Review

Einthoven and precordial lead accuracy of smartwatch-acquired electrocardiographs: a review of the literature

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Abstract

Introduction

This review aims to summarise the literature regarding the ability of commercial smartwatch products to produce an electrocardiograph of diagnostic quality for interpreting Einthoven and precordial leads.

Methods

PubMed, Embase, MEDLINE Complete, Web of Science, and Scopus were systematically searched. Articles were screened by a sole investigator against the inclusion criteria – first by title, then abstract, then full text. The reference lists of included articles were also screened. The inclusion criteria were: discussion of smartwatch-acquired tracing of Einthoven or precordial lead accuracy, and demonstrating sufficient rigor when undergoing critical appraisal using the Joanna Briggs Institute evaluation tools. A synopsis of results was provided in a summary of information table.

Results

Twelve articles were identified for inclusion, nine of which had physician (cardiology or emergency specialty) evaluation of tracings, one of which had statistical comparison of wave duration and amplitude, and two of which were expert commentary. Only evaluations of Apple Watch products were discovered during the literature search. All leads in all studies were considered suitable for interpretation, with no clinically significant differences. Four studies found that 100% of patients were able to accurately use a smartwatch as an electrocardiogram after a brief tutorial.

Conclusion

The current early evidence, based largely on visual evaluations by cardiologists during the previous year, suggests that electrocardiograph abnormality recorded by this technology is sufficiently precise to be presumed accurate until proven otherwise.

Keywords:

electrocardiography; myocardial infarction; wearable electronic devices

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Introduction

Prompt identification of myocardial ischaemia to enable rapid reperfusion is a fundamental role of paramedics. The new generation of smartwatches has electrocardiogram (ECG) capability, and recent research has investigated the accuracy of their bipolar limb and mimic precordial lead tracings. This field is likely to grow; research has demonstrated that consumers prefer using smartwatches to other diagnostic tools (1). As this technology develops, it is increasingly likely that dispatchers and paramedics will receive cases from members of the public alerted of electrocardiograph abnormalities by their smartwatch, with PDF files of the tracings able to be generated and provided to practitioners. An awareness of the current evidence of the accuracy of these tracings is likely to be beneficial in informing practitioners' clinical treatment decisions.

Myocardial ischaemia disrupts aerobic metabolism, impairing the sodium-potassium and calcium pumps, leading to an inability to repolarise – creating a region of relatively negative voltage (2). In transmural ischaemia, this presents as a negative vector towards the epicardium of the underperfused area. During ventricular depolarisation (represented by the ST segment) this vector is not apparent; however, when the unaffected myocardium is polarised (between the T wave and QRS complex) the relatively negative charge becomes visible and manifests as a depression of the isoelectric line. As ECG algorithms use the isoelectric line between the T wave and P wave to calculate their baseline, this T-QRS depression is erroneously depicted graphically as elevation of the ST segment (3). Conversely, subendocardial ischaemia will instead generate a negative vector towards the endocardium, and, during ventricular polarisation, produce TP elevation represented by ECGs as ST segment depression. Similarly, opposing cardiac regions will have a positive vector towards them from the ischaemic myocardium, also creating ST segment depression in reciprocal leads.

Both positive and negative poles are required to measure voltage, and in turn to generate an ECG. The term 'unipolar' is therefore somewhat of a misnomer, as these leads still require a negative pole – Goldberger's for the augmented limb leads, and Wilson's for the precordial leads – generated from a combination of electrodes (4). In a standard electrocardiograph, Goldberger's central terminal is calculated from the mean voltage readings of two limb electrodes acting as negative poles (any two of RA, LA and LL, excluding whichever is acting as positive terminal – therefore the central terminal's voltage changes depending on which lead is recorded) (4,5). Similarly, Wilson's central terminal is calculated from the mean voltage readings from three limb electrodes (RA, LA and LL, with RL not included in the algorithm but acting as a reference lead); precordial leads are determined by subtracting this negative pole from the precordial electrode's positive voltage (5,6). Unlike Goldberger's terminal, Wilson's terminal does not vary in voltage depending on which lead is recorded (5,6).

Recent smartwatch models have two electrodes in-built: one housed in the base of the unit (the positive pole, usually touching the wrist), and the other on a button to the side (the negative pole, able to be activated by touching any finger to it) (7). This technology was first introduced with the Apple Watch 4 in 2018 (8). Wearing the watch on the left wrist (with the positive electrode in a similar position to LA) and touching a right-sided finger to the negative electrode (to produce RA) will generate an analogue of lead I. This can be modified by placing the watch so the positive electrode in the base touches an LL location (such as the left iliac region, thigh or ankle) to obtain leads II and III.

With in-field troponin testing currently unavailable in Australia's domestic services, serial electrocardiographs demonstrating diagnostic abnormalities remain the highest predictor of occlusion myocardial infarction available to paramedics, with a likelihood ratio of 23.28 compared to the 58.92 for serum troponin three times above baseline (9,10). The advent of commercially available smartwatches with two in-built electrodes has begun an era of widespread consumer access to continual electrocardiograph monitoring. This has already led to clinical implications: a recent case study discussed the presentation of a female, 80 years of age, with angina and two episodes of pre-syncope (11). Her electrocardiograph was evaluated as unremarkable by the reviewing cardiologist, and her serum troponin was negative. However, the patient had an earlier tracing recorded by her Apple Watch, that displayed significant ST segment depression in lead I. Based on this, further tests were bypassed and the patient was taken directly for catheterisation. This revealed severe stenosis of the left main coronary artery and the bifurcation of the left anterior descending into D1.

This surprising case study demonstrates the potential benefits of smartwatch electrocardiographs. However, a single case study is insufficient to form broad recommendations, and therefore a review of the literature is likely to be beneficial in informing pre-hospital practitioners' clinical treatment decisions when presented with smartwatch-recorded electrocardiographs by patients. This review aims to summarise the literature regarding the ability of commercial smartwatch products to produce an electrocardiograph of diagnostic quality for interpreting Einthoven and precordial leads.

Methods

A three-step search strategy was performed as per the Joanna Briggs Institute recommended methodology (12). First, an initial limited search of Google Scholar was undertaken using initial PICOT search terms and four *prima facie* relevant articles were identified. Second, the text contained in the titles and abstracts of these relevant articles, and the index terms used to describe the articles, were used to develop a full search strategy performed on all selected databases on 8 September 2020 (Table 1). The databases searched were PubMed, Embase, MEDLINE Complete, Web of Science and Scopus. Some

research has suggested using multiple databases may provide increased relevant results (13,14). Based on this research, MEDLINE was separately searched (despite being indexed in PubMed and Embase). Studies published in English from any date were considered for inclusion.

Table 1. Search strategy

PICOT	Keyword	Alternative search terms
Population	watch	
Intervention	ECG	OR Electrocardiogra* OR EKG
Comparison		
Outcome	"myocardial infarction"	OR AMI OR infarct* OR "acute coronary syndrome*" OR ACS OR "heart attack" OR isch?emi* OR ?STEMI OR "ST#elevation" OR ?STEACS OR OMI
Time		

PubMed supports end-only truncation and no wildcards. Search terms were reformatted appropriately (Table 2).

Table 2. PubMed search results

Search	Query	Records retrieved
#1	watch	22,993
#2	ECG OR electrocardiogra* OR EKG	253,230
#3	"myocardial infarction" OR AMI OR infarct* OR "acute coronary syndrome*" OR ACS OR "heart attack" OR ischaem* OR ischem* OR STEMI OR NSTEMI OR "ST-elevation" OR "ST elevation" OR STEACS OR NSTEACS OR OMI	767,166
#4	#1 AND #2 AND #3	35
Limited to English language results		26

Embase supports truncation, single character wildcards, and nil character wildcards; however, wildcards cannot be used with field limiters. Search terms were reformatted appropriately (Table 3).

Table 3. Embase search results

Search	Query	Records retrieved
#1	watch	12,777
#2	ECG OR electrocardiogra* OR EKG	362,639
#3	"myocardial infarction" OR AMI OR infarct* OR "acute coronary syndrome*" OR ACS OR "heart attack" OR isch?emia OR STEMI OR NSTEMI OR ST?elevation OR STEACS OR NSTEACS OR OMI	1,008,675
#4	#1 AND #2 AND #3	52
Limited to English language results		46

MEDLINE Complete supports truncation, single character wildcards, and nil character wildcards. Search terms have been reformatted appropriately (Table 4).

Table 4. MEDLINE search results

Search	Query	Records retrieved
#1	watch	11,298
#2	ECG OR electrocardiogra* OR EKG	250,719
#3	"myocardial infarction" OR AMI OR infarct* OR "acute coronary syndrome*" OR ACS OR "heart attack" OR isch?emi* OR ?STEMI OR "ST#elevation" OR ?STEACS OR OMI	444,591
#4	#1 AND #2 AND #3	19
Limited to English language results		18

Web of Science supports truncation and multiple wildcards. Search terms have been reformatted appropriately (Table 5).

Table 5. Web of Science search results

Search	Query	Records retrieved
#1	watch	52,069
#2	ECG OR electrocardiogra* OR EKG	131,166
#3	"myocardial infarction" OR AMI OR infarct* OR "acute coronary syndrome*" OR ACS OR "heart attack" OR isch\$emi* OR ?STEMI OR "ST*elevation" OR ?STEACS OR OMI	796,932
#4	#1 AND #2 AND #3	18
Limited to English language results		18

Scopus supports truncation, single character wildcards, and nil character wildcards. Search terms have been reformatted appropriately (Table 6).

Table 6. Scopus search results

Search	Query	Records retrieved
#1	watch	31,802
#2	ECG OR electrocardiogra* OR EKG	371,148
#3	"myocardial infarction" OR AMI OR infarct* OR "acute coronary syndrome*" OR ACS OR "heart attack" OR isch?emi* OR ?STEMI OR "ST?elevation" OR ?STEACS OR OMI	596,391
#4	#1 AND #2 AND #3	31
Limited to English language results		28

Following the search, 136 citations were identified and uploaded to Mendeley 2019 version 1.19.4 (Mendeley Ltd, London, UK). With duplications removed, 68 citations remained. These were screened by title and abstract (56 excluded), and then by full text (three excluded), by a sole reviewer for assessment against the inclusion criteria for the review. Of the 56 articles excluded on title or abstract, 45 did not reference smartwatches, seven were used only for the detection of atrial fibrillation, two used attachments to take electrocardiographs (ie. electrocardiograph

was not smartwatch obtained), and two discussed other biometrics unrelated to the topic. Of the three articles excluded after full text review, one only discussed atrial fibrillation (15), one discussed artificial intelligence with smartwatch electrocardiographs only mentioned in passing (16), and one discussed SARS-CoV2 with smartwatch electrocardiographs only mentioned in passing (17). The remaining nine articles had their full text imported (7,11,16,18-24). Finally, the reference list of the nine studies selected for critical appraisal were screened, and three additional potentially relevant studies added for critique (25-27). The complete search strategy is presented in PRISMA format in Figure 1.

The final 12 articles were assessed using the Joanna Briggs Institute Critical Appraisal Tools. More than 24 tools for evaluation of secondary evidence are available; there remains debate as to which tool is optimal (28-30). The Joanna Briggs Institute tools were selected over other options recommended for systematic reviews both as they have been verified by peer review, and found to have good reliability, and also as there are specific evaluation tools for different methodologies (30,31). All 12 articles, when evaluated under these tools, were found to be sufficiently rigorous to be suitable for inclusion.

Results

The literature search discovered 12 articles discussing the accuracy smartwatch technology for Einthoven and precordial lead interpretation (Table 7) (7,11,16,18-27). Of these, three were case studies (7,11,18), seven were observational cohort studies (19-25), and two were text reviews (26,27).

Figure 1. PRISMA diagram of systematic search results

Nine studies compared Apple Watch and standard Einthoven lead I (n=408 participants, 1189 electrocardiographs), eight studies compared lead II (n=407 participants, 1188 electrocardiographs), and seven compared lead III (n=406 participants, 1186 electrocardiographs) (7,11,18-21,23-25). In the eight studies that used cardiologists' or emergency physicians' evaluations, all obtained electrocardiograph tracings were unanimously determined to be of diagnostic quality. The LL electrode was placed variously on the left lateral abdomen (n=403), central abdomen (n=1), left thigh (n=1), or left ankle (n=3); the tracings generated by all locations were considered suitable for interpretation by the assessing physicians (7,18-21,23-25). In four studies, 1050 of these Einthoven bipolar lead electrocardiographs' tracing quality was evaluated by cardiologists, who determined 100% to be of diagnostic quality (the studies found 92%, 92%, 89% and 100% were of 'good' quality respectively, with the remainder of 'moderate' quality). In three studies of 750 electrocardiographs, blinded cardiologists were able to correctly allocate the electrocardiograph to its corresponding lead over 90% of the time (100%, 91%, 93% respectively) (20,21,25). In another study, duration and amplitude of waves were found by Bland-Altman comparison to have 'very strong' agreement (>80%) in all cases except for lead I P wave and lead III T wave, both of which had 'strong' agreement (>60%) (23). This suggests a tracing of bipolar limb leads taken by the Apple Watch is, based on the current limited evidence, reasonably reliable.

Three studies evaluated mimic precordial leads (19,20,24). The first study compared three patients' (18 electrocardiographs) standard precordial leads to CR1 to CR6 (generated by a vector from RA to the corresponding precordial location used in V1-V6) (19). These were evaluated by a sole cardiologist, who concluded they 'bear a strong resemblance' (4). The second study instead created new 'Wilson-like' leads by taking CR1, CR4 and CR6, and while touching the negative electrode with a right finger additionally had the patient hold their right wrist with their left hand; the authors believe this will amalgamate RA with LA to create a new negative pole and termed these leads Wilson-like right (Wr), Wilson-like medial (Wm), and Wilson-like left (WI), respectively (20). The tracings of the 50 patients were evaluated by three independent cardiologists, who were able, while blinded, to allocate 92% of the tracings with their corresponding lead correctly, and who stated that the morphology was 'identical' (20). The third study compared 100 patients' (100 electrocardiographs) standard precordial leads to CR1 to CR6 (generated by a vector from RA to the corresponding precordial location used in V1-V6) (24). Electrocardiographs were evaluated by two independent, blinded cardiologists, and found to have a sensitivity and specificity of 84% and 100% respectively for normal electrocardiographs, 93% and 95% respectively for ST elevation, and 94% and 92% respectively for non-ST elevation.

Four studies found that 100% of patients (n=300) were able to accurately take their own electrocardiograph using an Apple Watch after a brief tutorial (20,21,23,25).

Discussion

There is a small body of evidence evaluating the accuracy of Apple Watch tracings for Einthoven and precordial lead interpretation, all of which supports the accuracy of these tracings. Current research has only evaluated Apple Watch products; other commercial products remain untested. While generating lead I or its inverse uses the normal positioning of the Apple Watch, generating any other lead requires the patient to remove the Apple Watch from their wrist and place it in a position normally occupied by an electrode recording the positive terminal of LL or the precordial leads. Four studies tested the ability of patients to place a positive electrode in these locations accurately after a brief tutorial, and found they were successful in all cases.

The positioning of the LL electrode remains controversial. Historically, it was placed on the ankle, and this method was used in the study of Cobos Gil (19,32). However, to reduce artefact it has been suggested this electrode should be moved to the proximal lower limb – known as the Lund system – and this method was adopted in the study of Frisch (18,33). A third option is the Mason-Likar placement, where electrodes are placed onto the torso – this approach was used in seven of the studies described here, despite the potential to hinder identification of inferior lead Q waves (7,18,20,21,23-25,34,35).

Furthermore, the tracings remain limited in which leads can be generated. As smartwatches have only two electrodes available, generating a true Wilson's pole to obtain precordial leads is not possible; two alternative approaches have been suggested. The first approach, recommended by Cobos Gil and Spaccarotella, is to use the bipolar chest leads CR1 through CR6 (19,24). These leads are generated similarly to V1 through V6, but with RA used as a proxy for Wilson's negative pole. This approach was first investigated in the 1930s, and as it is considered diagnostically similar to the current precordial leads it has previously been recommended during the 1990s for use in emergency settings (36-41). The second approach, recommended by Samol et al, is to use a similar technique but enclose the right wrist in the left hand, thereby combining LA and RA in the negative pole (20). They have titled these new negative poles 'Wilson-like' and proposed using three: V1 is substituted by Wilson-like right (Wr), V4 by Wilson-like medial (Wm), V6 by Wilson-like left (WI). Both approaches have been supported in their respective papers. In Spaccarotella's paper, the terminology V1-V6 is used; however, the description and photographs provided clearly demonstrate CR1-CR6 were used. This is most likely an intentional choice on the part of the author to make the findings broadly accessible; the authors also erroneously describe Samol's study as using standard V1-V6 precordial leads while the paper itself states using mimic precordial leads Wr, Wm, WI (20).

Similarly, using the bipolar leads to generate the augmented leads is not currently viable, as creating Goldberger's central terminal requires averaging simultaneous recordings from two negative poles (4). While normally Wilson's central

terminal can be used to create the non-augmented versions of Goldberger's leads (VR, VL, VF), as smartwatches are also unable to create a true Wilson's negative pole, substituting RA or an RA/LA combination (as in Cobos Gil-Spaccarotella and Samol et al's respective proposed methods for generating smartwatch precordial leads) will simply provide a bipolar limb lead. Therefore, aVR, aVL and aVF (and VR, VL, VF) remain unavailable. This impedes diagnosis of high lateral occlusion myocardial infarction without aVL to provide a contiguous reading to lead I; although, the two available inferior leads could be used to consider reciprocal ST segment depression in the case of transmural ischaemia (42). Additionally, the 10% of isolated aVR ST-elevation that represent left main coronary artery occlusion will not be identifiable (43).

Expert commentary has discussed that the more likely threat to patients is not from the risk of a false negative, but instead of a false positive. While the current evidence suggests the former is infrequent – especially when clinicians both exercise a high degree of suspicion for occlusion and take patient presentation into account while forming management plans – the latter is considered more common, due to practitioner reluctance to fail to treat a potential occlusion (27). Treatment of asymptomatic patients based purely on smartwatch notification increases the risk of overdiagnosis, where an individual is unnecessarily treated for a pathology that is present but causes them no adverse effects. This can cause complications to the patient and unwarranted cost to both patient and healthcare system; for a discussion of this topic, see Foster and Torous (27).

The specificity of ST segment elevation for acute coronary syndrome is low, and other possible causes include hyperkalaemia, pericarditis, early repolarisation, left ventricular hypertrophy, ventricular rhythms and bundle branch blocks (44,45).

Additionally, the sensitivity of contiguous ST segment elevation for myocardial ischaemia is also poor, with occlusions presenting differently in Sgarbossa's criteria, de Winter's T waves, Wellen's syndrome, posterior infarction and left main coronary artery occlusion (45,46). Consequently, while the current evidence appears cautiously optimistic, electrocardiography is only one tool in identifying occlusion myocardial infarction, and holistic interpretation of the patient remains critical.

Limitations

As with all literature reviews, the quality of the review's conclusions is limited to the quality of its contributing evidence. In this case, that is comprised of three case studies, seven observational cohort studies (six of which evaluated smartwatch-generated tracings) and two text articles. While the six relevant observation cohort studies collectively include 403 participants, 200 of these are from a series of papers published by the same authors from a single institution (20,21,25). This creates a limitation to generalisability. Furthermore, with no protocols published prior to the reviews and significant results from all

papers, the risk of publication bias is present. All 10 included articles were accepted for publication in either 2019 or 2020, highlighting the recency of this research and the risk of time lag bias for delayed publication of studies with non-significant findings.

While all physicians in the papers reviewed have determined the electrocardiographs to be of diagnostic quality, it is not clear in all studies if this determination is made from the absence of artefact, similarity of morphology to standard electrocardiographs, or similarity to an expected normal tracing. Existing diagnostic criteria are largely based on research using the current 12-lead electrocardiograph, and any modification to vectors used to generate tracings will have an unknown impact on the accuracy of these diagnostic criteria.

It was not possible to determine the amplitude of the Apple Watch. Based solely on the author's interpretation of the images provided in the assessed studies, it appears that the Apple Watch's electrocardiograph has less artefact on the isoelectric line, which would correspond with a narrower amplitude than the usual 0.05–150 mHz diagnostic quality setting on standard ECGs. Six articles reviewed have images attached showing a comparison of standard ECG and Apple Watch (7,18-21,23,25); readers are encouraged to view these images and form their own opinions. Based on the expert cardiologist and emergency physician opinions expressed in the evaluated studies, this does not currently appear to affect their use in diagnosis.

The techniques described in this paper are only capable of generating a single lead at a time, and while a 9-lead equivalent can be generated via serial electrocardiographs, neither a 12-lead nor a simultaneously generated 9-lead can currently be produced. This limits the ability to compare multiple leads in dynamic patients whose tracings are changing. Several studies of other handheld ECGs have shown that serial leads can be combined to form 9-lead and 12-lead electrocardiographs with reasonable levels of accuracy, and this may be further developed in smartwatches in the future (47-49).

All studies included only evaluated the Apple Watch device. Other devices have not yet been examined and cannot be commented on. The search terms in this article, as described in the Methods section, was limited to those using the keyword 'watch'. Other commercial devices, such as AliveCor's Kardia series of smartphone ECG attachments, QardioCore's wearable chest strap ECG, and Hexoskin's wearable 'smartshirt' with electrocardiograph functionality had no relevant studies assessing their accuracy returned in their search and have not been evaluated.

Conclusion

Despite the limitations of the current evidence, it is recommended that all smartwatch electrocardiograph tracings demonstrating abnormalities are presumed to be accurate and interpreted in conjunction with the patient's holistic presentation.

As the case study of Drexler et al demonstrates, evaluation may require going beyond serum troponin and standard 12-lead electrocardiography to include angiography. Practically, if practitioners attend a relevant dispatch, it is recommended that the PDF of the electrocardiograph (available on the phone paired to the smartwatch via the app) be sent to the destination hospital for pre-arrival analysis by the receiving physicians.

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Competing interests

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Table 7. Summary of articles discussing the feasibility of smartwatches for Einthoven and precordial lead interpretation

Citation	Methodology	Evaluators	Number and health of subjects	Smartwatch leads the standard 12-lead was compared against	LL location	Limitations	Key findings
Samol et al (20)	Observational cohort study	Three independent cardiologists assessed quality and then blindly matched the Apple Watch recordings to their corresponding lead	50 subjects, all healthy 300 electrocardiographs obtained	I, II, III, and novel leads W _r , W _m , W _i	Lateral abdomen	All patients were healthy; this study does not present data relevant to abnormalities	100% of patients were able to accurately take their own electrocardiograph; 100% of electrocardiographs were of diagnostic quality (92% good, 8% moderate); 100% of Einthoven leads were matched correctly by cardiologists; 92% of precordial leads were matched correctly by cardiologists
Cobos Gil (19)	Observational cohort study	Sole cardiologist	Three subjects, one healthy, one occlusion myocardial infarction presenting without ST-elevation, one occlusion myocardial infarction presenting with ST-elevation	I, II, III, CR1, CR2, CR3, CR4, CR5, CR6	Left ankle	Low sample size One of the subjects was the author The purpose of the study was purely a proof of concept	It is possible to record a 9-lead electrocardiograph using an Apple Watch, and this appears prima facie to have similar morphology to a standard 12-lead
Frisch (18)	Case study	Sole cardiologist	One subject, healthy	I, II	Thigh	Low sample size; all patients were healthy; this study does not present data relevant to abnormalities The 12-lead and Apple Watch recordings were generated on different days The purpose of the study was purely a proof of concept	It is possible to record a two-lead electrocardiograph using an Apple Watch, and this appears prima facie to have similar morphology to a standard 12-lead
Drexler (11)	Case study	Sole cardiologist	One subject, occlusion myocardial infarction presenting with ST-depression	Not applicable	Not applicable	Low sample size	A case study of an 80-year-old female who presented with angina and two episodes of pre-syncope, current electrocardiographs normal, troponin negative. Patient had an earlier Apple Watch electrocardiograph recording demonstrating lateral ST-depression, and on the basis of this was admitted to angiography, occlusion myocardial infarction of left main and the anterior descending bifurcation into D1 confirmed, and the patient stented

Samol et al (21)	Observational cohort study	Four independent cardiologists assessed quality and then blindly matched the Apple Watch recordings to their corresponding lead	50 subjects, all healthy 150 electrocardiographs obtained	I, II, III	Lateral abdomen	All patients were healthy; this study does not present data relevant to abnormalities The authors state the subjects were middle-aged and that it may be more difficult for older subjects to self-record using the Apple Watch ECG	100% of patients were able to accurately take their own electrocardiographs; 100% of electrocardiographs were of diagnostic quality (89% good, 11% moderate); 91% of Einthoven leads were matched correctly by cardiologists; 92% of precordial leads were matched correctly by cardiologists
Avila (7)	Case study	Sole emergency physician	Three subjects, one healthy, two occlusion myocardial infarction (complete right coronary artery block) presenting with ST-elevation	I, II, III	Hypogastric	The methodology is retrospective; patients were diagnosed with ST-elevation acute coronary syndrome, and subsequently gave permission for a 3-lead electrocardiograph to be taken for comparison, increasing the possibility of confirmation bias Assessment was by the author	All electrocardiographs determined to be the same by a sole emergency physician (the author)
Sameer et al (22)	Observational cohort study	Computer algorithm comparison of previous physician ST-elevation acute coronary syndrome diagnoses against computer algorithm generated diagnoses, where the algorithm is capable of being loaded onto a wearable device	5087 electrocardiographs 2543 instances of ST-elevation	Not stated	Not stated	Abstract only available Presumes the physician diagnosis is correct	97.2% accuracy; 95.8% sensitivity; 98.5% specificity
Samol et al (25)	Observational cohort study	Three independent cardiologists assessed quality and then blindly matched the Apple Watch recordings to their corresponding lead	100 subjects, all healthy 300 electrocardiographs obtained	I, II, III	Lateral abdomen	All patients were healthy; this study does not present data relevant to abnormalities The authors state the subjects were middle-aged and that it may be more difficult for older subjects to self-record on the Apple Watch ECG	100% of patients were able to accurately take their own electrocardiographs; 100% of electrocardiographs were of diagnostic quality (92% good, 8% moderate); 93% of Einthoven leads were matched correctly by cardiologists

Al-Alusi et al (26)	Expert opinion review	Professor of medicine, associate professor of medicine, epidemiologist, graduate researcher					Does not contain a systematic literature review	Expert discussion of the benefits and limitations of smartwatch electrocardiograph technology, with a focus on atrial fibrillation
Foster, Torous (27)	Expert opinion review	Professor of bioengineering, psychiatrist					Does not contain a systematic literature review	Expert discussion of the benefits and limitations of smartwatch electrocardiograph technology, with a focus on the harm caused by false-positive readings
Behzadi et al (23)	Observational cohort study	Duration and amplitude of electrocardiographs waves was calculated using Bland-Altman analysis, with Spearman's test used for correlation	100 subjects, all healthy	I, II, III	Lateral abdomen	All patients were healthy; this study does not present data relevant to abnormalities		100% of patients were able to accurately take their own smartwatch (mean age 63 years); 100% of electrocardiographs were of good quality and without artefact; 'very strong' correlations were found between all waves, with the exception of lead I P wave and lead III T wave, both of which had 'strong' correlation; 100% of segments had no clinical difference
Spaccarotella et al (24)	Observational cohort study	Two independent cardiologists	100 subjects, 19 healthy, 27 occlusion myocardial infarction presenting without ST-elevation, 54 occlusion myocardial infarction presenting with ST-elevation	I, II, III, CR1, CR2, CR3, CR4, CR5, CR6 Note: the study reports using V1-V6; however, the method described is CR1-CR6	Lateral abdomen			84% sensitivity for normal electrocardiograph; 100% specificity for normal electrocardiograph; 93% sensitivity for ST elevation; 95% specificity for ST elevation; 94% sensitivity for non-ST elevation; 92% specificity for non-ST elevation; agreement in amplitude of ST changes