatment-time" effect. Because AF-related electrical and structural remodeling begins within weeks of onset, the ability of wearables to detect arrhythmia in its subclinical phase is transformative. By compressing the diagnostic timeline, these devices "open" a therapeutic window for early rhythm control. As evidenced by the EAST-AFNET 4 data, maintaining sinus rhythm within the first year of diagnosis is responsible for 81% of the observed reduction in stroke and cardiovascular death. Wearables, therefore, serve as an essential gatekeeper to proactive disease modification,

allowing clinicians to intervene while the atrial substrate remains plastic and before the arrhythmia becomes refractory to treatment.

However, the transition from technical feasibility to systemic utility is contingent upon addressing profound socio-technical and behavioral challenges. This review evaluates wearables not as isolated gadgets, but as components of a broader transformation in healthcare. While hardware is increasingly capable of high-fidelity signal acquisition, the "human variable" - manifested through "gadget fatigue," digital literacy disparities, and varied psychological responses to alerts - remains the primary determinant of diagnostic efficacy. Furthermore, a "digital divide" exists where populations at the highest epidemiological risk, such as the elderly and those in lower socio-economic brackets, face the greatest barriers to device adoption. The effectiveness of these technologies is inextricably linked to the social contexts in which they are deployed, requiring a shift in focus from device-level precision to system-level integration.

For clinicians and policymakers, the path forward lies in developing standardized validation frameworks and interdisciplinary clinical pathways. Rather than viewing wearables as a wholesale replacement for Holter monitoring, they should be integrated as a high-sensitivity triage layer within a hybrid diagnostic ecosystem. The true value of this innovation will not be measured by the precision of its sensors alone, but by the responsibility and equity with which it is integrated into the social fabric of healthcare. By embedding these digital tools within transparent, clinician-guided frameworks, society can harness the full potential of wearable technology to reduce the global burden of stroke and improve the quality of life for millions at risk.

Ethical considerations

Ethics Approval: As this manuscript is a narrative review synthesizing previously published literature, no new primary data involving human or animal subjects were collected by the authors. Therefore, formal ethical approval from an institutional review board was not required.

Conflicts of Interest: The authors declare no conflicts of interest.

Plagiarism: The authors confirm that this manuscript is original work and all integrated sources have been appropriately cited and referenced.

REFERENCES

1. Abu-Alrub, S., Strik, M., Ramirez, F. D., Moussaoui, N., Racine, H. P., Marchand, H., Buliard, S., Haïssaguerre, M., Ploux, S., & Bordachar, P. (2022). Smartwatch electrocardiograms for automated and manual diagnosis of atrial fibrillation: A comparative analysis of three models. *Frontiers in Cardiovascular Medicine, 9*, Article 836375. https://doi.org/10.3389/fcvm.2022.836375
2. Albergoni, A., Hettinga, F. J., La Torre, A., et al. (2019). The role of technology in adherence to physical activity programs in patients with chronic diseases experiencing fatigue: A systematic review. *Sports Medicine - Open, 5*, Article 41. https://doi.org/10.1186/s40798-019-0214-z
3. Avanu, A. E., & Dodi, G. (2025). Wear your heart on your sleeve: Smart textile ECG wearables for comfort, integration, signal quality and continuous monitoring in paroxysmal atrial fibrillation. *Sensors, 25*(3), Article 676. https://doi.org/10.3390/s25030676
4. Bashar, S. K., Han, D., Soni, N. H., Chon, K. H., & McManus, D. D. (2019). Developing a relative power spectral density based algorithm for autonomous detection of atrial fibrillation using a smartphone. *Scientific Reports, 9*, Article 13054. https://doi.org/10.1038/s41598-019-49092-2
5. Bell, L., Garnett, C., Bao, Y., Cheng, Z., Qian, T., Perski, O., Potts, H. W. W., & Williamson, E. (2023). How notifications affect engagement with a behavior change app: Results from a micro-randomized trial. *JMIR mHealth and uHealth, 11*, e38342. https://doi.org/10.2196/38342
6. Blok, S., et al. (2025). Performance of a medical smartband with photoplethysmography technology and artificial intelligence algorithm to detect atrial fibrillation. *mHealth, 11*, Article 10. https://doi.org/10.21037/mhealth-24-10
7. Bonomi, A. G., Schipper, F., Eerikäinen, L. M., Margarito, J., van Dinther, R., Muesch, G., de Morree, H. M., Aarts, R. M., Babaeizadeh, S., McManus, D. D., & Dekker, L. R. C. (2018). Atrial fibrillation detection using a novel cardiac ambulatory monitor based on photo-plethysmography at the wrist. *Journal of the American Heart Association, 7*(15), e009351. https://doi.org/10.1161/JAHA.118.009351
8. Chang, P. C., Wen, M. S., Chou, C. C., Wang, C. C., & Hung, K. C. (2022). Atrial fibrillation detection using ambulatory smartwatch photoplethysmography and validation with simultaneous Holter recording. *American Heart Journal, 247*, 55–62. https://doi.org/10.1016/j.ahj.2022.02.002
9. Choi, J. H., et al. (2025). Sequential AI-ECG diagnostic protocol for opportunistic atrial fibrillation screening. *Journal of Clinical Medicine, 14*(18), Article 6675. https://doi.org/10.3390/jcm14186675

10. Ding, C., et al. (2024). Photoplethysmography based atrial fibrillation detection: A continually growing field. *Physiological Measurement, 45*(4), 04TR01. https://doi.org/10.1088/1361-6579/ad37f0
11. Ding, E. Y., Tran, K. V., Lessard, D., Wang, Z., Han, D., Mohagheghian, F., Mensah Otabil, E., Noorishirazi, K., Mehawej, J., Filippaios, A., Naeem, S., Gottbrecht, M. F., Fitzgibbons, T. P., Saczynski, J. S., Barton, B., Chon, K., & McManus, D. D. (2023). Accuracy, usability, and adherence of smartwatches for atrial fibrillation detection in older adults after stroke: Randomized controlled trial. *JMIR Cardio, 7*, e45137. https://doi.org/10.2196/45137
12. Eckardt, L., Sehner, S., Suling, A., Borof, K., Breithardt, G., Crijns, H., Goette, A., Wegscheider, K., Zapf, A., Camm, J., Metzner, A., & Kirchhof, P. (2022). Attaining sinus rhythm mediates improved outcome with early rhythm control therapy of atrial fibrillation: The EAST-AFNET 4 trial. *European Heart Journal, 43*(40), 4127–4144. https://doi.org/10.1093/eurheartj/ehac471
13. Francisco, A., et al. (2025). Wearables and atrial fibrillation: Advances in detection, clinical impact, ethical concerns, and future perspectives. *Cureus, 17*(1), e77404. https://doi.org/10.7759/cureus.77404
14. Fredriksson, T., Kemp Gudmundsdottir, K., Frykman, V., Friberg, L., Al-Khalili, F., Engdahl, J., & Svennberg, E. (2020). Intermittent vs continuous electrocardiogram event recording for detection of atrial fibrillation—Compliance and ease of use in an ambulatory elderly population. *Clinical Cardiology, 43*(4), 355–362. https://doi.org/10.1002/clc.23323
15. Frodi, D. M., Kolk, M. Z. H., Langford, J., Knops, R., Tan, H. L., Andersen, T. O., Jacobsen, P. K., Risum, N., Svendsen, J. H., Tjong, F. V. Y., & Diederichsen, S. Z. (2024). Long-term adherence to a wearable for continuous behavioural activity measuring in the SafeHeart implantable cardioverter defibrillator population. *European Heart Journal - Digital Health, 5*(5), 622–632. https://doi.org/10.1093/ehjdh/ztae055
16. Gaffey, A. E., Hooker, S. A., Lampert, R., Gehi, A. K., & Rosman, L. (2025). Psychological aspects of wearable health technologies in patients with cardiovascular disease: A literature review and call to action. *Current Cardiology Reports, 27*(1), 92. https://doi.org/10.1007/s11886-025-02234-7
17. Goevaerts, M., Tenbült-Van Limpt, N., Kop, W., Kemps, H., & Lu, Y. (2025). Patient-reported experiences with long-term lifestyle self-monitoring in heart disease: Mixed methods study. *JMIR Formative Research, 9*, e76978. https://doi.org/10.2196/76978
18. Guo, Y., Wang, H., Zhang, H., et al. (2019). Mobile photoplethysmographic technology to detect atrial fibrillation. *Journal of the American College of Cardiology, 74*(19), 2365–2375. https://doi.org/10.1016/j.jacc.2019.09.019
19. Guo, Y., Wang, H., Zhang, H., Liu, T., Liang, Z., Xia, Y., Yan, L., Xing, Y., Shi, H., Li, S., Liu, E., Cao, K., Chen, Y., Lip, G. Y. H., & Lane, D. A. (2020). Population-based screening or targeted screening for atrial fibrillation: A report from the Huawei Heart Study. *Journal of Clinical Medicine, 9*(5), Article 1493. https://doi.org/10.3390/jcm9051493
20. Hindricks, G., Potpara, T., Dagres, N., Arbelo, E., Bax, J. J., Blomström-Lundqvist, C., Boriani, G., Castella, M., Dan, G. A., Dilaveris, P. E., Fauchier, L., Filippatos, G., Kalman, J. M., La Meir, M., Lane, D. A., Lebeau, J. P., Lettino, M., Lip, G. Y. H., Pinto, F. J., ... Watkins, C. (2021). 2020 ESC guidelines for the diagnosis and management of atrial fibrillation developed in collaboration with the European Association for Cardio-Thoracic Surgery (EACTS). *European Heart Journal, 42*(5), 373–498. https://doi.org/10.1093/eurheartj/ehaa612
21. Inocian, E. P., Junia, A. T., Cordovez, M. G. O., Katada, K. T., & Paday, L. M. W., IV. (2024). Accuracy of the Apple Watch in detecting atrial fibrillation among patients undergoing 24-hour Holter monitoring: A prospective, pragmatic study. *Philippine Journal of Cardiology, 52*(2), 55–60. https://doi.org/10.69944/pjc.4dfc7cfcda
22. Iqhrammullah, M., Abdullah, A., Hermansyah, Ichwansyah, F., Rani, H. A., Alina, M., Simanjuntak, A. M. T., Rampengan, D. D. C. H., Al-Gunaid, S. T., Gusti, N., Damarkusuma, A., & Wikurendra, E. A. (2025). Accuracy and interpretability of smartwatch electrocardiogram for early detection of atrial fibrillation: A systematic review and meta-analysis. *Journal of Arrhythmia, 41*(3), e70087. https://doi.org/10.1002/joa3.70087
23. Joglar, J. A., Chung, M. K., Armbruster, A. L., Benjamin, E. J., Chyou, J. Y., Cronin, E. M., Deswal, A., Eckhardt, L. L., Goldberger, Z. D., Gopinathannair, R., Gorenek, B., Hess, P. L., Hlatky, M. A., Hogan, G., Ibeh, C., Indik, J. H., Kirtane, A. J., Kusumoto, F. M., Link, M. S., ... Van Wagoner, D. R. (2023). 2023 ACC/AHA/ACCP/HRS guideline for the diagnosis and management of atrial fibrillation: A report of the American College of Cardiology/American Heart Association Joint Committee on Clinical Practice Guidelines. *Journal of the American College of Cardiology*. Advance online publication. https://doi.org/10.1016/j.jacc.2023.08.017
24. Kim, D., Yang, P.-S., & Joung, B. (2022). Optimal rhythm control strategy in patients with atrial fibrillation. *Korean Circulation Journal, 52*(7), 496–512. https://doi.org/10.4070/kcj.2022.0078
25. Kim, H., Kim, E., Choi, C., & Yeo, W.-H. (2022). Advances in soft and dry electrodes for wearable health monitoring devices. *Micromachines, 13*(4), Article 629. https://doi.org/10.3390/mi13040629
26. Kirchhof, P., Camm, A. J., Goette, A., Brandes, A., Eckardt, L., Elvan, A., Fetsch, T., van Gelder, I. C., Haas, D., Kuck, K.-H., Metzner, A., Schotten, U., Senni, M., Zeppenfeld, K., Breithardt, G., Fabritz, L., Noack, H., & Brockmeyer, M. (2020). Early rhythm-control therapy in patients with atrial fibrillation. *New England Journal of Medicine, 383*(14), 1305–1316. https://doi.org/10.1056/NEJMoa2019422
27. Kwon, S., Hong, J., Choi, E. K., et al. (2019). Deep learning approaches to detect atrial fibrillation using photoplethysmographic signals. *JMIR mHealth and uHealth, 7*(6), e12770. https://doi.org/10.2196/12770

28. Lou, D. Y., Zhang, Z. W., Sibomana, O., & Izere, S. (2025). Comparison of diagnostic accuracy of electrocardiogram-based versus photoplethysmography-based smartwatches for atrial fibrillation detection: A systematic review and meta-analysis. *Annals of Medicine and Surgery, 87*(4), 2307–2323. https://doi.org/10.1097/MS9.0000000000003155
29. Lubitz, S. A., Fossa, M., Trevidi, N., Stewart, M., Simmons, G., Yoo, C., Sidorov, E., Rong, Y., Lu, J., Rosenberg, Y., & Singer, D. E. (2022). Detection of atrial fibrillation in a large population using wearable devices: The Fitbit Heart Study. *Circulation, 146*(19), 1415–1424. https://doi.org/10.1161/CIRCULATIONAHA.122.060291
30. Machino, T., Aonuma, K., Maruo, K., Komatsu, Y., Yamasaki, H., Igarashi, M., Nogami, A., & Ieda, M. (2023). Randomized crossover trial of 2-week garment electrocardiogram with dry textile electrode to reveal instances of post-ablation recurrence of atrial fibrillation underdiagnosed during 24-hour Holter monitoring. *PLOS ONE, 18*(2), e0281818. https://doi.org/10.1371/journal.pone.0281818
31. Nault, I., et al. (2019). Validation of a novel single lead ambulatory ECG monitor—Cardiostat™—compared to a standard ECG Holter monitoring. *Journal of Electrocardiology, 53*, 57–63. https://doi.org/10.1016/j.jelectrocard.2018.12.007
32. Niu, Y., Wang, H., Wang, H., Zhang, H., Jin, Z., & Guo, Y. (2023). Diagnostic validation of smart wearable device embedded with single-lead electrocardiogram for arrhythmia detection. *Digital Health, 9*. https://doi.org/10.1177/20552076231198682
33. Pamporis, K., Karakasis, P., Sagris, M., Theofilis, P., Milaras, N., Pantelidaki, A., Mourouzis, I., Fragakis, N., Vlachos, K., Kordalis, A., & Tsiachris, D. (2025). Prevalence of asymptomatic atrial fibrillation and risk factors associated with asymptomatic status: A systematic review and meta-analysis. *European Journal of Preventive Cardiology*. Advance online publication. https://doi.org/10.1093/eurjpc/zwaf138
34. Peimankar, A., & Puthusserypady, S. (2020). DENS-ECG: A deep learning approach for ECG signal delineation. *arXiv*. https://doi.org/10.48550/arXiv.2005.08689
35. Pereira, T., Tran, N., Gadhoumi, K., et al. (2020). Photoplethysmography based atrial fibrillation detection: A review. *npj Digital Medicine, 3*, Article 3. https://doi.org/10.1038/s41746-019-0207-9
36. Perez, M. V., Mahaffey, K. W., Hedlin, H., Rumsfeld, J. S., Garcia, A., Ferris, T., Balasubramanian, V., Russo, A. M., Rajmane, A., Cheung, L., Hung, G., Lee, J., Kowey, P., Talati, N., Nag, D., Gummidipundi, S. E., ... Turakhia, M. P. (2019). Large-scale assessment of a smartwatch to identify atrial fibrillation. *New England Journal of Medicine, 381*(20), 1909–1917. https://doi.org/10.1056/NEJMoa1901183
37. Rosman, L., Lampert, R., Zhuo, S., Li, Q., Varma, N., Burg, M., Gaffey, A. E., Armbruster, T., & Gehi, A. (2024). Wearable devices, health care use, and psychological well-being in patients with atrial fibrillation. *Journal of the American Heart Association, 13*(15), e033750. https://doi.org/10.1161/JAHA.123.033750
38. Saarinen, H. J., et al. (2023). Wrist-worn device combining PPG and ECG can be reliably used for atrial fibrillation detection. *Frontiers in Cardiovascular Medicine, 10*, Article 1100127. https://doi.org/10.3389/fcvm.2023.1100127
39. Samol, A., Masin, M., Gellner, R., Otte, B., Pavenstädt, H.-J., Ringelstein, E. B., Reinecke, H., Waltenberger, J., & Kirchhof, P. (2012). Prevalence of unknown atrial fibrillation in patients with risk factors. *Europace, 15*(5), 657–662. https://doi.org/10.1093/europace/eus366
40. Shahid, S., Iqbal, M., Saeed, H., Hira, S., Batool, A., Khalid, S., & Tahirkheli, N. K. (2025). Diagnostic accuracy of Apple Watch electrocardiogram for atrial fibrillation: A systematic review and meta-analysis. *JACC: Advances, 4*(2), Article 101538. https://doi.org/10.1016/j.jacadv.2024.101538
41. Smith, S., & Maisrikrod, S. (2025). Wearable electrocardiogram technology: Help or hindrance to the modern doctor? *JMIR Cardio, 9*, e62719. https://doi.org/10.2196/62719
42. Tamura, T. (2019). Current progress of photoplethysmography and SpO2 for health monitoring. *Biomedical Engineering Letters, 9*, 21–36. https://doi.org/10.1007/s13534-019-00097-w
43. Turakhia, M. P., et al. (2019). Rationale and design of a large-scale, app-based study to identify cardiac arrhythmias using a smartwatch: The Apple Heart Study. *American Heart Journal, 207*, 66–75. https://doi.org/10.1016/j.ahj.2018.09.002
44. Zarak, M. S., Khan, S. A., Majeed, H., Yasinzai, A. Q., Hamzazai, W., Chung, D., Koshkarian, G., & Fleming, K. S. (2024). Systematic review of validation studies for the use of wearable smartwatches in the screening of atrial fibrillation. *International Journal of Arrhythmia, 25*(1), Article 11. https://doi.org/10.1186/s42444-024-00118-5