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Patient Directed Recording of a Bipolar Three-Lead Electrocardiogram Using a Smartwatch with ECG Function

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TITLE:

Patient Directed Recording of a Bipolar Three-Lead Electrocardiogram Using a Smartwatch with ECG Function

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KEYWORDS:

smartwatch, smart device, electrocardiogram, bipolar ECG, multichannel ECG, Einthoven ECG

SUMMARY:

We describe a protocol for the patient-directed registration of a three lead bipolar electrocardiogram by a smartwatch that functions identically to the Einthoven leads from standard electrocardiograms. This enables patients to record electrocardiograms on their own immediately after the onset of symptoms.

ABSTRACT:

Cardiac arrhythmias and cardiovascular diseases are a major public health problem in developed countries. A major goal in preventive medicine is the reduction of cardiovascular death by early detection of atrial fibrillation (AF), which may cause stroke, or early detection of life-threatening myocardial ischemia in acute coronary syndrome. Detection of arrhythmia is often challenging if symptoms occur when patients have no chance for immediate electrocardiogram (ECG) diagnostic testing, or if the observation time period is short or an immediate visit to their doctor is not possible. Smartwatches and other wearable devices are able to record a single lead ECG recording, but a single lead ECG is often not sufficient for diagnosis of cardiovascular disorders. Even diagnosis of AF can be difficult with only information from a single lead bipolar ECG. Some smart devices use photoplethysmography for detection of cardiac rhythm, but this technique can only give indirect hints of the underlying cardiac rhythm, is prone to interferences, and cannot be used for detection of myocardial ischemia. A three-lead bipolar ECG like the Einthoven leads used in regular ECGs can add useful information concerning arrhythmia detection or even diagnosis of other cardiovascular diseases like ischemia. Therefore, we describe a protocol for

the patient-directed recording of an Einthoven three-lead ECG using a smartwatch.

INTRODUCTION:

Smartwatches or other so-called "wearable devices" show increasing popularity and a steeply rising daily use in Western countries. Nearly 80% of US-Americans own a smartphone and more than 10% have a smartwatch[1]. Due to a photoplethysmographic sensor using LED-light and photodiodes, some smartwatches can record pulse frequency and irregularities[1]. This feature enables the detection of arrhythmias, especially AF, with high diagnostic accuracy[2,3]. For authentic ECG arrhythmia detection, portable, handheld, and wearable ECG devices have been developed to enable smartphone-assisted ECG recordings. Nevertheless, these devices allow patient-activated recording of electrocardiograms only if the patients' compliance for carrying the ECG device is extremely high[4-7].

Thus, the optimal tool for a patient's medical surveillance would be a smart device for daily use. Some last generation smartwatches enable a single-lead ECG recording comparable to bipolar lead Einthoven I from a standard 12-channel ECG using the backside of the watch as the positive and the crown as the negative electrode[8]. ECG recording is patient-controlled and activated if symptoms occur. Thereafter, an application creates a PDF document for further analysis by a healthcare professional. Nevertheless, using only a single-lead ECG for discrimination of P waves for diagnosis of sinus rhythm is sometimes insufficient[9] for detection of the P wave and often multiple ECG leads are required[5]. In addition, multichannel ECG recording is mandatory for diagnosis of most acute or chronic structural heart diseases like myocardial infarction (MI), pulmonary embolism, or signs of acute heart failure,.

More than 100 years ago, Einthoven developed a method for recording of a bipolar three-channel ECG[10]. This three-channel ECG offers the opportunity to identify the electrical heart axis and possibly the myocardial ischemia as well, especially in inferior regions of the myocardium[11]. Therefore, in clinical daily practice bipolar Einthoven leads I-III are essential parts of the 12-lead ECG and enable heart rhythm determination or detection of myocardial ischemia.

Early diagnosis and especially early treatment of myocardial infarction has improved substantially during recent decades. Nevertheless, especially early after the onset of symptoms, many patients hesitate to contact professional help. Thus, first medical contact and initiation of adequate treatment is often delayed[12]. Registration and transmission of a patient-directed ECG early after the onset of symptoms might accelerate specific treatment and thus enable a better patient outcome[7]. Until now, ischemia detection by smart devices is limited, because mainly single-lead (Einthoven I), or as in our study, maximal three-lead (Einthoven I-III) ECGs can be recorded, which only represent a limited area of the myocardium.

Several studies used patient-directed devices like portable ECG recorders, smartphones, and very recently smartwatches, for detection of AF in heart patients[1,2,5,9]. The Apple Heart Study and the WATCH AF trial used the photoplethysmographic LED-light sensor of the smartwatch for detection of an irregular or variable pulse, which correlates with arrhythmia like AF[1,2]. Insufficient signal quality was the limiting factor in these trials, leading to a high dropout rate[2]. Another

smartwatch trial used photoplethysmography for AF detection, but also showed reduced diagnostic accuracy compared to regular ECGs[13].

The detection of AF by the registration of pulse irregularities is the limiting factor of photoplethysmography, because heartbeat variabilities due to extra systoles or sinus arrhythmia may also cause pulse irregularities. Thus, recording of an ECG by a smartphone or smartwatch may increase the sensitivity and specificity of arrhythmia detection. Several smartphone compatible devices can record a bipolar single-lead ECG simulating Einthoven lead I[5,9]. In one study, a bipolar smartphone ECG device was used for AF screening[9]. In this trial, a small voltage of P waves in lead I led to incorrect AF determination, a limitation when only a single-lead ECG is available[9]. ECG devices for AF screening were also tested in hospitalized patients on cardiologic and geriatric wards[5]. Diagnostic accuracy of the automated algorithms was only suboptimal and additional 12-lead ECGs were often mandatory. Most of these devices have the limitation of only one ECG lead recording (Einthoven I), which is not always sufficient to ensure arrhythmia or repolarization detection.

Only one small case series of five patients demonstrated that a conventional 12 lead ECG is recordable by a conventional bipolar smartphone device after modification for unipolar lead recordings with ECG tabs and wires with alligator clips[4]. They showed ECG recordings with good signal quality, but the limiting factor is the need for device modifications that complicates patient-directed self-ECG recording.

In contrast, we performed the first study for recording an ECG with a smartwatch with the three bipolar Einthoven leads as a proof of concept in healthy subjects. We were able to show a high grade of consistency between the smartwatch leads and the Einthoven leads from a standard ECG using the following simple protocol.

PROTOCOL:

This study was performed according to the Declarations of Helsinki and approved by the Ethics Committee of the Aerztekammer Westfalen-Lippe (reference number 2019-456).

1. Study

1.1. Instruct subjects on how to use the smartwatch for proper ECG recording.

2. Recording of a standard 12-lead ECG by a common device

2.1. Use a common ECG device for standard ECG recording.

2.2. Adjust the paper running speed to 50 mm/s.

2.3. Perform the ECG recording after a 5 min resting period in a supine position.

2.4. Place the right arm electrode near the right shoulder.

2.5. Place the left arm electrode near the left shoulder.

2.6. Place the right leg electrode near the right ankle.

2.7. Place the left leg electrode near the left ankle.

2.8. Place the V1 electrode in the fourth intercostal space at the right parasternal line.

2.9. Place the V2 electrode in the fourth intercostal space at the left parasternal line.

2.10. Place the V3 electrode between V2 and V4.

2.11. Place the V4 electrode in the fifth intercostal space at the midclavicular line.

2.12. Place the V5 electrode in the fifth intercostal space at the anterior axillary line.

2.13. Place the V6 electrode in the fifth intercostal space at the mid-axillary line.

2.14. Record a standard 12-lead ECG with the standard ECG device.

NOTE: The patient should not move during the ECG recording in order to prevent ECG artifacts.

3. Recording of Einthoven leads I-III by a smartwatch with ECG function

3.1. Record smartwatch ECGs directly after recording the standard ECGs.

3.2. Enable the application of the smartwatch for ECG recordings. A 30 s ECG will be recorded directly after proper skin contact with the smartwatch.

3.3. Record Einthoven I by placing the back of the smartwatch on the left wrist and the right index finger on the crown (**Figure 1A**).

3.4. Record Einthoven II by placing the back of the smartwatch on the left lower abdomen and the right index finger on the crown (**Figure 1B**).

3.5. Record Einthoven III by placing the back of the smartwatch on the left lower abdomen and the left index finger on the crown (**Figure 1C**).

NOTE: The right and left index finger should not contact the skin of the left wrist or left lower abdomen for adequate ECG recording. The patient should not move during the ECG recording in order to prevent ECG artifacts.

4. Analysis of the ECGs

4.1. Recorded smartwatch ECGs are digitally stored using the smartphone app.

4.2. Use the "send PDF to your doctor" function to create a PDF document of every single smartwatch ECG lead. Print the digital smartwatch ECG on paper for comparison with the standard ECG on printed paper.

4.3. Classify all recorded smartwatch ECGs as of moderate signal quality if at least three consecutive QRS-complexes show noise-free signal quality and there are no artifacts in the isoelectric lines between QRS-complexes.

4.4. Classify smartwatch ECGs as of good signal quality if at least ten QRS-complexes show noise-free signal quality and there are no artifacts in isoelectric lines between QRS-complexes.

5. Statistical analysis

5.1. Perform statistical analysis using IBM SPSS Statistics.

NOTE: Categorical variables are shown as absolute numbers and percentages. Continuous variables are presented as mean ± standard deviation. Differences of metric outcome variables were assessed by one way repeated analysis of variance (ANOVA) and paired t-test. In case of binary variables, the $\chi 2$-test was used.

REPRESENTATIVE RESULTS:

In a cohort of 100 healthy subjects (66 female) we investigated the feasibility of our smartwatch recording protocol. The subjects' characteristics are shown in **Table 1**. After a short tutorial all volunteers managed the ECG recording procedure with the smartwatch. All 300 smartwatch ECGs were useable for further analysis with at least adequate signal quality for diagnostics purposes. Of the total ECGs, 277 (92%) were of good quality and 23 (8%) of moderate signal quality. Three blinded cardiologists were asked to assign the smartwatch ECGs to the corresponding Einthoven leads in each subject. They correctly assigned 288 (96%) smartwatch ECGs to the corresponding Einthoven lead I, II, and III from the 12-lead ECG (range from 93%–97%). All blinded cardiologists assigned the ECGs from eighty-nine participants (89%) correctly to the corresponding Einthoven leads. A comparison of the single-leads to the corresponding Einthoven leads is shown in **Figure 2**. Assignment errors occurred in 11 volunteers. In five of these subjects more than one cardiologist assigned the single-lead ECGs incorrectly to the corresponding Einthoven leads. Fleiss kappa analysis showed moderate interrater reliability (kappa = 0.437; $p < 0.001$). The intraclass correlation coefficient was 0.703. All assignment errors were made in subjects with comparable amplitudes and morphologies in the two smartwatch ECGs or the corresponding standard ECG leads. At least one ECG lead was assigned correctly in all participants by all the cardiologists. All assignment errors were made in the ECGs with good signal quality. Thus, there was no correlation between the quality of the ECG recordings and correct assignment. Assignment errors occurred

in statistically older subjects (46 ± 10 vs.37 ± 11 years; mean ± SD). No other subject parameter listed in **Table 1** was associated with an incorrect assignment.

FIGURE AND TABLE LEGENDS:

Figure 1: Recording positions of the smartwatch for the three Einthoven leads. (**A**) Recording of Einthoven lead I between the left arm wrist and the right index finger. (**B**) Recording of Einthoven lead II between the left lower abdominal region and the right index finger. (**C**) Recording of Einthoven lead III between the left lower abdominal region and the left index finger.

Figure 2: Comparison of a typical standard ECG with Einthoven I–III leads (black ECG curves) to the smartwatch ECGs (red ECG curves). Despite a different writing speed of 50 mm/s of the black ECG curves from the standard ECG and 25 mm/s of the red ECG curves of the smartwatch ECGs, the morphologies of the three channels are clearly identical.

Table 1: Subject characteristics. BSA = body surface area; BMI = body mass index; HR = heart rate; lead I = Einthoven lead I; lead II = Einthoven lead II; lead III = Einthoven lead III.

DISCUSSION:

Smart devices like smartphones and smartwatches are increasingly used in daily life and medical care[1]. These new devices and apps may have a significant impact on health awareness of the population, but their effective use needs to be tested in studies[8]. To the best of our knowledge, our group was the first to develop this method of single-lead ECG recordings corresponding to the conventional Einthoven ECG leads I-III using a smartwatch[14].

An important part in the protocol for patient-directed ECG recording is sufficient instruction on the use of the smartwatch and the corresponding app. Patients need to be instructed where to place the back of the watch on the wrist of the left arm or left lower abdomen and the index finger of the left or right hand on the crown of the smartwatch. For optimization of smartwatch ECG quality, the user should be advised to not move during ECG recording in order to prevent ECG artifacts. Further, the index finger should not contact the wrist or abdomen. In addition, smartwatch ECG recording should be performed in a supine position, similar to standard ECG recordings. If patients detect insufficient ECG quality of the recorded ECG due to artifacts, optimization of skin contact may improve the signal quality. After a short tutorial, all of our 100 participants were able to perform the three-lead ECG recordings on their own by positioning the smartwatch in the required positions. Therefore, wider use of a smartwatch for patient-directed three-lead ECG recording may be feasible in the population at large after a short tutorial. This training may be performed by a short video clip or illustrated manual, for example. Our study cohort was middle-aged and may be more familiar with smart devices than older subjects. Therefore, in a cohort of older patients an appropriate use of a smartwatch for ECG recordings might be challenging due to difficulties in the use of the device or the app, the different positioning of the smartwatch, and a potential inability to lie still in a supine position due to comorbidities like Parkinson's disease. One recent study compared two handheld ECG devices and showed that approximately 7% of cardiology patients and 21.4% of geriatric patients did not manage correct use of the device[5].

The quality of all the recorded smartwatch ECGs was sufficient for further evaluation. Good signal quality was found in 92% and moderate signal quality in 8% of smartwatch ECGs. Of our smartwatch ECGs, 96% were correctly assigned to the corresponding Einthoven leads I-III from 12-channel standard ECGs by all blinded cardiologists. Morphological and quantitative ECG parameters like P wave, QRS complex, and T wave of the smartwatch recordings were highly comparable to the corresponding standard ECG leads. Assignment errors occurred in older subjects, but physiognomic parameters and physical aspects like sex or electrical heart axis did not influence the correct ECG assignment. In older patients, assignment errors were not due to insufficient signal quality but were caused by comparable ECG morphologies in two of the three leads.

A limitation of the technology and protocol used our study is that several steps are required for recording a three-lead smartwatch ECG. The complexity of positioning the smartwatch and right or left index finger on the watch as well as the correct application of the required app may impede widespread use in the general population. Further, the smartwatch used in our study also requires use of a smartphone from the same company. Thus, this smartwatch cannot be used in combination with other commercially available smartphones or smart devices.

A limitation of our protocol is that we only performed a visual comparison of the recorded smartwatch leads with the standard ECGs. Until now, we have not developed a computer-based algorithm for comparison of the smartwatch bipolar ECGs with the standard Einthoven leads recorded by a standard ECG device. So far, we could only record Einthoven leads I-III with the smartwatch. Due to this, we could only record ECGs of a limited area of the heart encompassing the inferior and anterolateral myocardium. In addition, we have not performed measurements in patients with heart diseases. The use of patient-directed smartwatch ECG recordings in the wider population might improve and accelerate diagnosis of acute cardiac diseases and shorten duration to medical contact. Of note, users and patients should be reminded that smartwatch ECG recording does not replace a standard 12-lead ECG during a doctor's visit.

An advantage of the smartwatch is that patients with documented or presumed AF can carry them in daily life. Other smart devices for bipolar ECG recording need to be carried in addition to a smartphone, which may limit their wider use in the population. Multichannel smartwatch ECG recording may optimize monitoring heart rhythm in patients if the P waves cannot sufficiently be detected in lead I. Broad deployment of smartwatches for AF detection may improve medical treatment for this group of patients, because 25% of all strokes are caused by AF, which is the most frequent rhythm disorder in Western populations[1]. Further, many individuals are unknowingly at risk: in 18% of AF-related strokes, AF was diagnosed for the first time after the stroke[1].

Recent studies[1,2] demonstrated good accuracy of smartwatch AF detection based on photoplethysmography. The Apple Heart Study recorded pulse disorders by smartwatch photoplethysmography as a surrogate marker for the detection of AF[1]. The authors demonstrated that the smartwatch reliably recorded pulse disorders for unmasking

asymptomatic AF[1,9]. The WATCH AF trial also used a smartwatch with photoplethysmography for AF detection[2]. This trial also showed a very high accuracy for AF detection by a smartwatch[2]. However, a limitation of the used algorithm was a high failure rate due to restricted signal quality[2]. An additional study with the smartwatch photoplethysmography technique confirmed the ability to record AF but also demonstrated reduced quality of AF detection compared to a standard ECG device[13]. A major limitation of the applied photoplethysmography in these studies is that pulse irregularities are used as a surrogate marker for AF detection. Cardiac extra systoles can also cause pulse disorders, which may be incorrectly interpreted as AF and therefore impede adequate AF detection. Therefore, the technique of smartwatch bipolar ECG recording may enhance the accuracy of detection of heart rhythm disorders compared to the smartwatch photoplethysmography technique. These true single-lead ECG recordings can be performed by several handheld electrocardiogram devices as additional tools for smartphones. One of these devices can record Einthoven lead I and showed a high sensitivity and specificity for AF detection in community-based AF screening[9]. Incorrect positive AF detection was caused by reduced P wave voltage in the only available lead Einthoven I[9]. An additional trial studied several one-lead ECG handheld devices for screening of AF in cardiologic and geriatric patients in hospital units[5]. This trial offered restricted diagnostic accuracy of the device algorithms and that supplemental 12-lead ECG recordings needed to be performed to increase diagnostic accuracy. A limitation of the one-lead ECG devices is that only Einthoven lead I can be applied, which impedes sufficient P wave detection. Further, these devices are used as an additional tool to a smartphone, which may limit wider use in the population, as the user must carry the ECG device in addition to the smartphone.

An advantage of the smartwatches is that they are worn like a normal watch, which may be useful in integrating these devices in daily life. This may contribute to a wider use of these smartwatches in the population, which may increase patient-directed ECG recording. Compared to the photoplethysmography of the older smartwatches and the single-lead ECG devices for smartphones, true bipolar three-lead ECG recording by the smartwatch in our study may improve detection of cardiac arrhythmias and myocardial ischemia as more ECG data are available. Our smartwatch ECG protocol may improve patient-directed AF detection and therefore optimize oral anticoagulation treatment of these patients, which in turn may decrease AF-related stroke rates. In addition, smartwatch ECG recordings may optimize the early detection of myocardial ischemia by the patients themselves, which may lead to improved initiation of adequate treatment and outcome in myocardial infarction[15]. Studies demonstrate that 75% of MI patients contact emergency medical services more than one hour after the onset of symptoms[12]. Studies showed that a delay between symptom onset and medical contact occurred because patients did not recognize that symptoms were caused by a heart disease or believed that the symptoms were harmless[12]. In this subgroup of MI patients, use of smartwatch ECG recording by the patients themselves may contribute to earlier detection of myocardial ischemia and diminish the time patients take to initiate medical contact, subsequently improving the treatment and outcome of MI.

Because our study evaluated the feasibility of recording a three-lead smartwatch ECG in healthy subjects, further studies should evaluate the feasibility of smartwatch ECG recordings in patients

with cardiac disease. These studies should examine whether the three-lead smartwatch ECG recordings (Einthoven I-III) actually improve the detection of cardiac arrhythmia compared to a single-lead ECG recording (Einthoven I) and a 12-lead ECG from a standard device. The comparison of the diagnostic accuracy of the three-lead smartwatch ECG recordings should be performed in patients with AF, atrial flutter, and premature supraventricular contractions.

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DISCLOSURES:

The authors have nothing to disclose.

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Figure 1

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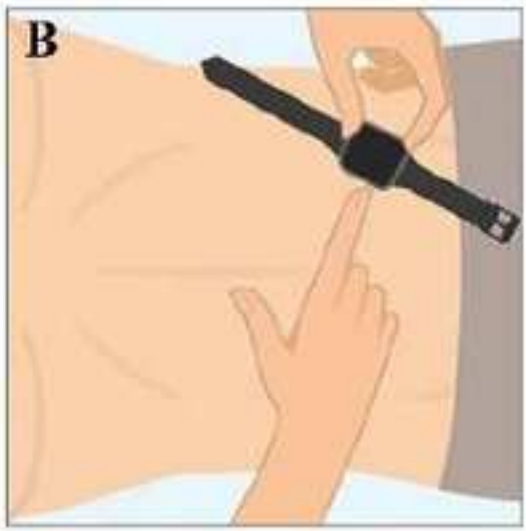

Figure 2

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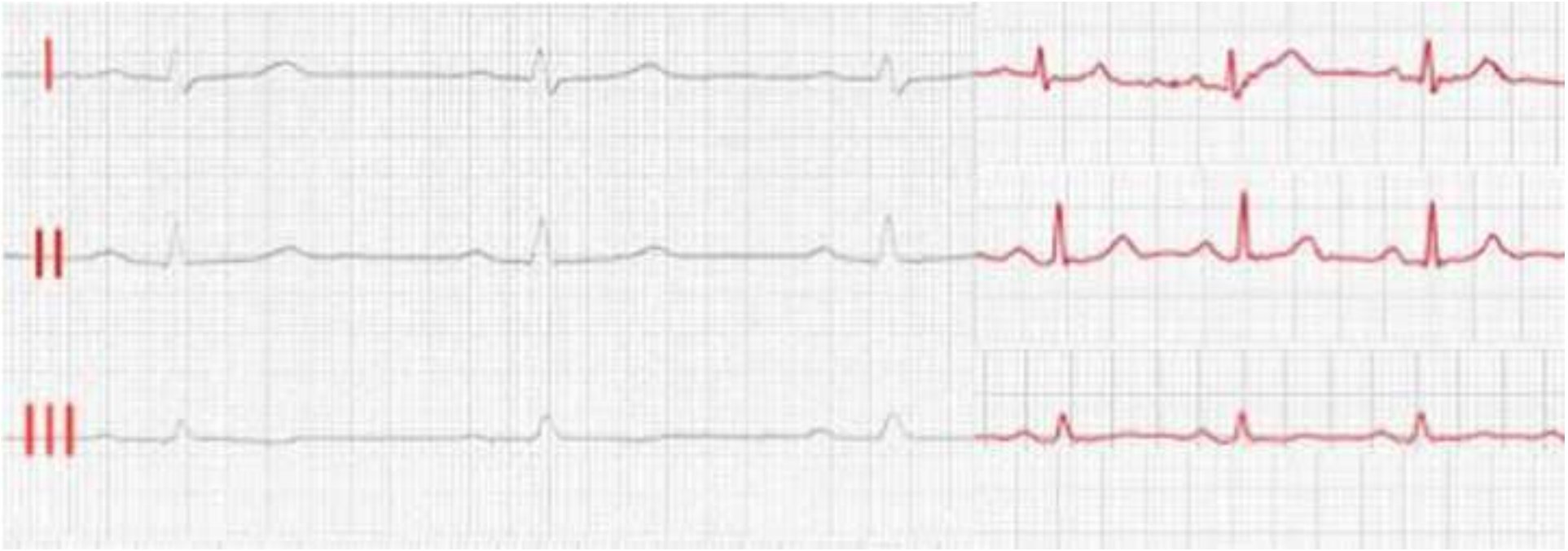

Table 1

	all	male	female	p
Size (cm)	171±19	176±32	169±6	0.053
Weight (kg)	74±14	83±14	69±11	<0.001
BSA (m^2)	1.86±0.26	1.98±0.36	1.79±0.15	0.001
BMI (kg/m^2)	24.5±4.1	25.0±4.0	24.3±4.1	0.396
Age (years)	38±12	38±10	38±13	0.933
QRS axis (°)	51±31	42±35	56±29	0.040
HR 12 lead ECG (bpm)	71±12	72±11	70±13	0.420
HR lead I (bpm)	71±11	72±9	70±11	0.301
HR lead II (bpm)	72±11	73±10	71±11	0.372
HR lead III (bpm)	72±11	74±10	70±11	0.096

Table of Materials

Click here to access/download;Table of Materials;JoVETable of Material.xlsx

Name of Material/Equipment	Company	Comments/Description
Apple Watch Series 4	Apple	Smartwatch with bipolar ECG function
IBM SPSS Statistics	IBM	version 25 for Mac
MAC 5500	GE Healthcare	Standard 12 channel ECG device

A method for patient directed recording of a bipolar three-lead electrocardiogram using a smartwatch with ECG function

Response to Editor

We are very thankful for your constructive and helpful review. In the revised version we have improved the content in accordance with your comments:

1. Please take this opportunity to thoroughly proofread the manuscript to ensure that there are no spelling or grammar issues.

We proofreaded the manuscript and checked the grammar.

2. Please obtain explicit copyright permission to reuse any figures from a previous publication. Explicit permission can be expressed in the form of a letter from the editor or a link to the editorial policy that allows re-prints. Please upload this information as a .doc or .docx file to your Editorial Manager account. The Figure must be cited appropriately in the Figure Legend, i.e. "This figure has been modified from [citation]."

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5. Each figure must be accompanied by a title and a description after the Representative Results of the manuscript text.

Figure legends were modified.

6. Please do not abbreviate journal titles for references.

We modified the reference list.

7. Please check the Standard Access or Open Access box in Author License Agreement (page 1).

Author license agreement was modified and has already been sent to your Journal.

8. Step 1.2: Please write this step in the imperative tense.

Step was written in imperative tense.

9. 4.3: Please write this step in the imperative tense.

Step was written in imperative tense.

10. 4.4: Please write this step in the imperative tense.

Step was written in imperative tense.

11. Figure 2: Please add a short description of the figure in Figure Legend.

A short description was added.

Response to Reviewer #1

Manuscript Summary:
The authors describe a novel use of an existing commercially available smartwatch device to acquire ambulatory EKG data.
The authors demonstrate a proof of useability of the apple watch in acquiring 3 lead EKG data which is novel and valuable to the scientific and commercial community

Major Concerns:
the paper is well written and describes a novel approach to improved data acquisition of more detailed EKG data from ambulatory patients

the extent and use of this technology will be inherently limited due to the number and complexity of steps required to acquire the EKG data; additionally, similar limitations exist with this use of the technology compared other commercially available EKG acquisition devices since it is essentially using the same equipment

This limitation was clarified in the Discussion section on page 6, second paragraph.

authors can further elaborate on the limitations to the use of this technology and the number of steps that may be required in allowing this device to create actionable data

This limitation was clarified in the Discussion section on page 6, second paragraph.

authors can go further in describing more far reaching uses and aspirational uses of wearable devices in the detection and treatment of disease

A paragraph was added in the Discussion section on page 7, last paragraph.

Minor Concerns:
typo on line 322 (trial and trail)

We apologize this typo. It was corrected to “trial”.

Response to Reviewer #2

Manuscript Summary:
In this manuscript the authors suggest a method of using a common smartphone device with an ability to record a single Lead I ECG tracing to record a 3 Einthoven leads ECG. Quality and accuracy of the recordings are presented and are asses by mean of a blinded assignment of each lead to it's corresponding lead on a standard 12 lead ECG.

Major Concerns:
Line 189: Please provide measures of agreement between cardiologists on the assignment of ECGs, and measures of agreement between individual cardiologist to the actual assignment (using a weighed kappa or an Intraclass correlation coefficient as appropriate).

Measures of agreement were added in the Representative Results section on page 4, lines 206 and 207.

Line 194: Was there any correlation between Tracings quality and malasiinment of ECG by the cardiologists?

We did not observe this correlation,this was added in the Representative Results section on page 4 lines 210 and 211.

Table 1: As there is no statistical methods paragraph , how were p values calculated? Consider adding a statistical paragraph to the methods.

A statistical paragraph was added on page 4 line 184 to 190.

General remark: As the main advantage of a 3 lead ECG is identifying the abnormalities in rhythm that are difficult to recognize on a one lead recording, I believe that mere assignment of Smartwatch recorded ECG tracing to a normally rerecorded 12 ECG is not enough to show the utility of this novel approach. For this experiment I would suggest adding measurements that are defendant on identifying small waves on the ECG such as the PR, QRS an QT interval lengths and comparing them with measurements derived from "normal" ECG tracings. Also interesting will be to see if the above measurements are closer to the "real" measurements from the 12 lead ECG when using 3 leads tracings rather than a single lead I tracing.

We totally agree with this reviewer, we just performed a qualitative analysis of Einthoven lead recordings from healthy subjects by blinded cardiologists showing a high grade of correct allocation in limb leads. An easy quantitative analysis of R-amplitude by counting the millimetres of Amplitude in the single lead recordings and comparing this amplitude to the standard lead ECGs was used by the cardiologist for correct allocation. The standard ECG recording speed in Germany for 12-channel-ECG is 50mm/s and the Apple Watch recording speed is 25mm/s, thus easy quantitative analysis comparing durations of QRS-complex, T-wave, etc., is not feasible. Also, the Apple Health App offers actually no tools for automatically measurements of amplitudes and durations. Therefore our recorded data are not sufficient to answer these quantitative questions, a new study is warranted with 12-channel ECG recordings in a paper speed with 25mm/s for manually comparative measurements of these parameters.

Also, as you mentioned in the manuscript, the main use of a 3 lead ECG

would be to better diagnose arrhythmias, hence I would add to the discussion part a suggestion for a future follow up study where one would asses the ability of the 3 lead ECG to identify arrhythmias in patients with known arrhythmias such as sinus arrhythmia, multiple APBS, atrial flutter and atrial fibrillation and comparing the diagnostic accuracy to a standard 12 lead and "regular" single lead I ECG.

This topic is now discussed on page 7 least paragraph.

Minor Concerns:
Line 51: Consider adding a reference to: Continuous heart rate monitoring for automatic detection of atrial fibrillation with novel bio-sensing technology. J Electrocardiol. 2019 Jan - Feb;52:23-27. doi: 10.1016/j.jelectrocard.2018.10.096.

This reference was added.

Lines 71-76: As the 3 Einthoven lead are not very sensitive to Acute MI/Ischemia I would focus less on ischemia detection and more on arrhythmia detection.

This limitation was clarified on page 1 line 76 to 78.

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Author(s):	Alexander Samol, Kristina Bischof, Blerim Luani, Dan Pascut, Marcus Wiemer and Sven Kaese

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