Systematic Review / Meta-analysis

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Comparison of diagnostic accuracy of electrocardiogram-based versus photoplethysmography-based smartwatches for atrial fibrillation detection

A Systematic Review and Meta-Analysis

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Background: Atrial fibrillation (AF), the most prevalent cardiac arrhythmia, significantly affects morbidity and mortality, making early detection crucial for preventing stroke and heart failure. Recent advancements in wearable technology have introduced smartwatches as potential tools for continuous non-invasive AF detection.

Objective: This systematic review and meta-analysis aimed to evaluate and compare the diagnostic accuracy of electrocardiography (ECG)-and photoplethysmography (PPG)-based smartwatches in detecting AF.

Methodology: A comprehensive search was conducted on PubMed, Google Scholar, and other databases from 18 August to 23 September 2024, to fetch original studies that evaluated performance metrics of ECG and PPG smartwatches in AF detection. The obtained literature was screened according to preset inclusion and exclusion criteria. For included studies, the random-effects model was used to calculate their pooled sensitivity and specificity in AF detection using Jamovi 2.3.28 software. A significance threshold of P <0.05 was applied to all statistical analyses.

Results: Out of the 2564 studies screened, 25 met the inclusion criteria: 11 on PPG and 14 on ECG smartwatches. PPG smartwatches exhibited higher diagnostic performance with a pooled sensitivity of 97.4% (95% CI: 96.5–98.3) and specificity of 96.6% (95% CI: 94.9–98.3). Conversely, ECG smartwatches showed a pooled sensitivity of 83% (95% CI: 78–88) and specificity of 88.4% (95% CI: 84.5–92.2), lower than PPG smartwatches.

Conclusion: PPG-based smartwatches outperformed ECG-based devices in AF detection, offering higher sensitivity and specificity. Even though both modalities are effective in AF detection, the considerable variability in ECG smartwatch performance highlights the need for further research and standardization.

Keywords: atrial fibrillation, cardiac arrythmia, ECG smartwatches, PPG smartwatches, wearable technology

Introduction

Atrial fibrillation (AF) is the most common form of cardiac arrhythmia[1]. It is characterized by disorganized atrial activity recognized in the electrocardiogram (ECG) as an irregularly irregular rhythm lasting more than 30 seconds, with no discernible P-waves preceding the QRS complex[2,3]. Estimates suggest that the number of individuals affected by AF could double or even triple by 2050[2,4]. While AF affects about 1% of the general population, this figure escalates to approximately 9% for those over 75, and the lifetime risk by age 80 reaches 22%[2]. Its prevalence and incidence are on the rise, varying across different genders and racial/ethnic groups, influenced by a combination of

HIGHLIGHTS

- Atrial fibrillation (AF) is the most common cardiac arrhythmia.
- This meta-analysis compared ECG and PPG smartwatches accuracy for AF detection.
- PPG smartwatches showed 97.4% sensitivity and 96.6% specificity in detecting AF.
- ECG smartwatches showed 83% sensitivity and 88.4% specificity in in detecting AF.
- Both ECG and PPG technologies can aid in early AF detection for early intervention.

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genetic, environmental, and socioeconomic factors. Men have a higher incidence compared to women. Even though women experience longer-lasting and more frequent symptomatic episodes, have a lower prevalence of coronary artery disease, and are less likely to receive appropriate anticoagulation therapy, leading to a higher adjusted risk of death[5].

It also varies among different racial and ethnic groups. In the United States, studies have shown that Black patients have a significantly lower compared to White patients. For instance, in a cohort of heart failure patients, Black patients had markedly less AF than White patients (20.8% vs. 44.8%, $P < 0.001$[6]. Similarly, research has found that Black patients had a significantly lower risk of AF compared to White patients, with an incidence rate of 21.4% in Black versus 25.5% in White patients[7]. Additionally, it is noted that AF is more commonly diagnosed in men and is relatively more prevalent in Caucasian populations compared to Black individuals[8,9].

When considering both gender and ethnic factors, disparities in AF Prevalence become more pronounced. A study reported that the prevalence of subclinical AF was 3.3% in White men, 2.5% in White women, 2.1% in Black men, and 1.6% in Black women[7]. Several risk factors contribute to its development including aging, hypertension, obesity, diabetes mellitus, coronary artery disease, etc[10].

Traditional diagnostic methods, particularly 12-lead ECG, are widely used in clinical settings; however, they provide a snapshot at a specific time instead of allowing for continuous monitoring required for capturing the transient nature of paroxysmal AF episodes[11,12]. Though these conventional techniques are reliable, there is an evident need for advanced screening devices to offer real-time monitoring and enhance clinical detection rates.

In recent years, wearable technology, especially smartwatches with integrated cardiac monitoring features, has emerged as a promising avenue for noninvasive AF detection[13]. They can identify arrhythmias independently, allowing patients to take control of their therapy. ECG and photoplethysmography (PPG) smartwatches are among the leading technologies developed for this purpose despite the rise of other innovations, such as bright rings, chest patches, smartphone-based sensors, and earring sensors.

ECG-based smartwatches, including popular models such as the Apple Watch and Samsung Galaxy Watch, monitor the heart's electrical activity to detect AF[14]. They are equipped with single-lead ECG capabilities, allowing users to record their heart's electrical signal directly from the wrist. In this setup, the watch's back serves as a positive electrode, and the user places a fingertip on the opposite hand to act as a negative electrode creating a lead similar to the standard ECG Lead I. This configuration enables the detection of AF by identifying irregularities in the heart's electrical patterns[15]. In contrast, PPG-based smartwatches are based on the optical technique that measures blood volume changes in the microvascular bed of tissue[16]. Sensors emit light into the skin and detect the amount of light that is either absorbed or reflected, which varies with blood flow and is used to calculate heart rate and rhythm[17].

Despite these advancements, challenges remain in AF detection. PPG signals are highly susceptible to motion artifacts, Even minimal arm movements can degrade signal quality, leading to false positives or missed detections. Additionally, PPG signals can be poor even without arm movement, due to various factors such as skin tone, ambient light, and sensor placement[17]. The intermittent nature of PPG monitoring can result in missed detections during short AF episodes[18]. On the other hand, ECG-based detection requires user compliance and may be less convenient for continuous monitoring[19].

While their effectiveness in detecting AF is less well-established than standard 12-lead ECG, various studies have assessed their diagnostic performance, with some elaborating on their potential impact on the diagnosis of those patients at higher risk, such as stroke patients[20]. Additionally, Smartwatches are emerging as valuable tools in healthcare, offering potential benefits for various populations. They can contribute to increased physical activity and weight loss in chronic patients, especially when integrated into broader lifestyle interventions[21]. These devices show promise in screening for AF and monitoring conditions such as Parkinson's disease, epilepsy, and diabetes[21,22]. However, most studies have been conducted in hospital settings, emphasizing more studies to evaluate their effectiveness in long-term ambulatory monitoring among diverse populations[23,24]. These studies demonstrate the potential of wearable devices with integrated AF detection algorithms for improving AF screening, diagnosis, and monitoring, demonstrating non-inferiority to standard care in arrhythmia detection and improving patient care while, on the other hand, reducing healthcare costs[25]. However, no thorough analysis has examined these devices' diagnostic accuracy in a way that considers how well their underlying algorithms work.

This knowledge gap is substantial, given consumers' and doctors' growing usage of smartwatches for ongoing AF monitoring and early intervention. Comprehending the relative efficacy of different devices is crucial to inform clinical judgments and assist users in choosing the most dependable alternative for AF detection.

This review aims to address this gap by evaluating and comparing the diagnostic performance of ECG and PPG smartwatches for detecting AF. We will clarify these technologies' sensitivity, specificity, and overall diagnostic effectiveness differences by analyzing available studies. Our findings aim to inform clinical practice and assist consumers in making informed choices regarding the most reliable option for continuous AF monitoring and early intervention.

Methodology

Registration

This systematic review and meta-analysis protocol was registered in Open Science Framework (OSF) (Registries: 10.17605/OSF.IO/D3QT8).

Reporting

The current systematic review and meta-analysis were conducted according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines-[26], and reported according to the Assessing the Methodological Quality of Systematic Reviews (AMSTAR) guidelines[27].

Databases literature searches

Between 18 August and 23 September 2024, an extensive and systematic search was carried out across several databases,

Table 1

Boolean operators based search parameters in PubMed

Search	Search string	Number of results
#1	(((((((ECG smartwatch) OR (PPG smartwatch)) OR (smartwatch)) OR (scan watch)) OR (Apple watch)) OR (Samsung watch)) OR (wrist wearable)) OR (wearable ECG)) OR (wearable PPG) Filters: from 2014 to 2024	5547
#2	((atrial fibrillation) OR (cardiac arrhythmia)) OR (cardiac monitoring) Filters: from 2014 to 2025	159 523
#3	#1 AND #2	1810

including PubMed/MEDLINE, Google Scholar, DOAJ, AJOL, and the Cochrane Library, to locate original studies evaluating the accuracy of ECG-based smartwatches or PPG-based smartwatches in detecting atrial fibrillation. Alongside these database searches, additional manual searches were performed using Google to gather relevant grey literature. The search strategy utilized vital terms such as "ECG smartwatch," "PPG smartwatch," "smartwatch," "scan watch," "Apple watch," "Samsung watch," "wrist-wearables," "wearable ECG," "wearable PPG," "cardiac monitoring," "atrial fibrillation," and "cardiac arrhythmia." As outlined in Table 1, Boolean operators are used for PubMed search. To ensure the inclusion of recent studies, the search was limited to literature published from 2014 onward, covering the most recent decade. The references collected, including those from gray literature, were imported into Rayyan software for deduplication and subsequently screened based on predefined inclusion and exclusion criteria.

Eligibility criteria

The inclusion criteria established for the studies analyzed in this systematic review and meta-analysis were meticulously crafted to ensure the selection of high-quality research studies focusing on the diagnostic efficacy of ECG or PPG-based smartwatches in detecting AF. The review encompassed only primary research articles, including clinical trials, cross-sectional studies, case-control studies, and prospective cohort studies that reported diagnostic metrics such as sensitivity, specificity, accuracy, positive predictive value (PPV), and negative predictive value (NPV).

The studies had to evaluate adult populations and concentrate specifically on smartwatches fitted with ECG or PPG sensors for AF detection, with a comparative analysis against reference standards such as 12-lead ECG, Holter monitors, or telemetry ECG systems. Only publications in English from 2014 to 2024 were considered to capture recent advancements in wearable technology. To uphold methodological rigor, studies were mandated to meet a minimum quality threshold and evaluated using the Joanna Briggs Institute (JBI) Critical Appraisal Tool, with only those rated as medium or high quality (JBI scores above 50%) being included.

Studies categorized as reviews, commentaries, case reports, or those unrelated to AF detection, along with non-English or inaccessible studies, were excluded to ensure consistency and relevance. Table 2 details all inclusion and exclusion criteria of this systematic review and meta-analysis.

Data extraction

Two authors independently extracted data from the selected studies using a standardized template in Microsoft Excel. The extracted data included details such as author identification, study design, study location, total and actual number of participants, mean age, male percentage, type of sensor used (ECG or PPG smartwatch), reference standard ECG measurements, and crucial performance metrics such as accuracy, sensitivity, specificity, PPV, and NPV. Any disagreements that arose during this process were resolved through discussion. If consensus could not be reached, a third reviewer was consulted to ensure the accuracy and consistency of the extracted data.

Quality assessment

The quality of the included studies was assessed using the Joanna Briggs Institute (JBI) critical appraisal tool[28]. Studies were

Table 2

Inclusion and exclusion criteria

Criterion	Included	Excluded
Study design	Diagnostic validation studies, clinical trials, cross-sectional, case-control, and prospective cohort studies	Commentaries, perspectives, case reports, conference proceedings, reports, reviews, opinions, and letters to the editors
Year of publication	2014 to 2024	Before 2014
Outcome of interest	Reporting performance of ECG or PPG smartwatches in the detection of atrial fibrillation (AF)	• Not reporting both sensitivity and specificity • Wrist-worn devices other than smartwatches • ECG or PPG smart watches for other cardiac monitoring purposes, not AF detection (ex: Heart rate or blood pleasure monitoring)
Accessibility	Abstract and full text assessable	• Abstract and full text inaccessible • Abstract accessible, full text inaccessible
Language	English	Other remaining languages besides English
Quality	Medium and high-quality studies	Low-quality studies

categorized into three distinct quality tiers: high-quality (JBI scores exceeding 70%), medium-quality (JBI scores ranging from 50% to 70%), and low-quality (JBI scores below 50%). Only studies rated as medium or high quality were deemed suitable for inclusion in this systematic review and meta-analysis, ensuring the analysis was based on sufficient rigor and reliability research.

Assessment of risk of bias

The risk of bias and applicability of the included studies was evaluated using the Quality Assessment of Diagnostic Accuracy Studies–2 (QUADAS-2) tool, as recommended by the Cochrane Collaboration and the U.K. National Institute for Health and Care Excellence (NICE). This assessment encompassed four domains: (1) participant selection, (2) index test, (3) reference standard, and (4) flow and timing. The results were visualized utilizing the Robvis tool, which facilitates the graphical representation of risk of bias assessments.

Statistical analysis

The meta-analysis employed a Restricted Maximum Likelihood (REML) random-effects model to separately calculate ECG and PPG smartwatches' aggregated sensitivity and specificity in detecting atrial fibrillation to address the anticipated variability among studies. The degree of heterogeneity was evaluated using the I^2 statistics. Meta-analyses were performed using Jamovi 2.3.28 software. A significance threshold of P <0.05 was applied to all statistical analyses.

Ethical approval and consent form

Ethical approval and consent forms were unnecessary since this study utilized publicly available secondary data and did not involve direct interaction with human or animal subjects.

Results

Study selection

A total of 2564 studies were initially identified through searches of electronic databases and grey literature sources. After removing 631 duplicate records, 1933 studies were available for the preliminary evaluation. Of these, 1796 were excluded during title and abstract screening due to irrelevance, leaving 137 studies for in-depth full-text assessment. Among these, 112 studies were discarded for various reasons: 47 did not address the outcomes of interest, 18 involved smart wearables other than smartwatches, 23 focused on cardiac monitoring unrelated to atrial fibrillation detection, 17 were not primary research articles, and seven had full texts that were inaccessible. As a result, 25 studies (11 on PPG smartwatches and 14 on ECG smartwatches) met all the specified criteria and were included in the systematic review and meta-analysis, as depicted in Fig. 1.

Characteristics of included studies

As detailed in Table 3, among the 25 entries analyzed, eight studies[29-36] (32%) were conducted in the USA, six studies[37-

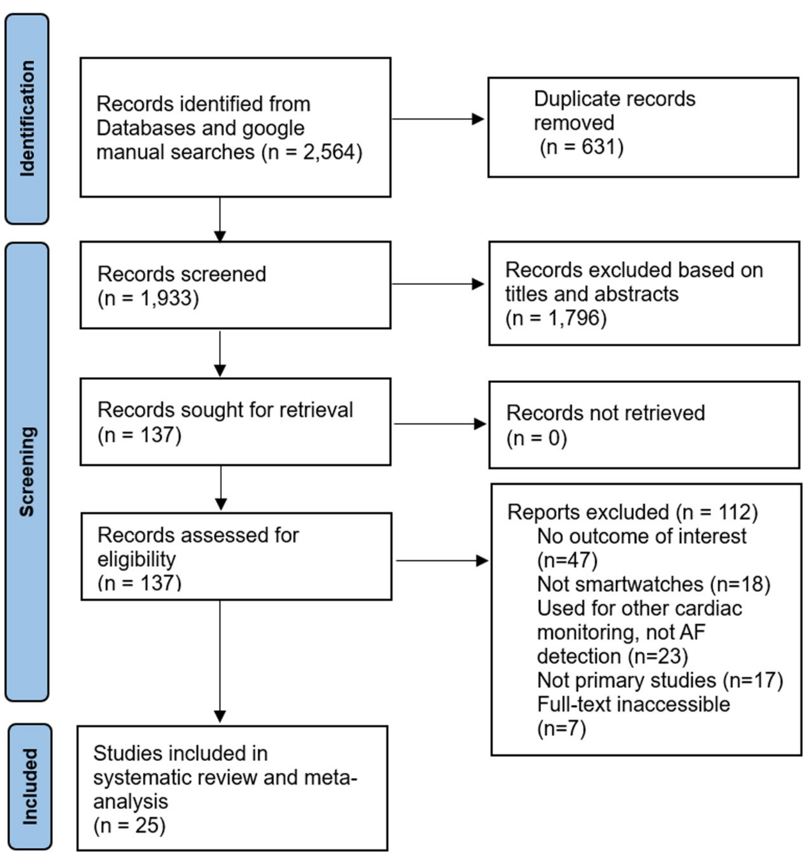

Figure 1. PIRSMA flowchart demonstrating selection of eligible studies.

Table 3

Summary and characteristics of included studies

Author ID	Study design	Country	Number of subjects	Total number screened	Mean age	Male (%)	Type of sensor	Gold standard	Accuracy	Sensitivity	Specificity	PPV	NPV
Dörr *et al*, 2019[55]	Prospective case-control trial	Germany and Switzerland	672	508	76.4	55.7	PPG Smartwatch	12-Lead ECG	96.1	93.7	98.2	97.8	94.7
Chang *et al*, 2022[47]	ProspectiveDiagnostic accuracy study	Taiwan	200	112	66.1	63.5	PPG Smartwatch	24-h Holter ECG	93.5	97.3	88.6	91.6	96.3
Selder *et al*, 2023[49]	ProspectiveDiagnostic accuracy study	Netherlands	78	78	66	53.5	PPG Smartwatch	12-Lead ECG	97	98	96	96	99
Nonoguchi *et al*, 2022[53]	Prospective single-centre study	Japan	1500	166	66.5	68	PPG Smartwatch	Single-lead Telemetry ECG		98	90.6	69.4	99.5
Bashar *et al*, 2019[35]	Prospective single-centre study	USA	46	46	-	-	PPG Smartwatch	7-Lead Holter ECG	97.54	98.18	97.43	-	-
Bashar *et al*, 2019[34]	ProspectiveDiagnostic accuracy study	USA	20	20	-	-	PPG Smartwatch	7-Lead Holter ECG	97.11	96.15	97.37	-	-
Bonomi *et al*, 2018[50]	Prospective cohort clinical trial	Netherlands	20	18	59.6	55.5	PPG Smartwatch	Single-lead ECG apparatus (Actiwave Cardio)	98	96	100	100	98
			40	34	67.4	61.1	PPG Smartwatch	24-h Holter ECG	97	93	100	100	95
Liao *et al*, 2022[48]	Prospective single-centre study	Taiwan	116	116	59.6	67	PPG Smartwatch	24-h Holter ECG	95.8	97	94	96	95.4
Han *et al*, 2020[32]	Prospective Diagnostic accuracy study	USA	37	37	70.49	78.3	PPG Smartwatch	7-Lead Holter ECG	97.95	98.18	97.9	91.53	99.57
Tison *et al*, 2018[36]	Prospective Diagnostic accuracy study	USA	9750	9750	42	63	PPG Smartwatch	12-Lead ECG	97	98	90.2	90.9	97.8
Ding *et al*, 2019[33]	Prospective Diagnostic accuracy study	USA	40	40	71	80	PPG Smartwatch	7-Lead Holter ECG	98.1	98.2	98.1	91.5	99.6
Mannhart *et al*, 2023[46]	Clinical diagnostic validation study	Switzerland	201	201	66.7	69	Single-lead ECG Apple Watch 6	12-Lead ECG		85	75	58	93
							Single-lead ECG Samsung Galaxy Watch 3	12-Lead ECG		85	75	57	93
							Single-lead ECG Withings Scanwatch	12-Lead ECG		58	75	48	82
							Single-lead ECG Fitbit Sense	12-Lead ECG		66	79	55	85
Fiorina *et al*, 2024[43]	Clinical diagnostic validation study	France	400	400	64.8	70.8	ECG smartwatch with DNN	12-Lead ECG		91	95		
							ECG smartwatch with Apple app	12-Lead ECG		61	97		
Müller *et al*, 2024[52]	Prospective observational study	Norway	105	93	68	78.5	Single-lead ECG Apple watch 5	2–4 days telemetry ECG	95	91	96	83	81
							Single-lead ECG Apple watch 5	12-Lead ECG		71	92	72	96
Gala *et al*, 2023[51]	Clinical diagnostic validation study	UK	400	393	63	73	Single-lead ECG Apple Watch Series 6	12-Lead ECG		67.4	74.9		

(*Continued*)

Table 3

(Continued).

Author ID	Study design	Country	Number of subjects	Total number screened	Mean age	Male (%)	Type of sensor	Gold standard	Accuracy	Sensitivity	Specificity	PPV	NPV
Fiorina *et al*, 2022[42]	Clinical diagnostic validation study	France	101	101			ECG Apple smartwatch with ECG 2.0 App	12-Lead ECG	89	81	97		
							ECG Apple smartwatch with DNN	12-Lead ECG	91	92	90		
Campo *et al*, 2022[41]	Clinical diagnostic validation study	France	262	262	67.7	61.1	Single-lead ECG ScanWatch	12-Lead ECG		96.3	100		
Rajakariar *et al*, 2020[54]	Clinical diagnostic validation study	Australia	200	200	67	56.5	ECG smartwatch (AliveCor KardiaBand)	12-Lead ECG	84.3	94.4	81.9	54.8	98.4
Wasserlauf *et al*, 2019[38]	Clinical diagnostic validation study	USA	26	24	72.1	65.4	ECG smartwatch (Apple Watch with KardiaBand)	Insertable cardiac monitor (ICM; Reveal LINQ)		97.7	98.9	76.8	99.9
Abu-Alrub *et al*, 2022[44]	Clinical diagnostic validation study	France	200	200	62	56	ECG smartwatch (Apple Watch)	12-Lead ECG		87	86	86	87
							ECG smartwatch (Samsung)	12-Lead ECG		88	81	82	87
							ECG smartwatch (Withings)	12-Lead ECG		78	80	80	78
Racine *et al*, 2022[39]	Clinical diagnostic validation study	France	734	734	66	58	ECG smartwatch (Apple Watch series 5)	12-Lead ECG		69	81		
Badertscher *et al*, 2022[45]	Clinical diagnostic validation study	Switzerland	319	319	67	52	ECG Withings Scanwatch	12-Lead ECG		76	99		
Velraeds *et al*, 2023[40]	Clinical diagnostic validation study	France	723	723			ECG smartwatch (Apple Watch Series 5)	12-Lead ECG	91.6	89.6	92.1	74.2	97.2
Seshadri *et al*, 2020[26]	Clinical diagnostic validation study	USA	50	47			ECG smartwatch (Apple Watch Series 4)	Telemetry ECG		96	100		
Bumgarner *et al*, 2018[37]	Clinical diagnostic validation study	USA	100	100	68.2	83	ECG smartwatch (Apple Watch)	12-Lead ECG		93	84		

42] (24%) in France, and two studies (8%) each in Switzerland[43,44], Taiwan[45,46], and the Netherlands[47,48]. One study (4%) was conducted in the UK[49], Norway[50], Japan[51], and Australia[52]. One study[53] (4%) was international and involved Germany and Switzerland. Most of these were diagnostic clinical validation studies and clinical trials, encompassing 16 440 participants, of whom 14 622 actively participated. The mean age of the participants was 62.44 years, with a sex distribution of 65.66% males and 34.34% females. These studies evaluated two types of smartwatches: 11 ECG smartwatches (44%) and 14 PPG smartwatches (56%). To assess the accuracy of these sensors, the most commonly used gold standards were the 12-lead ECG, Holter ECG, and telemetry ECG.

Assessment of risk of bias

Of the included studies, five demonstrated a high risk of bias in patient selection, three in the index test, one in the reference standard, and three in flow and timing. The remaining studies were assessed as having either low risk or unclear risk of bias. Overall, nine studies were categorized as having a high risk of bias, three as having some concerns, and twelve as having a low risk of bias (Fig. 2).

Performance of ECG and PPG smartwatches in atrial fibrillation detection

The current meta-analysis evaluated the efficacy of ECG and PPG smartwatches in detecting atrial fibrillation, highlighting differences in their pooled sensitivity and specificity. ECG smartwatches exhibited a pooled sensitivity of 83% (95% CI: 78–88), accompanied by significant heterogeneity (I^2 = 93.75%) (Fig. 3). The pooled specificity for ECG smartwatches was 88.4% (95% CI: 84.5–92.2), also with substantial heterogeneity (I^2 = 96.15%) (Fig. 4). In contrast, PPG smartwatches showed a higher pooled sensitivity of 97.4% (95% CI: 96.5–98.3) with minimal heterogeneity (I^2 = 3.16%) (Fig. 5) and a pooled specificity of 96.6% (95% CI: 94.9–98.3) with moderate heterogeneity (I^2 = 75.94%) (Fig. 6).

When comparing the two technologies, PPG-based smartwatches were 17.3% more sensitive than ECG-based smartwatches in detecting atrial fibrillation, with sensitivity rates of 97.4% and 83%, respectively. Moreover, PPG smartwatches demonstrated 9.2% higher specificity than ECG smartwatches, achieving 96.6% specificity compared with 88.4%. This significant difference suggests that PPG-based smartwatches may offer superior accuracy in detecting atrial fibrillation compared to their ECG counterparts.

The Summary ROC (SROC) curves for both ECG and PPG smartwatches in detecting atrial fibrillation revealed distinct performance characteristics. The ECG smartwatch curve demonstrated high sensitivity at lower false positive rates (FPR), gradually plateauing as FPR increases, indicating strong initial diagnostic ability but diminishing returns with higher false positive rates. Meanwhile, the curve stayed above the chance line, showing a reliable ability to detect atrial fibrillation (Fig. 7). In contrast, the PPG smartwatch SROC curve was almost flat, remaining near the upper left corner, suggesting consistently high sensitivity with few false positives. However, the PPG curve showed little improvement with increasing FPR, indicating that while it performs well at low FPRs, its sensitivity does not significantly improve with higher thresholds (Fig. 8). Both devices demonstrated effectiveness, though the ECG smartwatch exhibits a more pronounced trade-off between sensitivity and false positive rates, while the PPG smartwatch maintains stable sensitivity across varying FPRs.

Publication bias

The publication bias assessment for sensitivity and specificity in studies evaluating ECG smartwatch performance for detecting atrial fibrillation revealed consistent findings. For sensitivity, the fail-safe N was 137 743 (P < .001), indicating that a large number of unpublished "null" studies would be required to change the observed effect size, suggesting robust results. However, both the Rank Correlation Test (Kendall's Tau = –1.000, P < .001) and Regression Test (Egger's Test: Z = –13.362, P < .001) showed funnel plot asymmetry (Fig. 9), pointing to potential publication bias or selective reporting. For specificity, the fail-safe N was notably higher at 371 468 (P < .001), further supporting the robustness of the findings. For specificity, similar asymmetry was observed in both the Rank Correlation Test (Kendall's Tau = –1.000, P < .001) and Regression Test (Egger's Test: Z = –14.472, P < .001), showing funnel plot asymmetry (Fig. 10).

The publication bias assessment for sensitivity and specificity in studies evaluating PPG-based smartwatches for detecting atrial fibrillation indicates robust findings, though potential bias may influence the results. For sensitivity, the fail-safe N was 192 463 (P < .001), suggesting that a large number of unpublished "null" studies would be needed to alter the observed effect, supporting the stability of the findings. However, significant funnel plot asymmetry was observed (Fig. 11), with Kendall's Tau of –1.000 (P < .001) and Egger's Test showing a Z value of –2.789 (P = 0.005), pointing to possible publication bias. For specificity, the fail-safe N was 236 072 (P < .001), further reinforcing the robustness of the findings. Yet, similar asymmetry was observed in both the Rank Correlation Test (Kendall's Tau = –1.000, P < .001) and Regression Test (Egger's Test: Z = –5.688, P < .001), suggesting publication bias (Fig. 12).

Subgroup analysis

Subgroup analysis was conducted to explore the significant heterogeneity identified in the main studies. Stratification was performed based on the type of ECG used as the gold standard, the country of study, and the mean age of participants. For ECG-based smartwatches, heterogeneity remained high across all subgroups for the type of ECG and mean age of participants (P < 0.001), suggesting these variables did not explain the observed variability. However, stratification by the country of study revealed that studies conducted in the USA demonstrated lower heterogeneity for sensitivity (I^2 = 18.6%, P = 0.277). Despite this reduction for studies conducted in the US, heterogeneity remained overall high, indicating that other unaccounted factors might contribute to the observed variation (Table 4).

For PPG-based smartwatches, heterogeneity was successfully explained across specific subgroups (Table 5). For sensitivity, studies utilizing 7-lead ECG, conducted in the USA, or including participants with a mean age >65 years exhibited no heterogeneity at all. Conversely, minimal heterogeneity was observed in studies employing 24-hour Holter ECG and those with a mean age <65 years, with values below 1%. The highest heterogeneity

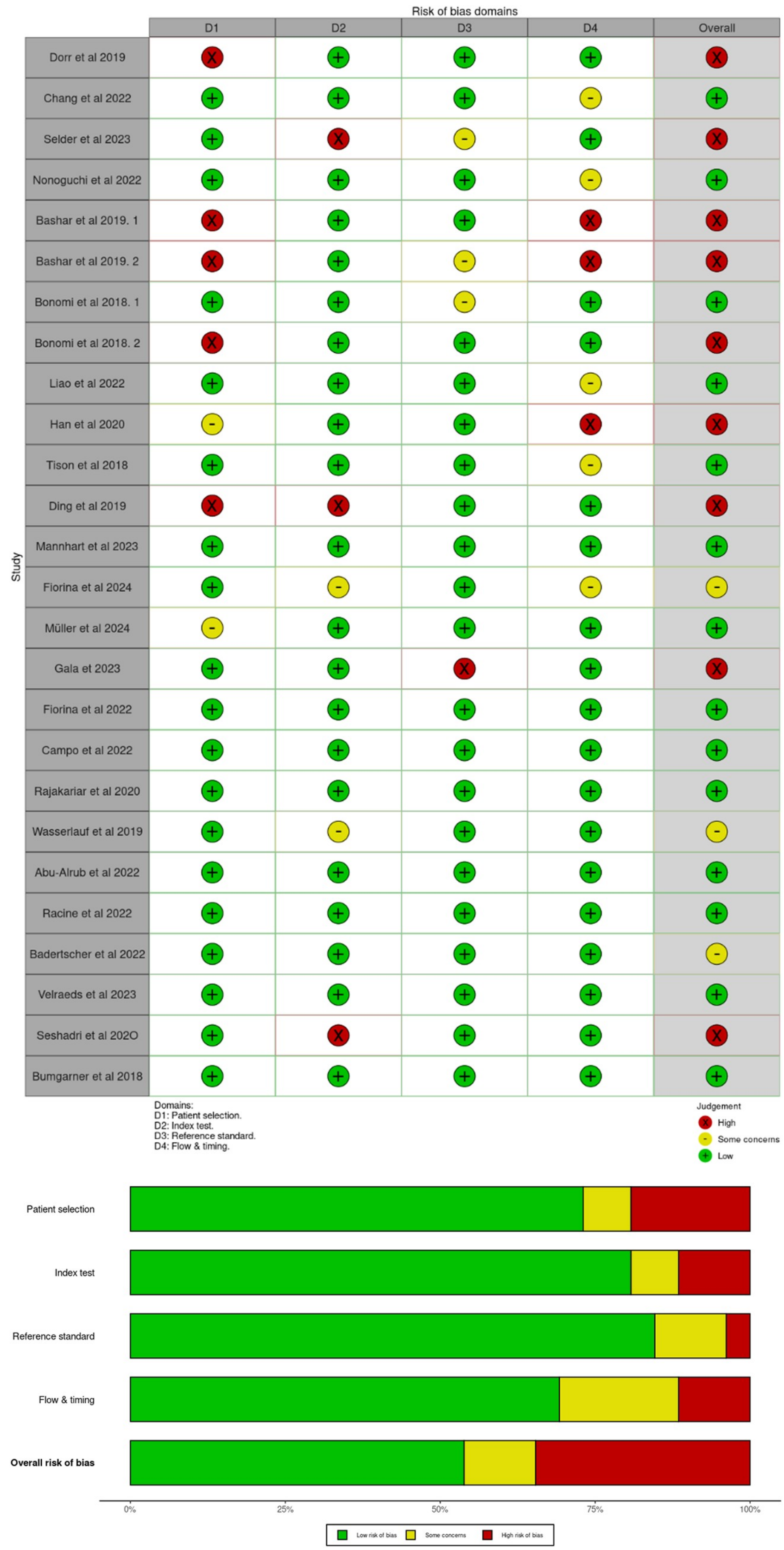

Figure 2. Risk of bias graph': review authors' judgments about each risk of bias item presented as percentages across all included studies, and "risk of bias summary": review authors' judgments about each risk of bias item for each included study.

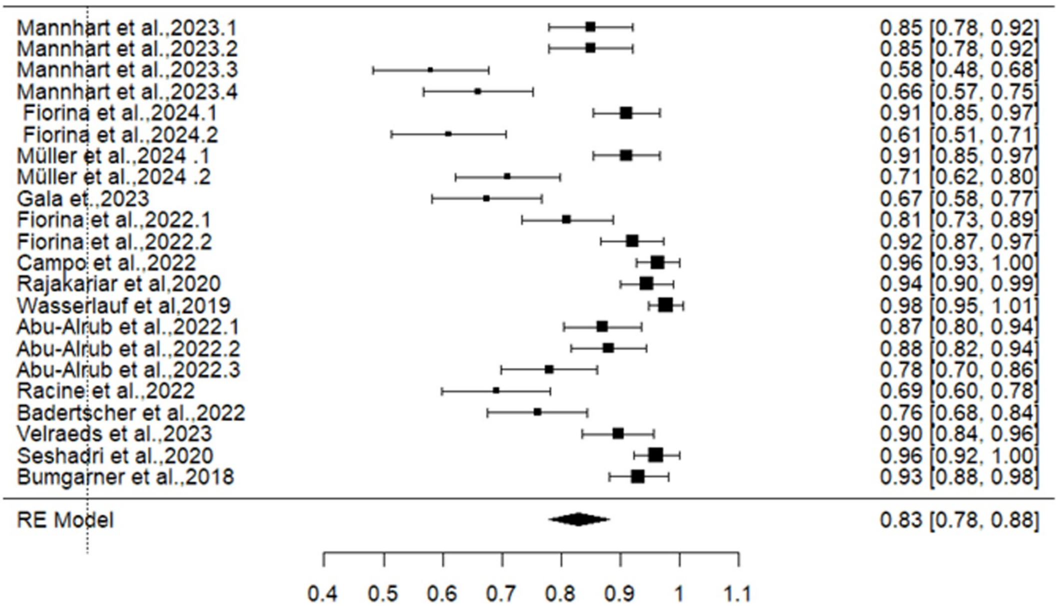

Figure 3. Pooled sensitivity of ECG smartwatches in detecting atrial fibrillation.

occurred in studies conducted in the Netherlands (I^2 = 34.35%, P = 0.214), although it was not statistically significant. For specificity, heterogeneity remained non-significant except for studies utilizing 24-hour Holter ECG (I^2 = 86.3%, P < 0.001), 12-lead ECG (I^2 = 71.0%, P = 0.046), and those with a mean age <65 years (I^2 = 88.2%, P < 0.001).

Discussion

The current systematic review and meta-analysis analyzed 25 high-quality studies to compare the accuracy of ECG smartwatches versus PPG smartwatches in detecting atrial fibrillation. The findings from this systematic review and meta-analysis are pivotal in addressing the increasing prevalence of AF and its associated complications, such as stroke, which contributes to rising healthcare costs and mortality rates worldwide. With advances in wearable technology and brilliant watches, there is a growing interest in their potential to serve as convenient tools for early AF detection and continuous heart rhythm monitoring, particularly outside clinical settings.

Diagnostic accuracy of PPG-based smartwatches

Among the 11 PPG-based smartwatch studies, pooled sensitivity and specificity estimates were remarkably high, with a pooled

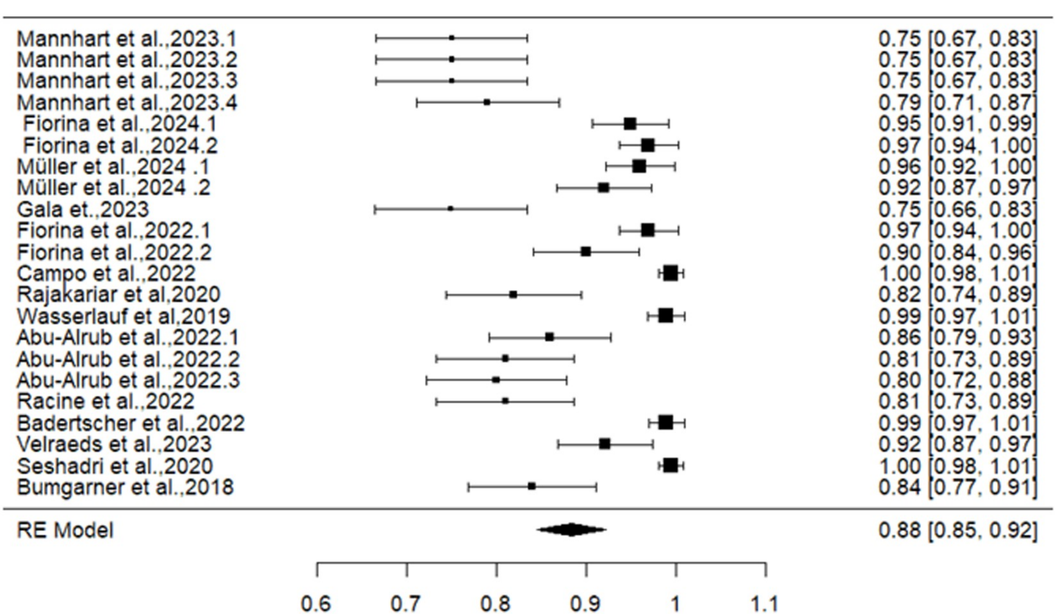

Figure 4. Pooled specificity of ECG smartwatches in detecting atrial fibrillation.

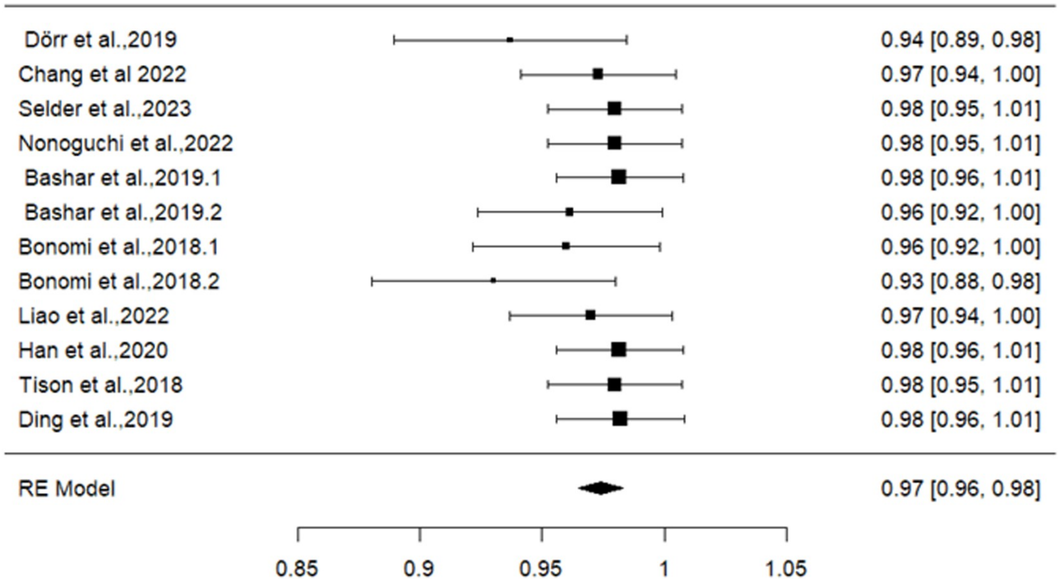

Figure 5. Pooled sensitivity of PPG smartwatches in detecting atrial fibrillation.

sensitivity of 0.97 (0.96, 0.98) and a pooled specificity of 0.97 (0.95, 0.98). This suggests that PPG-based smartwatches perform well at detecting AF episodes. For example, studies by Dörr *et al* (2019)[53] and Tison *et al* (2018)[34] demonstrated high diagnostic accuracy, with a sensitivity of 93.7% and 98% and specificity of 98.2% and 90.2%, respectively.

Interestingly, Bashar *et al* (2019)[32] evaluated two separate PPG-based devices, showing consistent results in detecting AF, with both studies reporting sensitivities above 96% and specificities above 97%. Similarly, Bonomi *et al* (2018)[48] reported a specificity of 100%, which underscores the reliability of PPG-based devices for detecting abnormal heart rhythms, particularly AF.

Recent studies have demonstrated the potential of PPG smartwatches to detect AF (Ding *et al*, 2019)[54]. Using a smartwatch algorithm, we have reported high accuracy (98.1%) in identifying irregular pulses among older adults. Similarly, Bashar *et al* (2019) achieved 97.54% accuracy in AF detection from wrist PPG signals, which aligns with our findings.

PPG-based smartwatches are more accessible to the general population because of their affordability, ease of use, and non-invasive nature. However, some limitations, such as the potential for false positives from motion artifacts, remain a concern, as indicated by Nonoguchi *et al* (2022)[51], who reported a specificity of 69.4%, significantly lower than that reported in other studies with different results. This highlights the variability

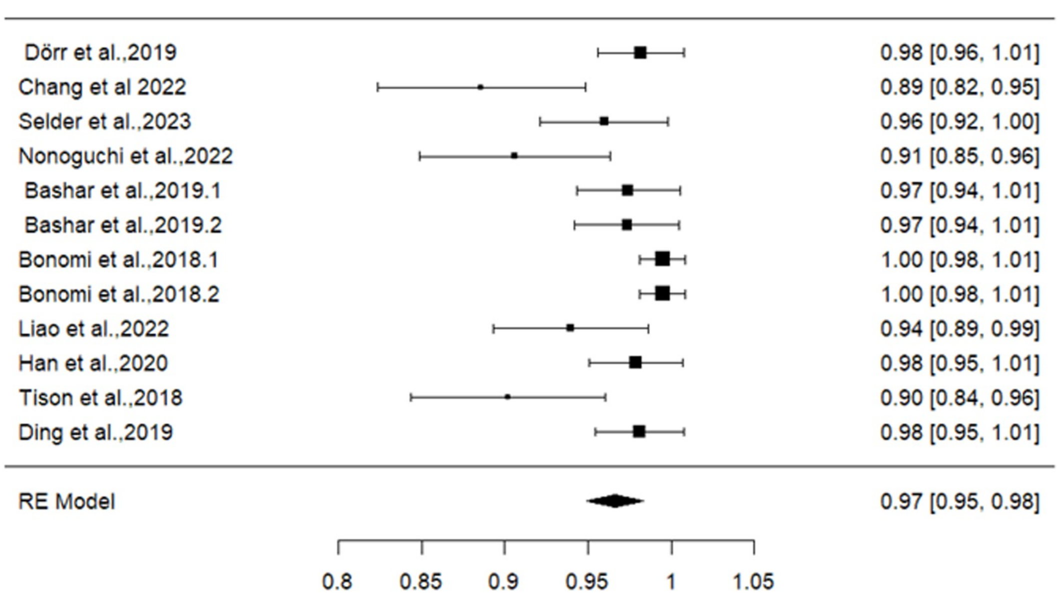

Figure 6. Pooled specificity of PPG smartwatches in detecting atrial fibrillation.

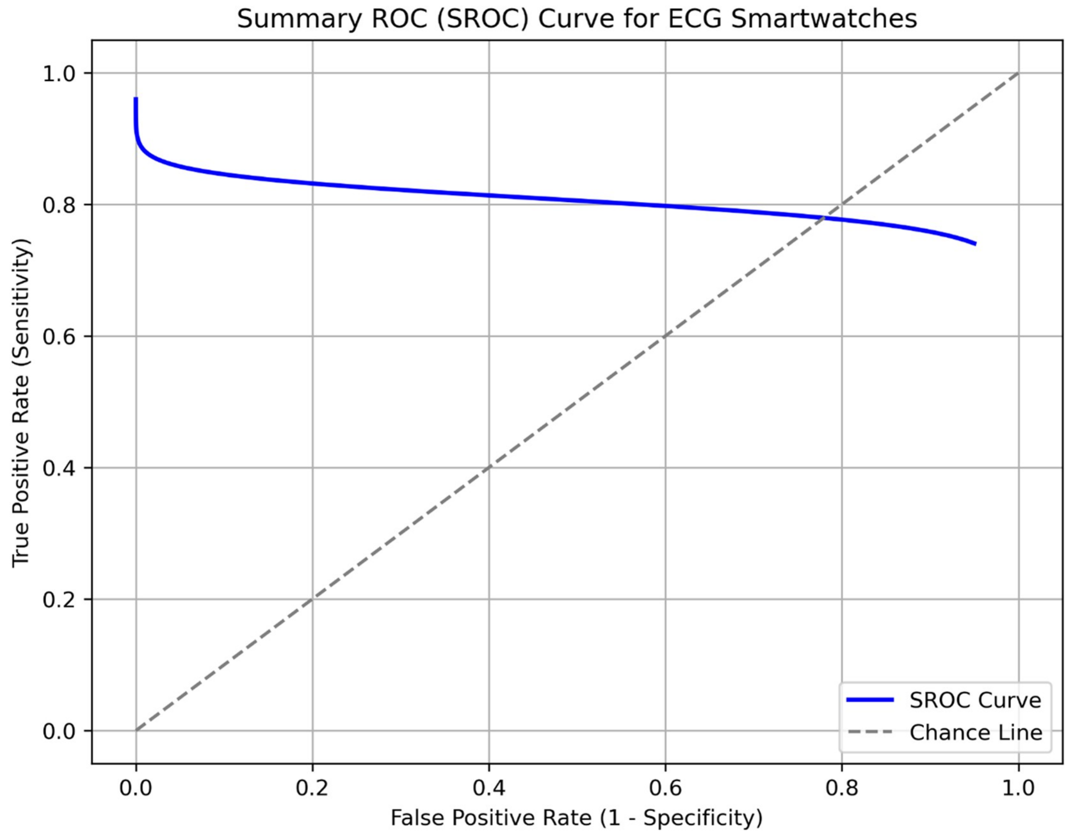

Figure 7. Summary ROC (SROC) curve for performance of ECG smartwatches in detecting atrial fibrillation.

that can occur depending on the device's algorithm and the user's activity levels.

Diagnostic accuracy of ECG-based smartwatches

Fourteen studies investigating the accuracy of ECG-based smartwatches showed a slightly lower overall diagnostic accuracy than PPG-based smartwatches. The pooled sensitivity was 0.83 (0.78, 0.88), and the specificity was 0.88 (0.85, 0.92). Some studies have reported higher and lower accuracy levels of ECG smartwatches in AF detection compared to our findings. Avram *et al* (2021)[55] validated a novel algorithm combining PPG and ECG, showing excellent performance with 96.9% sensitivity and 99.3% specificity when using both modalities. Additionally, Selder *et al* (2023)[47] reported a high sensitivity of 98% and specificity of 96% for ECG smartwatches, aligning with another study that revealed that deep neural networks applied to smartwatch ECGs achieved a sensitivity of 91% and a specificity of 95%, outperforming traditional methods[41]. Neri *et al* (2024)[56] validated an algorithm for ECG signal quality, achieving a sensitivity of 94.7% and specificity of 95.3%, demonstrating the reliability of wearable ECG devices, further contrasting the findings of our review. Similarly, Perera *et al* (2016)[57] reported a sensitivity of 80% and a specificity of 97% for ECG smartwatches, reaffirming their reliability in clinical settings.

However, other studies have reported lower accuracy for ECG-based devices (Mannhart *et al,* 2023)[44]. The Apple Watch 6 had a sensitivity of 75% and a specificity of 58% in detecting AF. Similarly, Abu-Alrub *et al* (2022)[42] reported mixed results across different ECG smartwatch models, with sensitivities ranging from 81% to 92% and specificities ranging from 86% to 97%. Differences likely influence these variations in device hardware, algorithm sensitivity, and the gold standard used for comparison, such as telemetry or 12-lead ECG.

A notable finding from studies such as Rajakariar *et al* (2020)[52] and Wasserlauf *et al* (2019)[36] was that while ECG-based smartwatches generally provided accurate results, they are more commonly used in clinical or higher-risk populations where detailed heart rhythm readings are crucial. These devices, which generate a direct ECG trace, are more suitable for individuals with known cardiovascular conditions or those requiring closer monitoring by healthcare professionals.

The role of wearable technology in promoting patient engagement and self-monitoring has been well-documented. Smartwatches facilitate continuous monitoring of heart rhythm, which can lead to increased patient awareness of their health status[58]. Studies indicate that patients using smartwatches are more likely to report irregularities, thereby seeking medical advice sooner, which is vital for timely interventions[59]. According to Del-Valle-Soto *et al* (2024)[60], these devices facilitate real-time health monitoring and enhance user engagement through personalized feedback and gamification, encouraging widespread adoption among patients.

High perceived ease of use and favorable attitudes toward wearable technology have been reported, particularly among younger demographics[61], with over 80% of global consumers expressing willingness to utilize these wearable devices for health monitoring[60]. Despite these advantages, challenges,

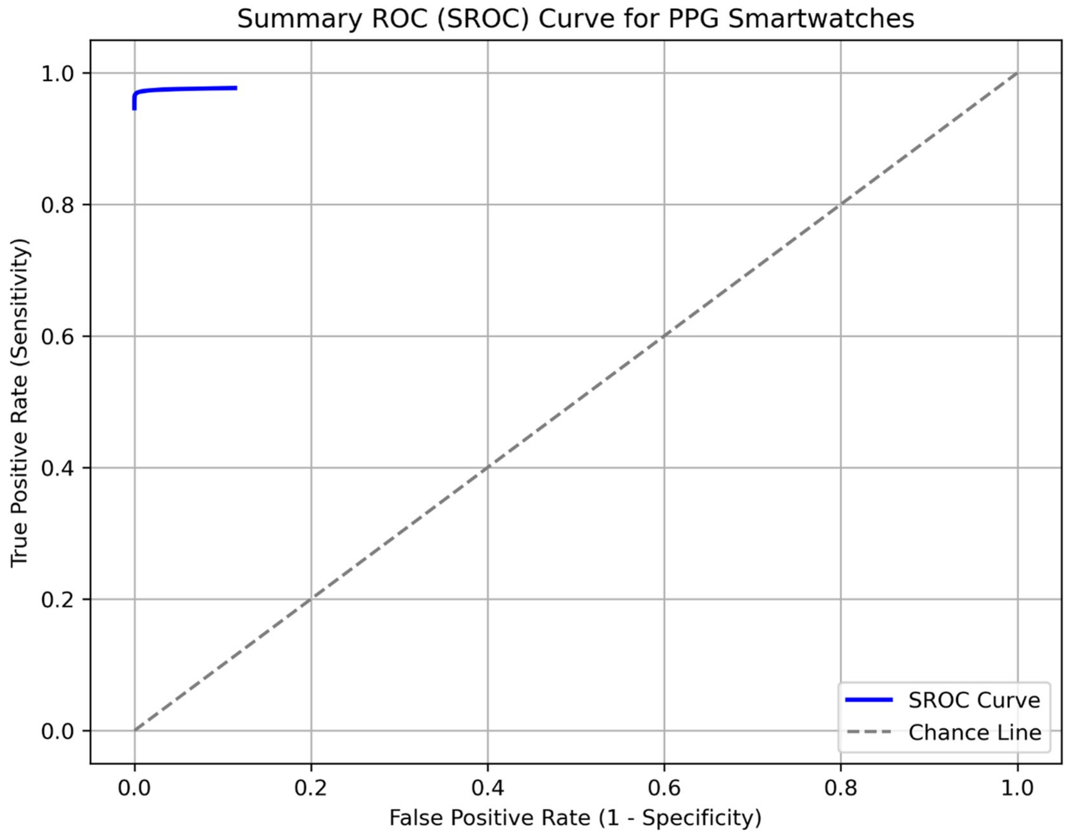

Figure 8. Summary ROC (SROC) curve for performance of PPG smartwatches in detecting atrial fibrillation.

such as data privacy and demographic disparities in usage, persist, necessitating ongoing research and tailored strategies to enhance accessibility.

Overall, the findings from this systematic review and meta-analysis reinforce the existing literature and highlight the significant potential of ECG and PPG smartwatches in the early detection of atrial fibrillation. The pooled sensitivity and specificity rates and comparisons to more than 25 studies demonstrated a consistent trend toward high diagnostic accuracy. They underscored the importance of technological advancements in improving patient care.

Clinical implications of the findings

The high diagnostic accuracy of PPG-based smartwatches makes them particularly well suited for general population screening and long-term AF monitoring, where continuous heart rate variability tracking is essential. Their non-invasive and easy-to-use nature can enable constant cardiac monitoring. In addition, PPG-based devices are relatively affordable, increasing their accessibility to larger populations, particularly in community settings.

By contrast, ECG-based smartwatches, which are slightly less sensitive and specific, provide more precise diagnostic information by directly measuring the heart's electrical activity. This makes them more appropriate for clinical use, especially in patients with a higher risk of AF or pre-existing cardiovascular conditions. The ability to generate an ECG waveform that healthcare professionals can review adds value to ECG-based devices, particularly in high-risk populations, where more detailed heart rhythm information is necessary.

The role of smart wearables, such as smartwatches, is increasingly significant in managing high-risk patients. Early detection and prediction of atrial fibrillation (AF) risks are crucial for identifying individuals who may benefit from these devices[20,62]. This early diagnosis is essential as it facilitates timely interventions, potentially reducing the disease's progression and associated complications[63].

Study strengths and limitations

The primary strength of this review is the inclusion of high-quality studies with rigorous methodologies. The consistency of the results across studies further reinforces the validity of the pooled estimates for sensitivity and specificity. However, this study has several limitations that need to be acknowledged.

First, the studies used different gold standards for AF detection, including 12-lead ECG, Holter monitors, and telemetry ECG, which could have introduced variability in diagnostic accuracy estimates. Second, the demographic characteristics of the study participants varied significantly, with some studies focusing on older populations while others included younger cohorts. These differences could affect the generalizability of the results, mainly when applied to diverse populations.

In addition, while most studies have reported high diagnostic accuracy for PPG and ECG smartwatches, issues such as motion artifacts, environmental conditions, and user adherence may

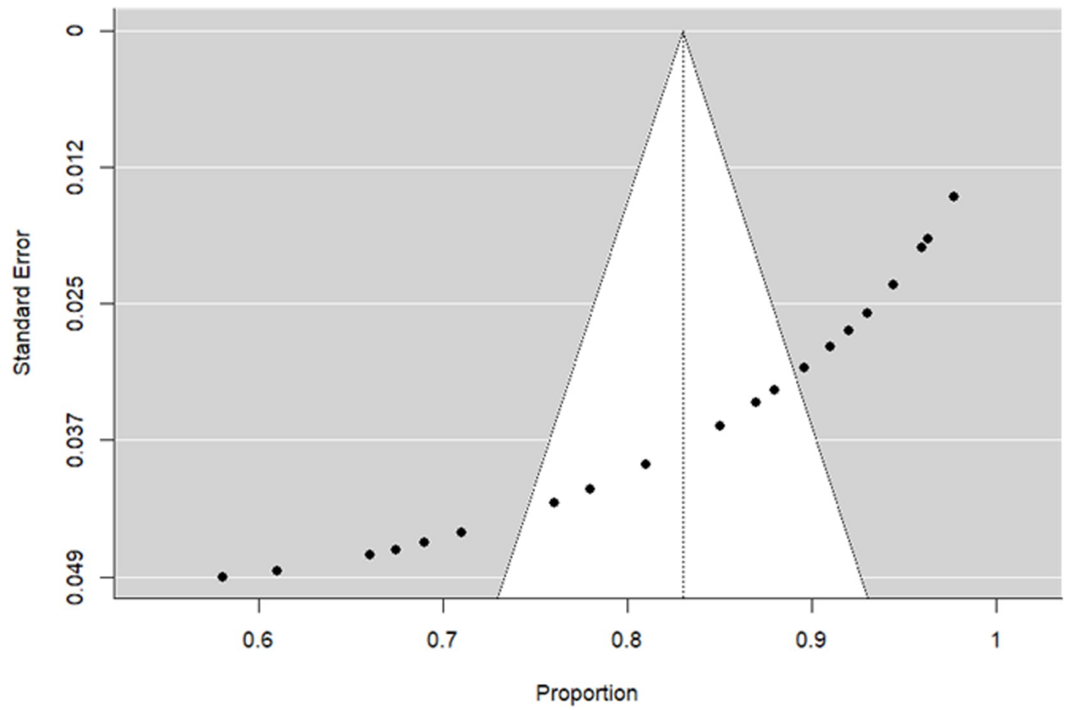

Figure 9. Funnel plot for the sensitivity of ECG smartwatches in detecting atrial fibrillation.

affect real-world performance, particularly for PPG-based devices. These factors should have been consistently addressed across studies, warranting further investigation in future research.

Conclusion and future direction

In conclusion, PPG- and ECG-based smartwatches demonstrate significant potential for detecting AF, with PPG-based devices

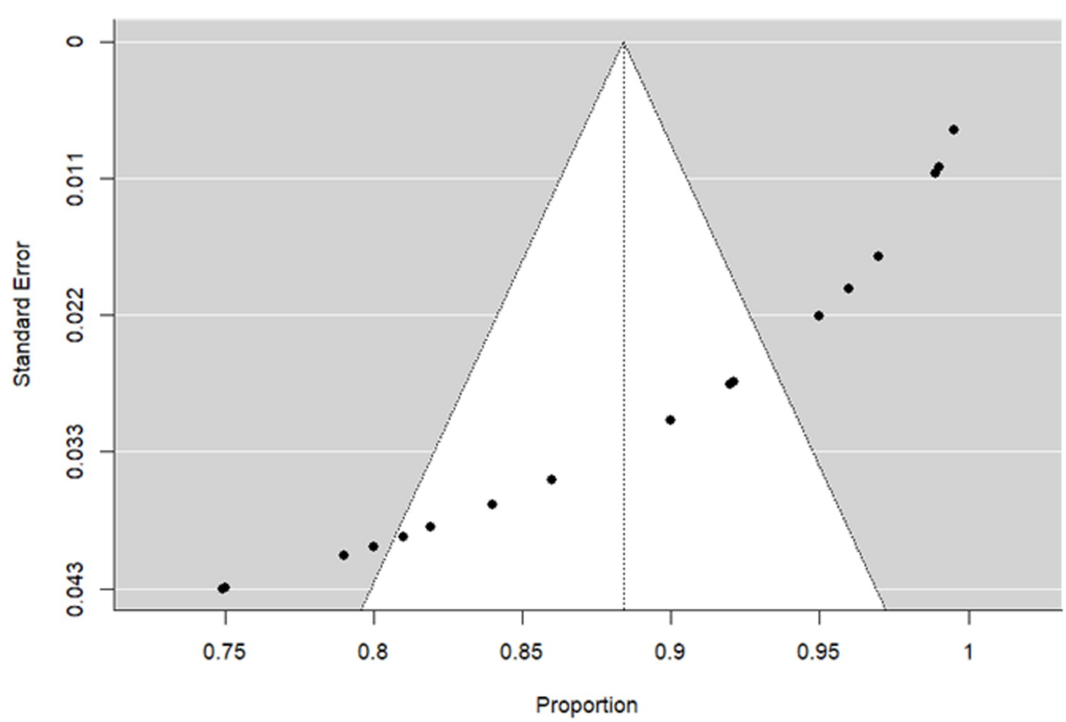

Figure 10. Funnel plot for specificity of ECG smartwatches in detecting atrial fibrillation.

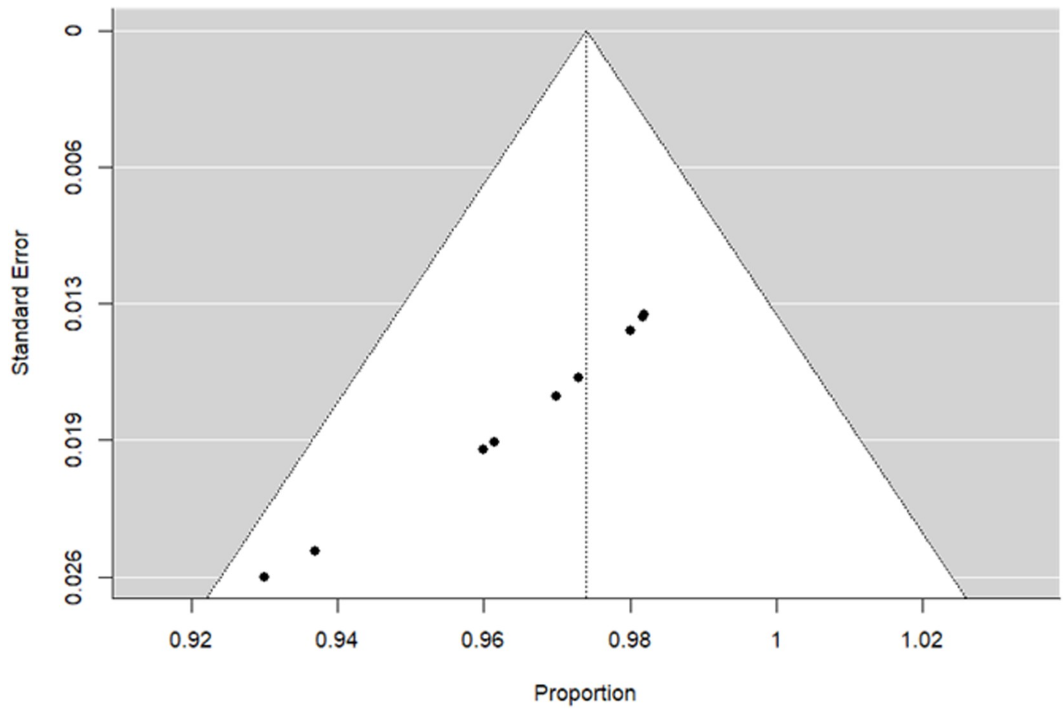

Figure 11. Funnel plot for sensitivity of PPG smartwatches in detecting atrial fibrillation.

showing superior sensitivity and specificity. Although ECG-based smartwatches remain valuable for clinical applications, PPG-based devices offer a reliable and accessible solution for continuous monitoring in the general population.

Future research should focus on improving the accuracy of these devices, particularly by refining algorithms to reduce false positives and account for factors such as motion artifacts and skin tone variability. Direct comparisons between PPG- and

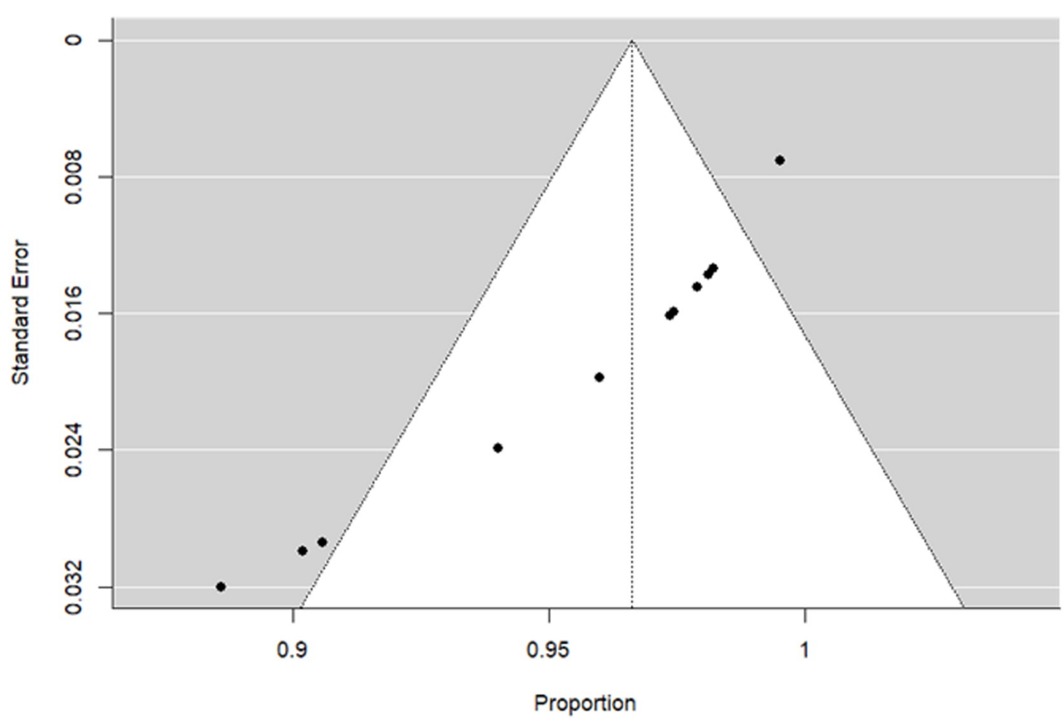

Figure 12. Funnel plot for specificity of PPG smartwatches in detecting atrial fibrillation.

Table 4

Subgroup analysis for studies on the performance of ECG smartwatches in detecting AF.

Subgroup	Category	Sensitivity (95% CI)	I^2	*P* value	Specificity (95% CI)	I^2	*P* value
Gold standard*	12 Lead ECG	81.9 (76.6, 87.2)	93.4	<0.001	87.4 (83.3, 91.4)	94.8	<0.001
The mean age of the participants	Below 65	81.2 (73.5, 88.8)	89.5	<0.001	88.3 (82.5, 94.1)	89.8	<0.001
	Above 65	82.4 (74.9, 89.9)	95.2	<0.001	87 (81.3, 92.8)	96.7	<0.001
Country of study	France	83.8 (77.2, 90.5)	91	<0.001	90.6 (86.1, 95.1)	91.5	<0.001
	USA	96.2 (93.8, 98.6)	18.6	<0.277	94.7 (85.4, 100)	97.7	<0.001

*Other types of ECG used as the gold standard (telemetry ECG and ICM) had insufficient observations for meta-analysis.

ECG-based smartwatches in real-world settings would further clarify their role in AF detection. Moreover, Concerns about equity and bias in wearable device adoption persist, with lower usage rates among underserved populations[64]. A study of smartwatch ECG users in the US found that younger individuals and those in states with higher innovation indices were likelier to use these devices[65]. The observed AF prevalence among users was lower than expected, suggesting a potential demographic gap in access to this technology. As smartwatches become more prevalent in healthcare, addressing these disparities and ensuring equitable distribution of innovation is crucial for maximizing their clinical impact across diverse populations[64]. Moreover, studies with larger sample sizes and more varied populations would help generalize the findings and ensure broader applicability across different patient demographics.

Ethical approval

No ethical approval was needed as the study was secondary, using publicly available data.

Consent

No consent was needed as study did not directly involve human subjects.

Sources of funding

No funding was received.

Author's contribution

D.Y.L.: Conceptualization, methodology, supervision, resources, manuscript writing; Z.W.Z.: Conceptualization, methodology, resources, manuscript writing; O.S.: Conceptualization, methodology, resources, data analysis, visualizations, manuscript writing

S.I.: Conceptualization, methodology, resources, data analysis, visualizations, manuscript writing. All authors reviewed and approved the final draft.

Conflicts of interest disclourse

Authors have no conflict of interest to declare.

Guarantor

Olivier Sibomana.

Research Registration Unique Identifying Number (UIN)

Registry name: Open Science Framework (OSF) registries.

Registration DOI: 10.17605/OSF.IO/D3QT8.

Provenance and peer review

Not invited.

Data availability statement

Essential data are contained in the manuscript. Additional data are available from the corresponding author upon reasonable request.

Table 5

Subgroup analysis for studies on the performance of PPG smartwatches in detecting AF

Subgroup	Category	Sensitivity (95% CI)	I[2]	*P* value	Specificity (95% CI)	I[2]	*P* value
Gold standard	12 Lead ECG	97.4 (95.6, 99.2)	1.95	0.261	95.4 (91.2, 99.6)	71	0.046
	7 Lead ECG	97.9 (96.5, 99.3)	0	0.809	97.7 (96.3,99.2)	0	0.982
	24 hrs Holter ECG	96.4 (94.3, 98.5)	0.06	0.332	94.6 (88.4, 100)	86.3	<0.001
The mean age of participants	Below 65	96.9 (956, 98.2)	0.78	0.472	96 (93, 98.9)	88.2	<0.001
	Above 65	98.1 (96.6, 99.7)	0	0.994	96.2 (92.3, 100)	74.8	0.055
Country of study	Netherlands	96.3 (93.6, 98.9)	34.35	0.214	99.3 (98.3, 100)	3	0.222
	USA	97.9 (96.7, 99.2)	0	0.914	97.3 (95.9, 98.7)	0.19	0.183

References

[1] Atrial fibrillation: the most common arrhythmia. Accessed September 6, 2024. https://pubmed.ncbi.nlm.nih.gov/11093410/

[2] Nesheiwat Z, Goyal A, Jagtap M. Atrial fibrillation. StatPearls. 2024; StatPearls Publishing. September 6, 2024. http://www.ncbi.nlm.nih.gov/books/NBK526072/

[3] Kirchhof P, Benussi S, Kotecha D, *et al*. 2016 ESC guidelines for the management of atrial fibrillation developed in collaboration with EACTS. Eur Heart J 2016;37:2893–962.

[4] CDC. About atrial fibrillation. Heart Disease. May 20, 2024. Accessed September 6, 2024. https://www.cdc.gov/heart-disease/about/atrial-fibrillation.html

[5] Volgman AS, Merz CNB, Benjamin EJ, *et al*. Sex and race/ethnicity differences in atrial fibrillation. J Am Coll Cardiol 2019;74:2812–15.

[6] Thomas KL, Piccini JP, Liang L, *et al*. Racial differences in the prevalence and outcomes of atrial fibrillation among patients hospitalized with heart failure. J Am Heart Assoc 2013;2:e000200.

[7] Tamirisa KP, Al-Khatib SM, Mohanty S, *et al*. Racial and ethnic differences in the management of atrial fibrillation. CJC Open 2021;3:S137–S148.

[8] Kowlgi GN, Gunda S, Padala SK, *et al*. Comparison of frequency of atrial fibrillation in Blacks versus Whites and the utilization of race in a novel risk score. Am J Cardiol 2020;135:68–76.

[9] Marcus GM, Olgin JE, Whooley M, *et al*. Racial differences in atrial fibrillation prevalence and left atrial size. Am J Med 2010;123:375.e1–375.e7.

[10] Elliott AD, Middeldorp ME, Van Gelder IC, *et al*. Epidemiology and modifiable risk factors for atrial fibrillation. Nat Rev Cardiol 2023;20:404–17.

[11] Computational diagnostic techniques for electrocardiogram signal analysis. Accessed September 9, 2024. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7664289/

[12] Sattar Y, Chhabra L. Electrocardiogram. StatPearls. 2024; StatPearls Publishing. September 9, 2024. http://www.ncbi.nlm.nih.gov/books/NBK549803/

[13] Original research: smartphone detection of atrial fibrillation using photoplethysmography: a systematic review and meta-analysis. Accessed September 9, 2024. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC9554073/

[14] Sohn J, Shin H, Lee J, *et al*. Validation of electrocardiogram based photoplethysmogram generated using U-Net based generative adversarial networks. J Healthc Inform Res 2024;8:140–57.

[15] Papalamprakopoulou Z, Stavropoulos D, Moustakidis S, *et al*. Artificial intelligence-enabled atrial fibrillation detection using smartwatches: current status and future perspectives. Front Cardiovasc Med 2024;11:1432876.

[16] Heart rate monitoring – an overview. Accessed September 9, 2024. https://www.sciencedirect.com/topics/computer-science/heart-rate-monitoring

[17] Pereira T, Tran N, Gadhoumi K, *et al*. Photoplethysmography based atrial fibrillation detection: a review. Npj Digit Med 2020;3:1–12.

[18] Sijerčić A, Tahirović E. Photoplethysmography-based smart devices for detection of atrial fibrillation. Tex Heart Inst J 2022;49:e217564.

[19] Yan R, Ding C, Xiao R, *et al*. SQUWA: signal quality aware DNN architecture for enhanced accuracy in atrial fibrillation detection from noisy PPG signals. Published online April 15, 2024. doi:10.48550/arXiv.2404.15353

[20] Hayıroğlu Mİ, Çınar T, Selçuk M, *et al*. The significance of the morphology-voltage-P-wave duration (MVP) ECG score for prediction of in-hospital and long-term atrial fibrillation in ischemic stroke. J Electrocardiol 2021;69:44–50.

[21] Imeraj A, Olesen TB, Laursen DH, *et al*. Agreement between clinically measured weight and self-reported weight among patients with type 2 diabetes through an mhealth lifestyle coaching program in Denmark: secondary analysis of a randomized controlled trial. JMIR Form Res 2022;6:e40739.

[22] Reeder B, David A. Health at hand: a systematic review of smart watch uses for health and wellness. J Biomed Inform 2016;63:269–76.

[23] Mikhail JA, Tadros D, Shehata R. Smartwatch technology's diagnostic use in atrial fibrillation detection – a literature review. Undergrad Res Nat Clin Sci Technol URNCST J 2023;7:1–9.

[24] Eerikäinen LM, Bonomi AG, Dekker LRC, *et al*. Atrial fibrillation monitoring with wrist-worn photoplethysmography-based wearables: state-of-the-art review. Cardiovasc Digit Health J 2020;1:45–51.

[25] Kamga P, Mostafa R, Zafar S. The use of wearable ECG devices in the clinical setting: a review. Curr Emerg Hosp Med Rep 2022;10:67–72.

[26] PRISMA. PRISMA statement. PRISMA statement. Accessed September 10, 2024. https://www.prisma-statement.org

[27] AMSTAR. AMSTAR – assessing the methodological quality of systematic reviews. Accessed November 7, 2024. https://amstar.ca/Amstar-2.php

[28] JBI. JBI critical appraisal tools. Accessed September 10, 2024. https://jbi.global/critical-appraisal-tools

[29] Seshadri DR, Bittel B, Browsky D, *et al*. Accuracy of apple watch for detection of atrial fibrillation. Circulation 2020;141:702–03.

[30] Premature atrial and ventricular contraction detection using photoplethysmographic data from a smartwatch. Accessed September 6, 2024. https://pubmed.ncbi.nlm.nih.gov/33028000/

[31] Accuracy and usability of a novel algorithm for detection of irregular pulse using a smartwatch among older adults: observational study. Accessed September 6, 2024. https://pubmed.ncbi.nlm.nih.gov/31758787/

[32] Smartwatch based atrial fibrillation detection from photoplethysmography signals. Accessed September 6, 2024. https://pubmed.ncbi.nlm.nih.gov/31946820/

[33] Atrial fibrillation detection from wrist photoplethysmography signals using smartwatches. Accessed September 6, 2024. https://pubmed.ncbi.nlm.nih.gov/31636284/

[34] Passive detection of atrial fibrillation using a commercially available smartwatch. Accessed September 6, 2024. https://pubmed.ncbi.nlm.nih.gov/29562087/

[35] Smartwatch algorithm for automated detection of atrial fibrillation. Accessed September 6, 2024. https://pubmed.ncbi.nlm.nih.gov/29535065/

[36] Smartwatch performance for the detection and quantification of atrial fibrillation. Accessed September 6, 2024. https://pubmed.ncbi.nlm.nih.gov/31113234/

[37] Role of coexisting ECG anomalies in the accuracy of smartwatch ECG detection of atrial fibrillation. Accessed September 6, 2024. https://pubmed.ncbi.nlm.nih.gov/36334937/

[38] Improving automatic smartwatch electrocardiogram diagnosis of atrial fibrillation by identifying regularity within irregularity. Accessed September 6, 2024. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC10674836/

[39] Atrial fibrillation detection with an analog smartwatch: prospective clinical study and algorithm validation. Accessed September 6, 2024. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC9675016/

[40] Fiorina L, Lefebvre B, Gardella C, *et al*. Smartwatch-based detection of atrial arrhythmia using a deep neural network in a tertiary care hospital. Accessed September 6, 2024. doi:10.1093/europace/euac053.563

[41] Artificial intelligence–based electrocardiogram analysis improves atrial arrhythmia detection from a smartwatch electrocardiogram. Accessed September 6, 2024. https://academic.oup.com/ehjdh/advance-article/doi/10.1093/ehjdh/ztae047/7708688

[42] Smartwatch electrocardiograms for automated and manual diagnosis of atrial fibrillation: a comparative analysis of three models. Accessed September 6, 2024. https://www.frontiersin.org/journals/cardiovascular-medicine/articles/10.3389/fcvm.2022.836375/full

[43] Badertscher P, Lischer M, Mannhart D, *et al*. Clinical validation of a novel smartwatch for automated detection of atrial fibrillation. Heart Rhythm O2 2022;3:208–10.

[44] Clinical validation of 5 direct-to-consumer wearable smart devices to detect atrial fibrillation: BASEL wearable study. Accessed September 6, 2024. https://pubmed.ncbi.nlm.nih.gov/36858690/

[45] Atrial fibrillation detection using ambulatory smartwatch photoplethysmography and validation with simultaneous holter recording. Accessed September 6, 2024. https://pubmed.ncbi.nlm.nih.gov/35131229/

[46] Impact of recording length and other arrhythmias on atrial fibrillation detection from wrist photoplethysmogram using smartwatches. Accessed September 6, 2024. https://pubmed.ncbi.nlm.nih.gov/35354873/

[47] Accuracy of a standalone atrial fibrillation detection algorithm added to a popular wristband and smartwatch: prospective diagnostic accuracy study. Accessed September 6, 2024. https://pubmed.ncbi.nlm.nih.gov/37234033/

[48] Atrial fibrillation detection using a novel cardiac ambulatory monitor based on photo-plethysmography at the wrist. Accessed September 6, 2024. https://pubmed.ncbi.nlm.nih.gov/30371247/
[49] Briosa E, Gala A, Sharp AJ, *et al*. Automated atrial fibrillation detection with a smartwatch and smart-ring in individuals with cardiovascular disease. Europace 2023;25:euad122.618.
[50] Müller M, Hanssen TA, Johansen D, *et al*. Validity of a smartwatch for detecting atrial fibrillation in patients after heart valve surgery: a prospective observational study. Scand Cardiovasc J SCJ 2024;58:2353069.
[51] Accuracy of wristwatch-type photoplethysmography in detecting atrial fibrillation in daily life. Accessed September 6, 2024. https://pubmed.ncbi.nlm.nih.gov/36712156/
[52] Accuracy of a smartwatch based single-lead electrocardiogram device in detection of atrial fibrillation. Accessed September 6, 2024. https://pubmed.ncbi.nlm.nih.gov/31911507/
[53] Dörr M, Nohturfft V, Brasier N, *et al*. The WATCH AF trial: SmartWATCHes for detection of atrial fibrillation. JACC Clin Electrophysiol 2019;5:199–208.
[54] JMIR cardio – accuracy and usability of a novel algorithm for detection of irregular pulse using a smartwatch among older adults: observational study. Accessed September 9, 2024. https://cardio.jmir.org/2019/1/e13850/
[55] Validation of an algorithm for continuous monitoring of atrial fibrillation using a consumer smartwatch – heart rhythm. Accessed September 9, 2024. https://www.heartrhythmjournal.com/article/S1547-5271(21)00318-0/fulltext
[56] Validation of a new and straightforward algorithm to evaluate signal quality during ECG monitoring with wearable devices used in a clinical setting. Accessed September 9, 2024. https://www.mdpi.com/2306-5354/11/3/222
[57] Perera M, Papa N, Christidis D, *et al*. Sensitivity, specificity, and predictors of positive 68Ga-prostate-specific membrane antigen positron emission tomography in advanced prostate cancer: a systematic review and meta-analysis. Eur Urol 2016;70:926–37.
[58] Smartwatch interventions in healthcare: a systematic review of the literature. Accessed September 9, 2024. https://www.sciencedirect.com/science/article/abs/pii/S1386505624002235?via%3Dihub
[59] Artificial intelligence-enabled atrial fibrillation detection using smartwatches: current status and future perspectives. Accessed September 9, 2024. https://www.frontiersin.org/journals/cardiovascular-medicine/articles/10.3389/fcvm.2024.1432876/full
[60] Unveiling wearables: exploring the global landscape of biometric applications and vital signs and behavioral impact. Accessed September 9, 2024. https://biodatamining.biomedcentral.com/articles/10.1186/s13040-024-00368-y
[61] User's perceived attitudes and acceptance towards wearable devices in healthcare. Eur J Med Health Sci Accessed. September 9, 2024; https://www.ej-med.org/index.php/ejmed/article/view/1990
[62] Yumurtaş AÇ, Pay L, Tezen O, *et al*. Evaluation of risk factors for long-term atrial fibrillation development in patients undergoing typical atrial flutter ablation: a multicenter pilot study. Herz Published online August 13, 2024. doi: 10.1007/s00059-024-05261-2
[63] Şaylık F, Çınar T, Akbulut T, *et al*. Comparison of catheter ablation and medical therapy for atrial fibrillation in heart failure patients: a meta-analysis of randomized controlled trials. Heart Lung 2023;57:69–74.
[64] Zinzuwadia A, Singh JP. Wearable devices – addressing bias and inequity. Lancet Digit Health 2022;4:e856–e857.
[65] Truong H, Nayar N, Zinzuwadia A, *et al*. Abstract 14970: early observations of population characteristics for an electrocardiogram-enabled smartwatch in the United States. Circulation 2022;146:A14970.