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# Enregistrements ECG et montres connectées capacités et limites diagnostiques des tracés ECG réalisées par AppleWatch

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**Enregistrements ECG et montres connectées**  
**Capacités et limites diagnostiques des tracés ECG réalisées par AppleWatch**

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# Enregistrements ECG et montres connectées : Capacités et limites diagnostiques des tracés ECG réalisés par AppleWatch

## **Résumé :**

Les objets connectés occupent une grande place de notre quotidien, et ce de manière croissante ces dernières années. Nous nous sommes intéressés aux enregistrements ECG réalisés par des montres connectées. Nous avons collecté plus de 2000 tracés sur un an, chez des patients présentant un rythme sinusal, des troubles du rythme et de la conduction avec ou sans cardiopathie associée. Nous avons évalué les capacités de ces tracés à mener à un diagnostic après interprétation par un expert. La référence étant l'électrocardiogramme 12D standard. Dans un deuxième temps, nous avons évalué la possibilité de mesurer et suivre l'intervalle QT.

**Mots clés :** ECG applewatch smartwatch AF atrial fibrillation palpitation holter AVB atrio-ventricular block VT ventricular tachycardia sinus



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## Abréviations

- ACC : American College of Cardiology
- ACS : Acute Coronary Syndrom
- AFLT/AT : atrial flutter/atrial tachycardia
- AV : Atrioventricular
- AW : Apple Watch
- bpm : battements par minutes
- CHADs Vasc :

C	Congestion
H	HTA
A	Age
D	Diabète
S	Stroke (AVC)
V	Maladie vasculaire
A	Age
sc	Sexe féminin

- COVID19 : Coronavirus Disease 2019
- ECG : Electrocardiogramme
- FA ou AF : Fibrillation Atriale ou Atrial Fibrillation
- FDA : Food and Drug Administration
- LBBB : Left Bundle Branch Block (bloc de branche gauche)
- LED : Light-Emitting Diode ou Diode Electroluminescente
- ICC : Interclass Correlation
- QTc : QT corrigé
- RBBB : Right Bundle Branch Block (bloc de branche droit)

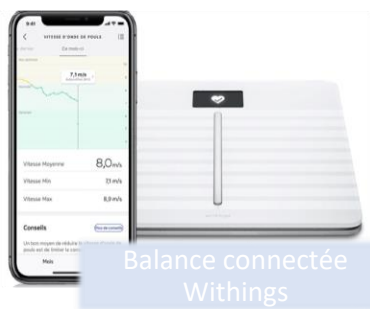
# I. INTRODUCTION

## 1-Objets connectés

La technologie et les innovations modifient notre quotidien. Tous les domaines sont impactés par les avancées de la science et de l'ingénierie. Dans la santé, l'utilisation d'instruments est permanente : d'un point de vue biologique, dans l'imagerie ou encore dans l'électrophysiologie.

La miniaturisation des processeurs a permis d'équiper une partie de nos objets du quotidien de petits ordinateurs avec leurs propres algorithmes, la capacité de communiquer entre eux et avec l'utilisateur. Ce sont des objets dit connectés. Le téléphone mobile est devenu le centre de contrôle de ces objets connectés. C'est notre interface pour communiquer avec eux. Dans le domaine de la santé, ces dernières années ont vu émerger différents outils connectés :

Certains permettent de faciliter la prise en charge du patient comme les piluliers ou balances connectés ; d'autres de mesurer des paramètres vitaux (saturomètre, tensiomètre, cardiofréquencemètre) ou des paramètres biologiques (glucomètre).



## 2-Montres connectées

Après le téléphone mobile, la montre est la deuxième interface privilégiée pour la communication et l'utilisation des objets connectés. Sa taille et son accessibilité permettent une bonne portabilité et la capacité à suivre son utilisateur en permanence. Dans le domaine de la santé, les constructeurs se sont d'abord intéressés aux sportifs. Ils proposent de fournir à l'utilisateur des renseignements sur le nombre de pas effectués, la quantité de calories dépensées, la fréquence cardiaque et différents paramètres d'exercices. Récemment, sont apparus des outils de dépistage logés dans la montre ou le téléphone.

C'est le cas par exemple de la prévention de la diminution de l'audition, la détection de chutes ou le diagnostic d'arythmies cardiaques.



Les constructeurs ont développé (Apple Watch, Withings, Samsung ...) un ECG 1 dérivation portable à loger dans la montre. Le principe est l'utilisation de 2 électrodes ; une sous le corps de la montre directement en contact avec le poignet et l'autre sur la couronne.

En touchant la couronne avec la main opposée, on ferme le circuit et on enclenche l'acquisition d'un tracé.

L'Apple Watch comprend 2 techniques de recueil de la fréquence cardiaque et de l'enregistrement de l'ECG.

-*Photopléthysmographie* : il s'agit de sa technologie équipée comme cardiofréquencemètre. Le principe est la mesure de l'onde de pouls. Elle se fait via une LED verte émettrice associée à des photodiodes récepteurs ou via une émission Infrarouge.

La montre réalise :

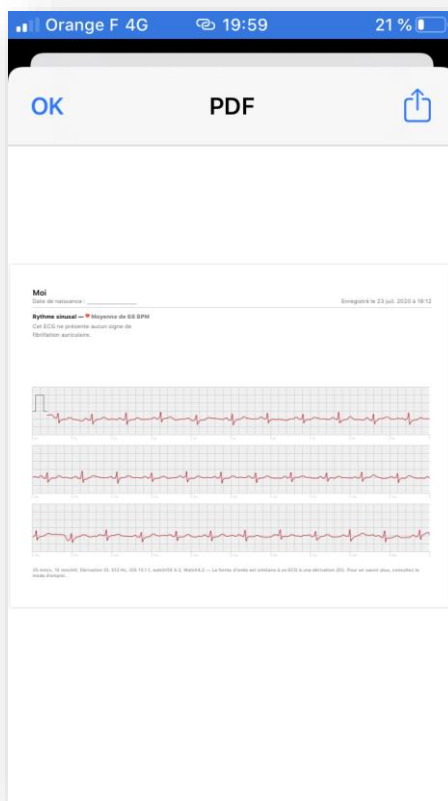
- un tachogramme toute les 2 à 5 heures puis le classe en régulier ou irrégulier.
- si irrégulier, augmentation de la fréquence de recueil (minimum toutes les 15 minutes).
- si 5/6 tachogrammes sont classés irréguliers dans un délai de 48h, l'utilisateur reçoit une alerte.

La technique a été testée dans un sous-groupe de l'Apple Watch Heart Study (AHS). Sur 450 patients étant porteurs de l'ePatch (holter ECG 3 pistes), 86 ont eu une alerte par leur montre : on retrouve 84% de concordance avec une vraie FA. (1)

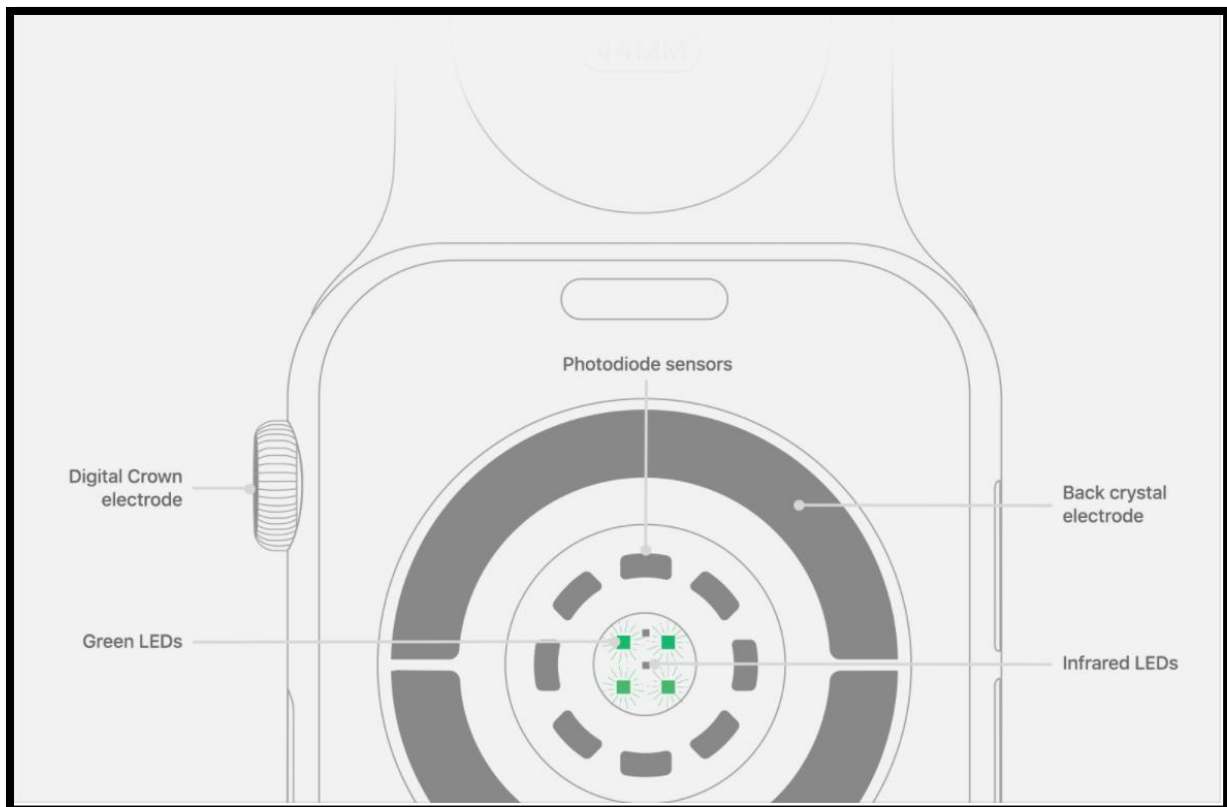
-*ECG*: il est possible grâce à l'intégration de 2 électrodes dans la montre.

- Une électrode en titane logée sur la digital crown, sur laquelle l'utilisateur va venir établir le contact.
- Une électrode au dos de la montre utilisant une couche d'un composite de chrome, silicone et de carbone apposé sur le dos de la montre en verre de saphir (saphir synthétique).

Le tracé est recueilli dans le téléphone de l'utilisateur. Un algorithme permet de classifier le tracé : Inférieur à 50bpm, supérieur à 120bpm et entre 50 et 120bpm. Dans cette gamme de fréquences, il peut classer le tracé en *rythme sinusal*, *FA* et *peu concluant*. L'utilisateur peut stocker ses tracés ou les convertir au format PDF et les partager (avec un professionnel de santé ou autres).



D'un point de vue constructeur, Apple justifie son intérêt par le dépistage de la FA en population générale (dispositif approuvé par la FDA dans ce but, idem pour la Samsung Galaxy Watch 3). Il est actuellement recommandé de dépister la FA dans la population générale asymptomatique à partir de 60 ans par une prise de pouls en cabinet (2). Effectivement, avec les données actuelles, dépister une autre population n'est pas justifié : découvrir une FA paroxystique asymptomatique chez un sujet jeune avec un score de CHADS-Vasc à 0 n'entraînera pas de prise en charge diagnostique particulière mais peut être source d'anxiété et de morbidité par sur-traitement.



D'un point de vue médical, l'intérêt est surtout de disposer chez des patients symptomatiques d'un ECG portable disponible de manière permanente et la possibilité de réaliser un ECG 1 dérivation en tout lieu, à tout moment. Il trouve donc sa place naturellement dans le bilan de palpitations où la clé est l'enregistrement d'un ECG pendant la crise. Actuellement, c'est l'utilisation d'holter 24-48h qui est employé mais ceux-ci sont trop courts selon la fréquence des crises. Les holters longue durée sont peu disponibles et surtout très contraignants. Les montres connectées se placent alors au côté des accessoires type Kardia (bracelet pour montre), Omron, Zenicor et autres ECG portatifs.

D'un point de vue santé publique, l'intérêt se concentre sur la population générale asymptomatique (majorité des utilisateurs) afin de faire progresser les données de prévalence.

### 3-Problématique

La mise à disposition de cet outil entraîne la réalisation de très nombreux tracés. Actuellement l'interprétation par les montres est sommaire. Tout d'abord elle ne relève que de l'étude du rythme, n'est possible qu'entre 50 et 120bpm et ne distingue que la FA du rythme sinusal. Une lecture par un médecin expérimenté dans l'électrocardiographie est donc théoriquement nécessaire, mais quelles informations tirer d'un tracé 1 dérivation réalisée par une montre ?

Les deux principales limites semblent être :

- la qualité du tracé
- la limitation liée à une dérivation unique.

Pour la qualité du tracé, dans l'Applewatch Study 12% des tracés étaient ininterprétables ou inclassés mais le détail des caractéristiques de la population étudiée n'est pas connu et nous pouvons craindre notamment chez les personnes âgées ou non familière avec ce type de technologie une part plus importante. De plus il semble que les tremblements et la sueur altèrent significativement la qualité du tracé.

Pour la dérivation unique, plusieurs autres outils ont déjà été étudié pour la FA. *Jelle C.L. Himmelreich et al* ont montré une bonne sensibilité et spécificité pour la détection de la FA par un enregistrement 1D mais moins performant pour les troubles de la conduction. (3)

*Agam Bansal et al* ont réalisé une revue de la littérature sur 15 études évaluant des 1lead devices. Les FA sont discriminées avec des sensibilités >90%, mais moindre dans les études avec une prévalence plus basse. (4)

*Lea Usadel and all* ont étudié dans une population pédiatrique la capacité du Zenicor d'identifier un ECG anormal. Ils retrouvent une sensibilité à 77% et une spécificité à 92%. (5)

De plus, plusieurs études ont démontré les capacités de la montre à réaliser des tracés d'autres dérivations. *Samol et al.* ont inclut 50 patients en bonne santé (avec ECG normaux) et ont enregistré des tracés 12 dérivations standards puis avec l'AppleWatch, ils ont reproduit D1 D2 D3 en plaçant respectivement la montre sur le poignet gauche, la racine du membre inférieur gauche avec l'index gauche sur la couronne puis la racine du membre inférieur gauche avec l'index droit sur la couronne. Quatre cardiologues ont ensuite dû identifier les dérivations avec l'aide du 12D. 78% ont été identifiés par les 4 et 86% des tracés on globalement bien été identifié. (6)

## 4.Enjeux

Au vu de l'augmentation de la place prise par les objets connectés dans notre environnement, le nombre d'utilisateurs de montres connectés va très probablement beaucoup augmenter dans les années à venir.

Apple, en intégrant l'ECG dans son AppleWatch redéfinit un nouveau standard qui deviendra la norme chez les autres constructeurs. Ainsi un nombre important d'utilisateurs aura accès à un ECG portatif produisant une quantité de tracés, notamment dans une population jeune et en bonne santé dans laquelle la prévalence de la FA est faible, conduisant à de faux positifs, avec potentiellement des retentissements psychologiques. A l'inverse tous les autres troubles du rythme, de la repolarisation ne sont pas détectés par les montres.

L'enjeu va porter sur la bonne utilisation de l'outil et l'éducation des utilisateurs notamment sur le traitement de toutes ces données.

L'intelligence artificielle va ouvrir un nouveau champ de possibilité avec cette fois ci un diagnostic complet grâce aux techniques de machine learning via des réseaux neuronaux. Ils ont déjà fait leurs preuves pour détecter l'hyperkaliémie ou la FA sur des ECG en rythme sinusal. (7)(8)

Nous avons enregistré sur un an plus de 2000 tracés Applewatch afin d'apprécier les capacités de la montre à mettre en évidence différents troubles du rythme, de la conduction et de cardiopathies. Nous avons utilisé des dérivations complémentaires (DII, V1 et V6) pour juger l'intérêt diagnostic. (chapitre II)

Nous avons donc secondairement évalué la possibilité de mesurer et monitorer l'intervalle QT. L'enjeu est d'autant plus important dans le contexte de pandémie à COVID19, de distanciation sociale et d'auto-surveillance. Les instances de santé comme la FDA prenant même position en faveur d'une utilisation plus large dans le contexte d'outils connectés utilisé par les patients à leurs domiciles.



II. ARTICLE I



# Accuracy of a smartwatch-derived ECG to detect various electrocardiographic abnormalities

**Short Title:** Diagnostic accuracy of smartwatch ECG

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e-mail: [marcstrikgmail.com](mailto:marcstrikgmail.com) @StrikMarc

Proposed tweet: Smartwatch ECGs could serve telemedicine beyond AF detection. The accuracy of the Apple Watch ECG to detect various 12-lead ECG diagnoses was investigated in 260 subjects. @StrikMarc @BordacharPierre

The data from this study are available from the corresponding author upon reasonable request.

## Introduction

Telemedicine is an increasingly integral aspect of contemporary clinical care, particularly given the ongoing coronavirus disease (COVID-19) pandemic.<sup>(9)</sup> The ability to self-register ECGs and to digitally send them to healthcare providers may prove to be particularly valuable in settings of limited resources, enforced physical distancing, and quarantines. The Apple Watch Series 4 and 5 (Apple Inc., Cupertino, CA, USA) can record a single-lead ECG corresponding to Einthoven's lead I. The watch is connected to a proprietary smartphone application that can record a 30-second ECG, which it then automatically interprets as sinus rhythm, atrial fibrillation (AF), or inconclusive. Today, the smartwatch's diagnostic algorithms are presently limited and focused on detecting AF for which it received FDA clearance. However, the FDA recently published guidance expanding the use of certain noninvasive patient-monitoring technologies, including the ECG app, during the COVID-19 public health emergency.<sup>(10)</sup> The technology could indeed also prove useful for the detection of other arrhythmias, conduction abnormalities, and perhaps even repolarization abnormalities associated with cardiac ischemia, cardiomyopathies, and channelopathies. (11–15)

A major limitation of smartwatch recordings is that single-lead ECGs provide a limited view of cardiac electrical activity relative to standard 12-lead ECGs, impacting their ability to detect clinically meaningful abnormalities. However, diagnostic accuracy could be improved by recording single-lead ECGs from unconventional positions, for example by placing the smartwatch on the chest.<sup>(15–18)</sup> Evaluating the diagnostic accuracy of conventional smartwatch-derived ECGs for diagnosing cardiac abnormalities as well as the feasibility and incremental value of unconventional smartwatch tracings could create opportunities to enhance cardiovascular telemedicine and to empower patients.

In the present study, we sought to evaluate the accuracy of smartwatch-derived single-lead ECG recordings for diagnosing various electrocardiographic abnormalities compared with conventional 12-lead ECGs. Additionally, we evaluated the potential incremental benefit of incorporating non-standard smartwatch positioning to record lead II and simulated leads V1 and V6.

## Methods

Between July 2019 and January 2020, 260 patients with or without a history of cardiovascular disease who presented to our hospital outpatient and emergency departments were prospectively enrolled for this study. The study was approved by our institutional review committee and the subjects gave informed consent. Participants had a standard 12-lead ECG performed, followed immediately by four smartwatch ECG recordings using the Apple Watch Series 4<sup>®</sup> (Apple Inc, Cupertino, CA, USA), all performed at rest. Patients were shown how to record ECG tracings using the smartwatch, and the first

complete 30-second tracings were included for analysis. Recording of Einthoven lead I was performed with the watch on the left wrist and the right index finger on the crown (AW-I). Einthoven lead II was recorded with the watch on the left ankle and the right index finger on the crown (AW-II). Wilson-like chest leads were recorded corresponding to the locations of V1 (watch in the right parasternal area at the level of the fourth intercostal with the right index finger on the crown, AW-ANT) and of V6 (in the fifth intercostal space at the left midaxillary line with the right index finger on the crown, AW-LAT). All recorded Apple Watch ECGs were digitally stored using the Health Application of an iPhone Series 7 (Apple Inc, Cupertino, CA, USA). Using the “Send PDF to your doctor” function, a PDF document of every ECG lead was stored for analysis. Examples of smartwatch positions and derived ECGs are shown in Figure 1.

### ECG analyses

All 12-lead and smartwatch ECGs were de-identified. All 12-lead ECGs were independently evaluated by two blinded cardiologists with disagreements adjudicated by a third blinded cardiologist. (13,19) 12-lead ECGs were classified as normal or abnormal; the latter ECGs were then subclassified into one or more of the following groups:

1. Bradycardia (<55 bpm): 2<sup>nd</sup> or 3<sup>d</sup> degree atrioventricular (AV) block or sinus bradycardia
2. Atrial arrhythmia: AF or atrial flutter/tachycardia (AFL/AT)
3. Bundle branch block: left bundle branch block (LBBB), right bundle branch block (RBBB), intraventricular conduction delay (IVCD)
4. Cardiac ischemia-related abnormality: pathological Q-waves, abnormal ST-segment or T-waves. These were patients with either acute coronary syndrome (ACS) or stable coronary artery disease. Patients with bundle branch blocks were excluded from Q-wave/ST-segment/T-wave analysis.
5. Rare abnormality: ventricular tachycardia (VT), pre-excitation pattern, Brugada pattern.

In a similar fashion, all Apple Watch ECGs were independently evaluated by two blinded cardiologists with disagreements adjudicated by a third blinded cardiologist. The two cardiologists first analyzed all smartwatch AW-I tracings and classified each as normal or abnormal. In cases of abnormal tracings, detected abnormalities were selected as done for 12-lead ECGs. Afterwards, smartwatch AW-4 tracings were similarly classified as normal/abnormal and detected abnormalities selected. Interobserver agreement was assessed based on AW-I tracings.

## Statistical analysis

Interobserver agreement was expressed as the proportion of cases with perfect diagnostic profile matches, and Cohen's kappa ( $\kappa$ ) statistics were calculated for the classification of tracings as normal versus abnormal and for the detection of the three most prevalent abnormalities. We analyzed the accuracy of AW-I and AW-4 for diagnosing abnormalities defined on 12-lead ECGs as sensitivity, specificity, and positive and negative predictive values, when the abnormality was present in at least 10 subjects. We compared sensitivity between AW-I and AW-4 for reported group and specific diagnoses using McNemar's Chi-squared test. Categorical variables are presented as absolute numbers and percentages. Continuous variables are shown as mean  $\pm$  standard deviation. Differences in binary variables were examined using Fisher exact tests. Statistical analyses were performed using SPSS for Windows, version 19.0 (SPSS, Inc., Chicago, IL, USA).

## Results

A total of 260 patients underwent simultaneous standard 12-lead and smartwatch AW-I and AW-4 recordings. The mean age was  $66 \pm 6$  years and 58% were male. One-hundred eighty-nine patients (73%) had at least one abnormality on 12-lead ECG (Table 1).

### Interobserver agreement

Cardiologist 1 and 2 demonstrated high levels of agreement when classifying AW-I tracings as normal or abnormal ( $\kappa=0.85$ ). In 85% of cases there was a perfect agreement along the full diagnostic profile (agreement on all 15 possible abnormalities). Disagreements included presence of ST-segment/T-wave abnormalities ( $n=16$ ), the existence of bundle branch block ( $n=13$ ) and differentiating AF versus atrial tachycardia ( $n=10$ ). When considering the three most prevalent abnormalities, agreement was excellent for sinus rhythm ( $\kappa=0.91$ ), RBBB ( $\kappa=0.81$ ), and LBBB ( $\kappa=0.88$ ).

### Accuracy of smartwatch ECGs

Of the 189 patients with abnormalities identified on 12-lead ECG, 38 (20%) were missed using AW-I and thus incorrectly given a diagnosis of "normal tracing". Most missed abnormalities were pathological Q-waves ( $n=17$ ) or ST/T abnormalities ( $n=13$ ), which were most often identified in leads other than lead I on the 12-lead ECG. Compared with AW-I, AW-4 improved the ability to correctly detect a tracing as "abnormal", increasing sensitivity from 80% to 91% ( $P<0.01$ ). Specificity was 96% and 94%, respectively. In fact, specificity was high among all diagnoses. Summaries of sensitivities and specificities for diagnostic groups and for individual diagnoses with a prevalence of at least 10 patients are shown in Figures 2 and 3, respectively. The complete dataset, including positive and negative predictive values, is shown Online Supplemental Table.

### Bradycardia

AW-I and AW-4 both identified 40/40 patients with bradycardia. AW-I was highly accurate in diagnosing sinus bradycardia (se 93%, sp 98%). Using AW-I, complete AV block was detected in 7/10 cases and of 2<sup>nd</sup> degree AV block in 0/3 cases. In these missed cases, incorrect diagnoses of sinus bradycardia were made due to difficulties identifying the P-waves. AW-4

detected all 10 cases of complete AV block and 2/3 cases of 2<sup>nd</sup> degree AV block cases, with P-waves more clearly identifiable in at least one of the additional leads. Therefore, in case of bradycardia detected using AW-I, AW-4 enabled better differentiation between AV block and sinus bradycardia (81% to 95% correct, P=0.03) (Figure 4).

### Atrial arrhythmias

Sixty-one patients (23%) were diagnosed with an atrial arrhythmia (AF or AFL/AT) based on 12-lead ECG. AW-I correctly diagnosed an atrial arrhythmia in 57/61 cases (93%). Diagnostic accuracies for sinus rhythm (93% se, 98% sp) and atrial arrhythmia (98% se, 95% sp) were high using AW-I. The diagnostic accuracy for AF was similarly high (96% se, 91% sp) but was low for AFL/AT (25% se, 99% sp) with most of the latter cases misclassified as AF due to difficulty identifying organized atrial activity in AW-I tracings. Using AW-4, the accuracy in diagnosing AFL/AT improved significantly (69% se, 100% se, P=0.04 vs AW-I) due to the presence of clearly identifiable atrial depolarizations in at least one of additional leads AW-II, AW-ANT, and AW-LAT (Figure 5). When an atrial arrhythmia was detected using AW-I, an analysis of AW-4 improved the differentiation between AF and AFL/AT (71% to 89% correct, P=0.01).

### Bundle branch block

Forty-two subjects (16%) had complete bundle branch block on the 12-lead ECG (20 RBBB, 18 LBBB, and 4 IVCD). AW-I showed high accuracy for the diagnosis of complete bundle branch block (85% se, 98% sp). When complete bundle branch block was detected using AW-I, an analysis of AW-4 did not significantly improve the differentiation between LBBB, RBBB, and IVCD (79% to 87% correct, P=0.54) (Figure 6).

### Ischemic heart disease

Sixty-seven subjects (26%) had abnormal Q-waves and/or ST/T-wave abnormalities on the 12-lead ECG. Fifty percent of ST/T-wave abnormalities were seen in the context of ACS, whereas the remaining 50% were seen in patients with stable coronary artery disease. The ability of AW-I to detect these abnormalities was limited (7% se, 100% sp for Q-waves; 34% se, 100% sp for ST/T-wave abnormalities). Presence of abnormal Q-wave, ST elevation or depression or negative T-wave could be systematically detected when present in 12-lead ECG lead I. But the diagnosis was missed when these abnormalities were found not in lead I but in another lead on the 12-lead ECG (Figure 7). Compared with AW-I, AW-4 significantly improved the detection of pathological Q-waves (41% se, 99% sp; P=0.01 vs AW-I) and of ST/T-wave abnormalities (77% se, 92% sp; P<0.01 vs AW-I).

### Rare abnormalities

The two cases of ventricular pre-excitation and the two cases of VT were detected using AW-I, whereas the two cases of Brugada patterns were missed. The Brugada pattern was detected by AW-4, however, given the characteristic coved-type ST-segment readily seen in AW-ANT.

## Discussion

Telemedicine is becoming an increasingly valuable aspect of clinical care, particularly as the COVID-19 pandemic continues. Smartwatches can allow patients to independently record ECGs and digitally send them to healthcare providers, raising the likelihood that abnormalities can be diagnosed and empowering patients to play active roles in their cardiac care. This technology's ability to detect AF has been studied previously; however, its diagnostic potential for other ECG abnormalities had thus far remained poorly characterized. Our results demonstrate that Apple Watch ECG tracings can provide clinically relevant information with acceptable to excellent diagnostic accuracy for diagnoses other than AF, although the smartwatch's performance varies depending on the arrhythmia or electrocardiographic abnormality. Repositioning the smartwatch to non-standard locations (i.e. left ankle or chest wall) can improve its diagnostic accuracy, particularly for AT/AFL and hemiblocks. This technology should not be solely relied upon to detect signs of ischemic heart disease, however.

### Bradyarrhythmias

Our results demonstrate that the Apple Watch can be used to accurately detect bradycardic ventricular rates, which is not unexpected given that a single lead is usually adequate to estimate RR intervals. To differentiate between bradycardic rhythms, however, correct identification of P-waves is paramount. Our data suggest that in some patients AW-I is suboptimal for identifying P-waves, likely because much of atrial depolarization propagates perpendicular to this bipolar recording vector. This may be compounded by filters and signal processing by the smartwatch, resulting in less pronounced P-waves than one would expect from the equivalent lead in a conventional 12-lead ECG. (19) (20) Accordingly, differentiating between AV block and sinus node dysfunction, for instance, can be challenging in certain individuals when using this single lead. Our analysis of the incremental value of recording tracings from non-standard smartwatch positions suggests that this limitation can be meaningfully overcome with this strategy.

### Tachyarrhythmias

The occurrence of palpitations is probably the most important reason for many to acquire an ECG smartwatch since it is often difficult to record a conventional 12-lead ECG during short-lived arrhythmic episodes. The Apple Watch accurately detected the presence of an atrial tachyarrhythmia in 93% of cases, demonstrating high sensitivity and specificity for this diagnostic group. Additionally, it performed well in cases of AF, but performed poorly in cases of AFL/AT when only the standard smartwatch position was used for recordings, primarily due to difficulties in detecting organized atrial activity in lead AW-I. One could envision situations in which this distinction would be valuable, including when considering ablative interventions or when following patients' post-atrial ablative procedures. Once again, the use of non-standard smartwatch recordings significantly improved the ability to distinguish between AF and AFL/AT. VT was correctly diagnosed using AW-I, but there were only two such cases in our sample. Unfortunately, there were no cases of AV nodal reentrant or AV reentrant tachycardia.



## Syncope

In the context of syncope, a major limitation of using smartwatch ECG recordings for this indication is that the patient must be conscious at the time of recording since the crown must be pressed for 25 to 30 seconds to record a tracing. Thus, in contrast to implantable loop recorders, syncopal episodes are almost impossible to register. However, it is possible to perform recordings leading up to an episode if a patient recognizes the symptoms and immediately after a syncopal episode. If the tracing is adequate, our data suggest that helpful findings could be captured (for instance, interval prolongations consistent with a vagal response or new bundle branch blocks suggestive of AV block). Indeed, bundle branch blocks were accurately diagnosed using AW-I. Similarly, the finding of sinus rhythm in an individual known to be in AF prior to the syncope may raise suspicion for a post-conversion pause and sinus node dysfunction.

## Chest pain syndromes

Apple, Inc. specifies that the smartwatch is not intended to be used for the diagnosis of cardiac ischemia or myocardial infarction. Our findings support this advice, particularly given the potential ramifications of a delayed or missed diagnosis. Given the importance of simultaneously interpreting multiple ECG leads to evaluate for evidence of cardiac ischemia or necrosis, it is unsurprising that a single-lead ECG would be adequate. In our study, Q waves, ST-deviation, and T-wave abnormalities could be detected, but only when they were present in the single lead being recorded, thus yielding a very low sensitivity for these findings. Although incorporating additional lead recordings (AW-4) improved the diagnostic accuracy in this regard, it remained suboptimal. Additionally, its performance was not tested in a heterogeneous group of chest pain syndromes (e.g. acute pericarditis or pulmonary embolism), in which its performance may be poorer. It is important to not dismiss ST-elevation myocardial infarction even when the tracing is normal. In this context, repositioning the smartwatch increased the diagnostic yield. One can imagine that a patient telephones an emergency center and that he is asked to make these additional recordings to improve the performance.

## Rare abnormalities

Most consumers of smartwatch technology are young adults, most of whom are expected to not have known cardiac disease. In this group, the potential for screening for signs of an elevated risk of sudden cardiac death could be of interest. Although there were relatively few young adults in our study, using AW-I, the smartwatch did correctly identify the two cases of ventricular pre-excitation but missed the two cases with Brugada patterns. AW-4 detected all three rare abnormalities, highlighting the importance of multi-lead recordings for conditions that have lead-specific findings.

## Limitations

Several limitations should be mentioned. First, this study was not designed to determine to what extent smartwatch wearers or healthcare providers are able to interpret smartwatch ECG tracings, but rather to quantify the diagnostic performance of the smartwatch itself in a heterogeneous outpatient sample when analyzed by experts. Second, reported positive and negative predictive values were calculated based on our study population, which had a high

prevalence of ECG abnormalities for validation purposes. Certain ECG abnormalities or arrhythmias were not captured in our sample. Finally, the present study was not designed to evaluate the impact of using smartwatch ECGs on patient management.

## Conclusion

Smartwatch-derived ECG tracings accurately detected bradycardias, atrial arrhythmias, and bundle branch blocks, but showed less sensitivity for signs of cardiac ischemia or myocardial infarction. Recording ECG tracings from non-standard smartwatch positions significantly improves diagnostic accuracy.

**Acknowledgements:** none

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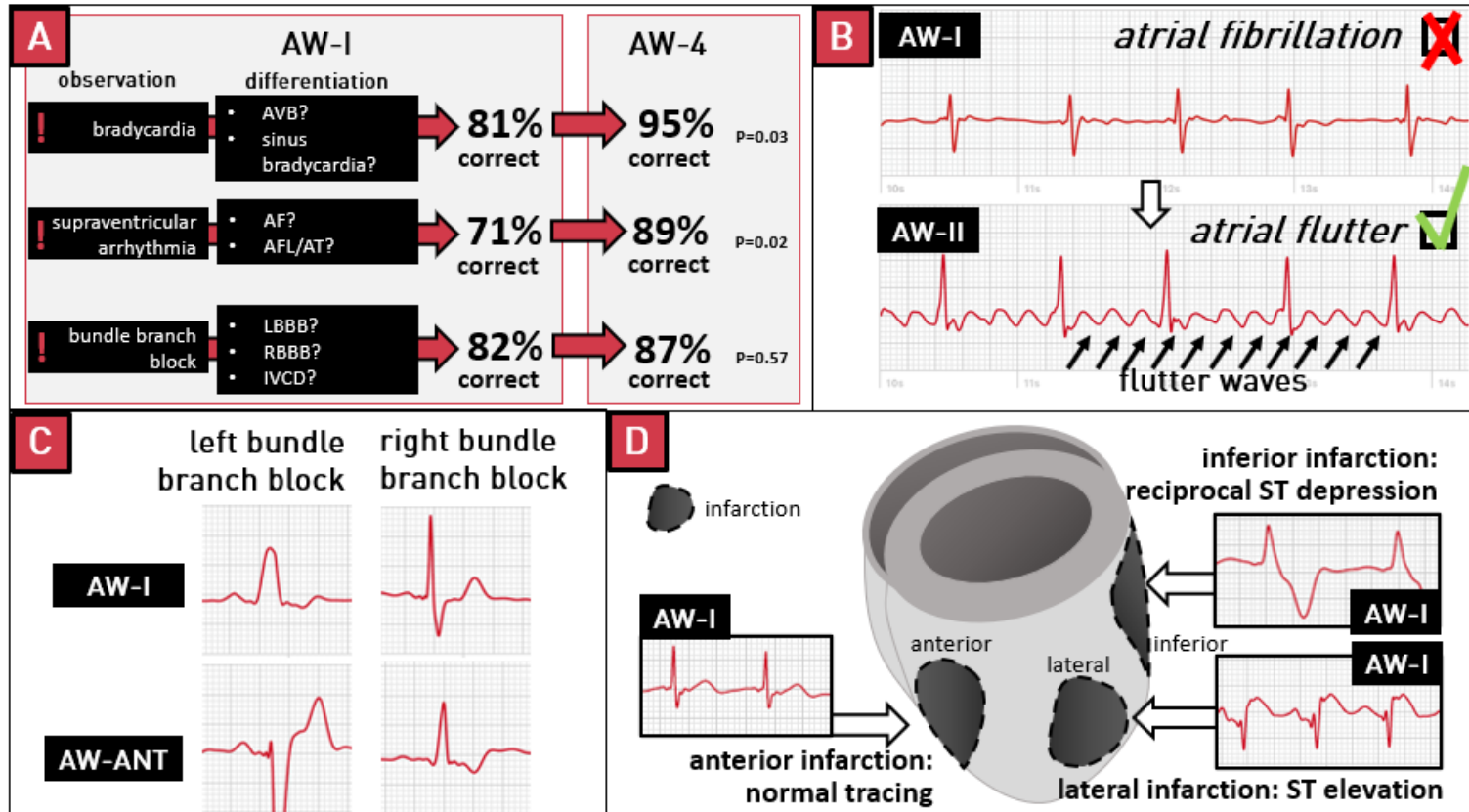
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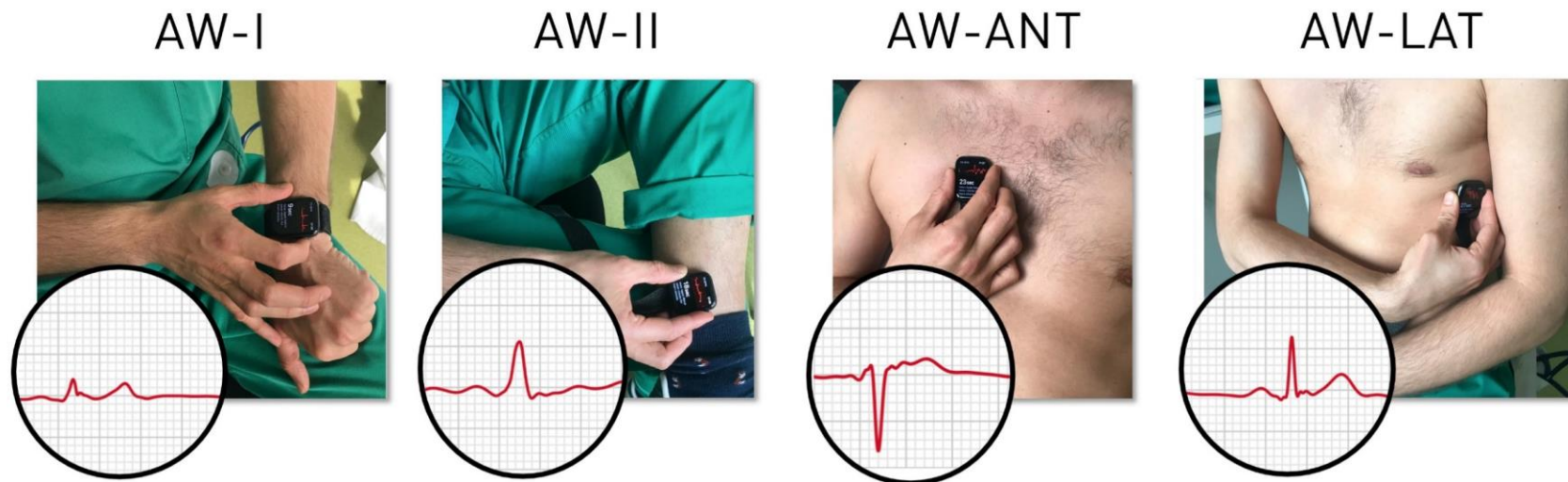
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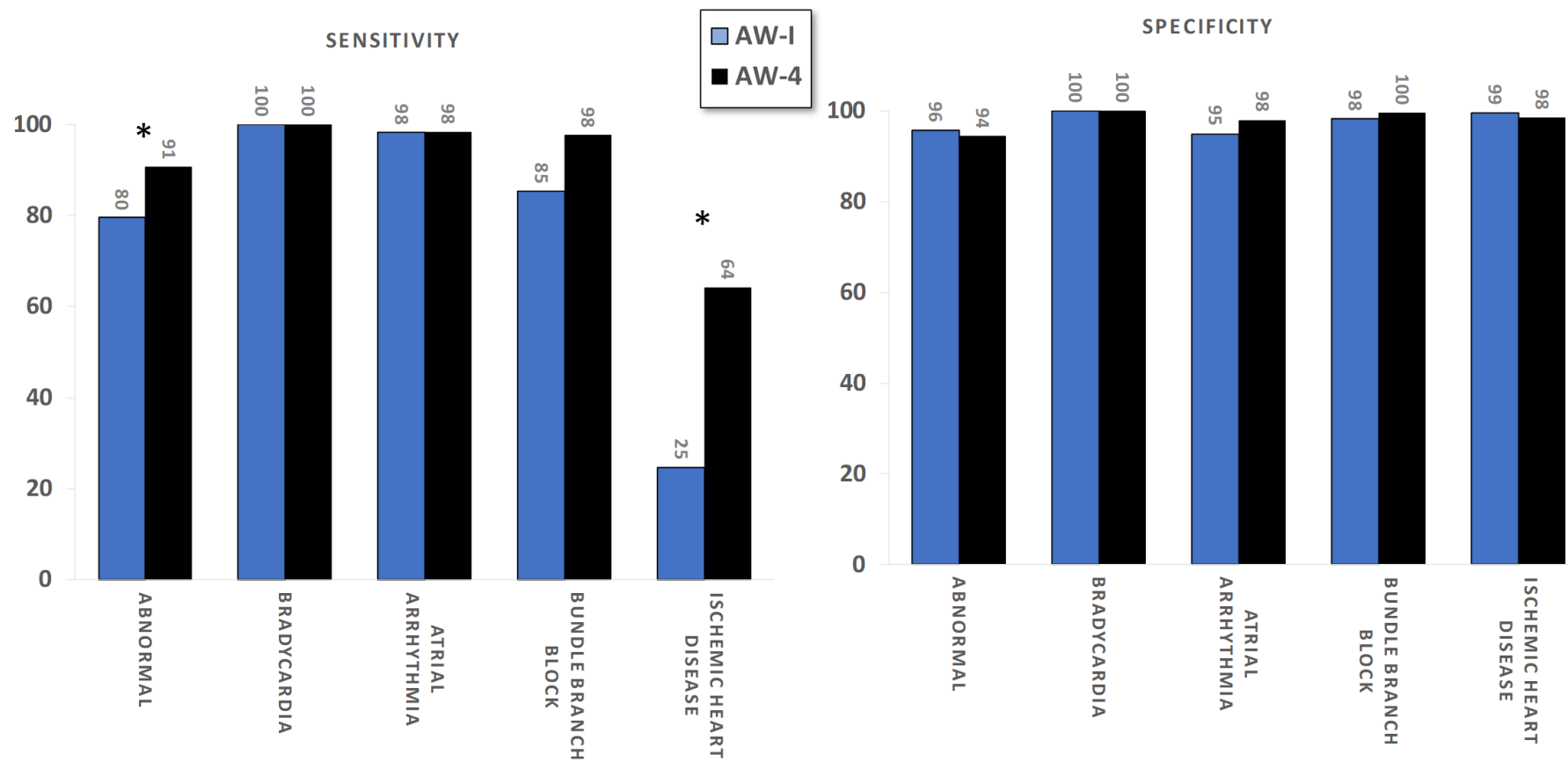
## Figures



**GRAPHICAL ABSTRACT** Using the Apple Watch ECG to differentiate between various diagnoses. A) Ability (% correct) of AW-I and AW-4 to differentiate between types of bradycardia, tachycardia, and bundle branch block (detected by AW-I). B) Example of typical atrial flutter not detected by AW-I (misdiagnosed as atrial fibrillation). The characteristic flutter waves are seen in AW-II. C) Typical examples of left and right bundle branch block with the smartwatch placed on the left wrist (AW-I) and on the V1 position (AW-ANT). D) Typical examples of ST-elevation myocardial infarctions in different coronary distributions with corresponding AW-I tracings. AF: atrial fibrillation; AFL/AT: atrial flutter/atrial tachycardia; AVB: atrioventricular block; IVCD: intraventricular conduction delay; LBBB: left bundle branch block; RBBB: right bundle branch block.

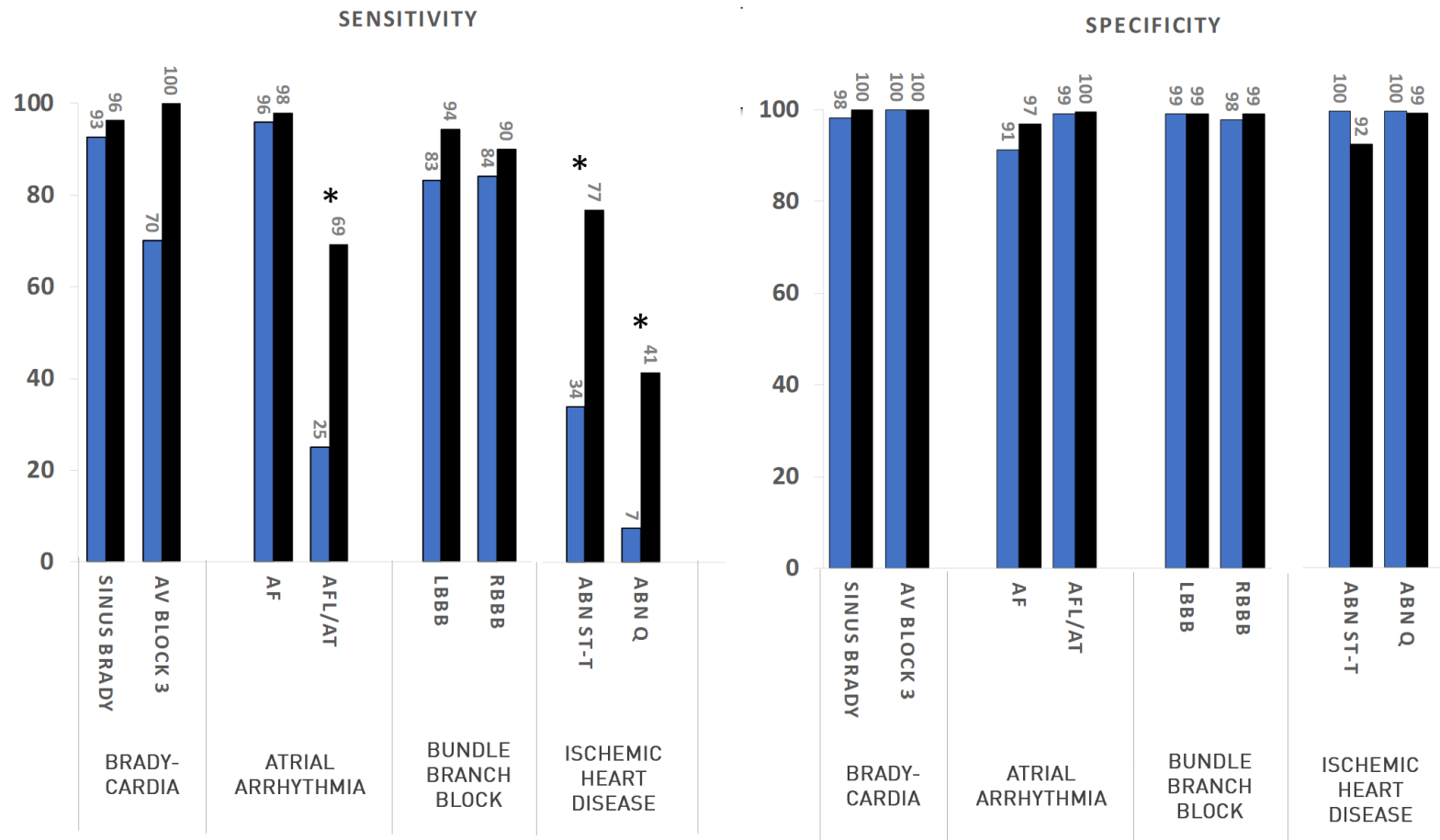


**Figure 1. The four smartwatch positions evaluated in this study:** AW-I (left wrist, standard position), AW-II (left ankle), AW-ANT (left parasternal), and AW-LAT (left midaxillary line). The combined four recordings (AW-4) were compared with AW-I alone to evaluate the incremental benefit of recording additional leads.



**Figure 2. Sensitivities (left panel) and specificities (right panel) of AW-I and AW-4 for diagnostic groups. \*P<0.05 for comparison between AW-I and AW-4.**





**Figure 3. Summary of sensitivities (left panel) and specificities (right panel) of AW-I and AW-4 for individual diagnoses with a prevalence of  $\geq 10$  patients.** ABN: abnormal; AF: atrial fibrillation; AFL/AT: atrial flutter/atrial tachycardia; AV: atrioventricular; LBBB: left bundle branch block; RBBB: right bundle branch block; sinus brady: sinus bradycardia. \* $P < 0.05$  for comparison between AW-I and AW-4.

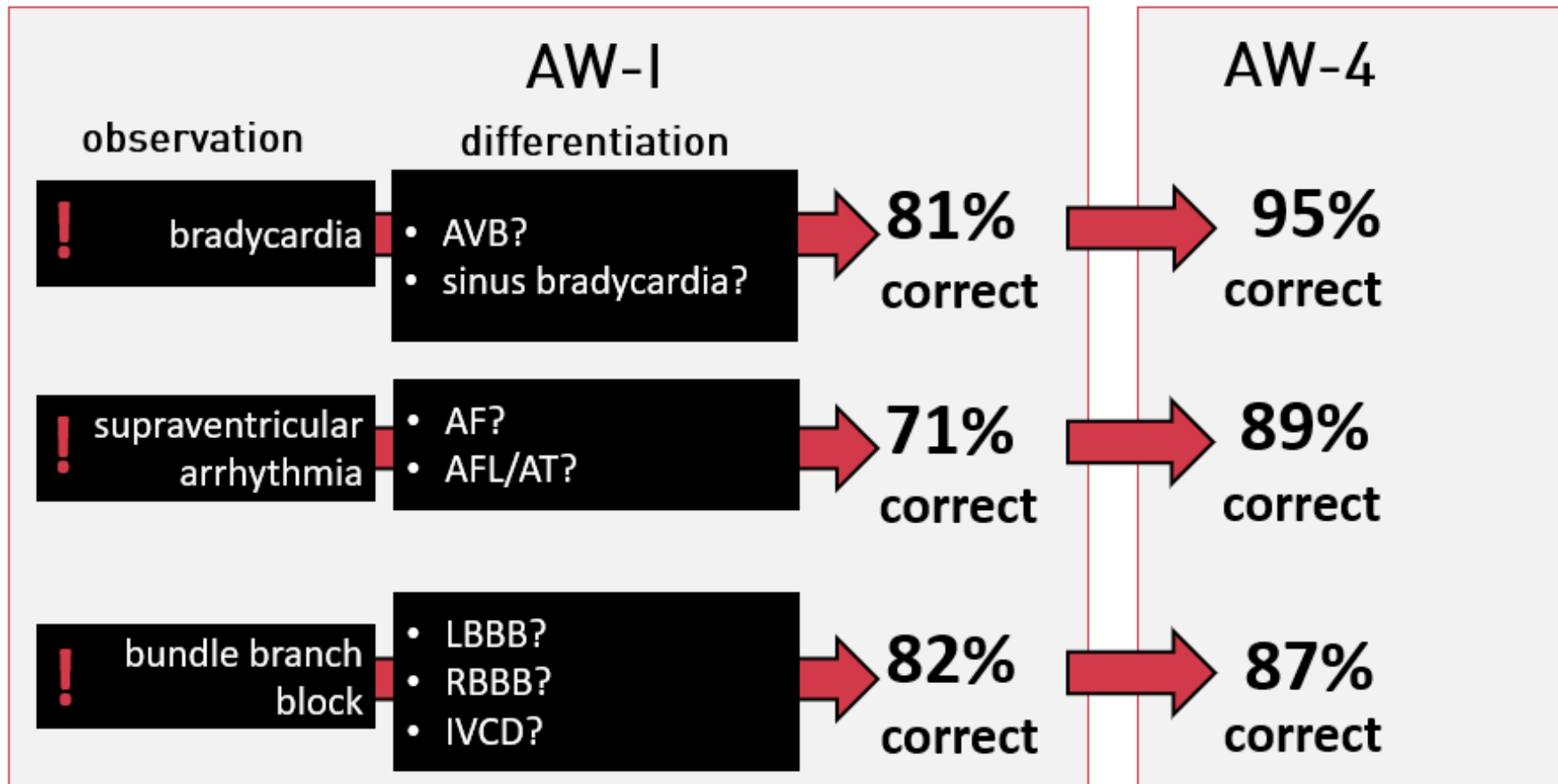


Figure 4. Ability (% correct) of AW-1 and AW-4 to differentiate between types of bradycardia, tachycardia, and bundle branch block (detected by AW-1). AF: atrial fibrillation; AFL/AT: atrial flutter/atrial tachycardia; AVB: atrioventricular block; IVCD: intraventricular conduction delay; LBBB: left bundle branch block; RBBB: right bundle branch block.

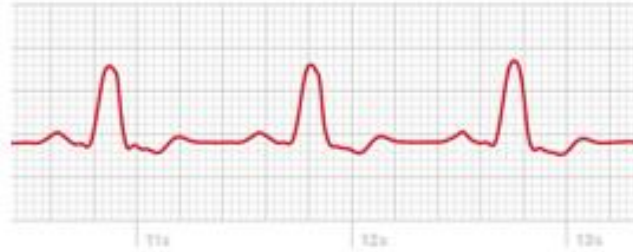


**Figure 5. Example of typical atrial flutter not detected by AW-I (misdiagnosed as atrial fibrillation). The characteristic flutter waves are seen in AW-II.**

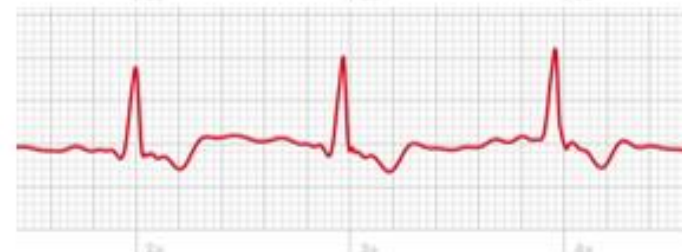
## left bundle branch block

## right bundle branch block

AW-I



AW-ANT



**Figure 6. Typical examples of left bundle branch block (left panel) and right bundle branch block (right panel) with the smartwatch placed on the left wrist (AW-I) and on the V1 position (AW-ANT). Note that when analyzing AW-I, right bundle branch block often has an isoelectric segment at the end of the QRS complex, which may lead to underestimation of the QRS width.**

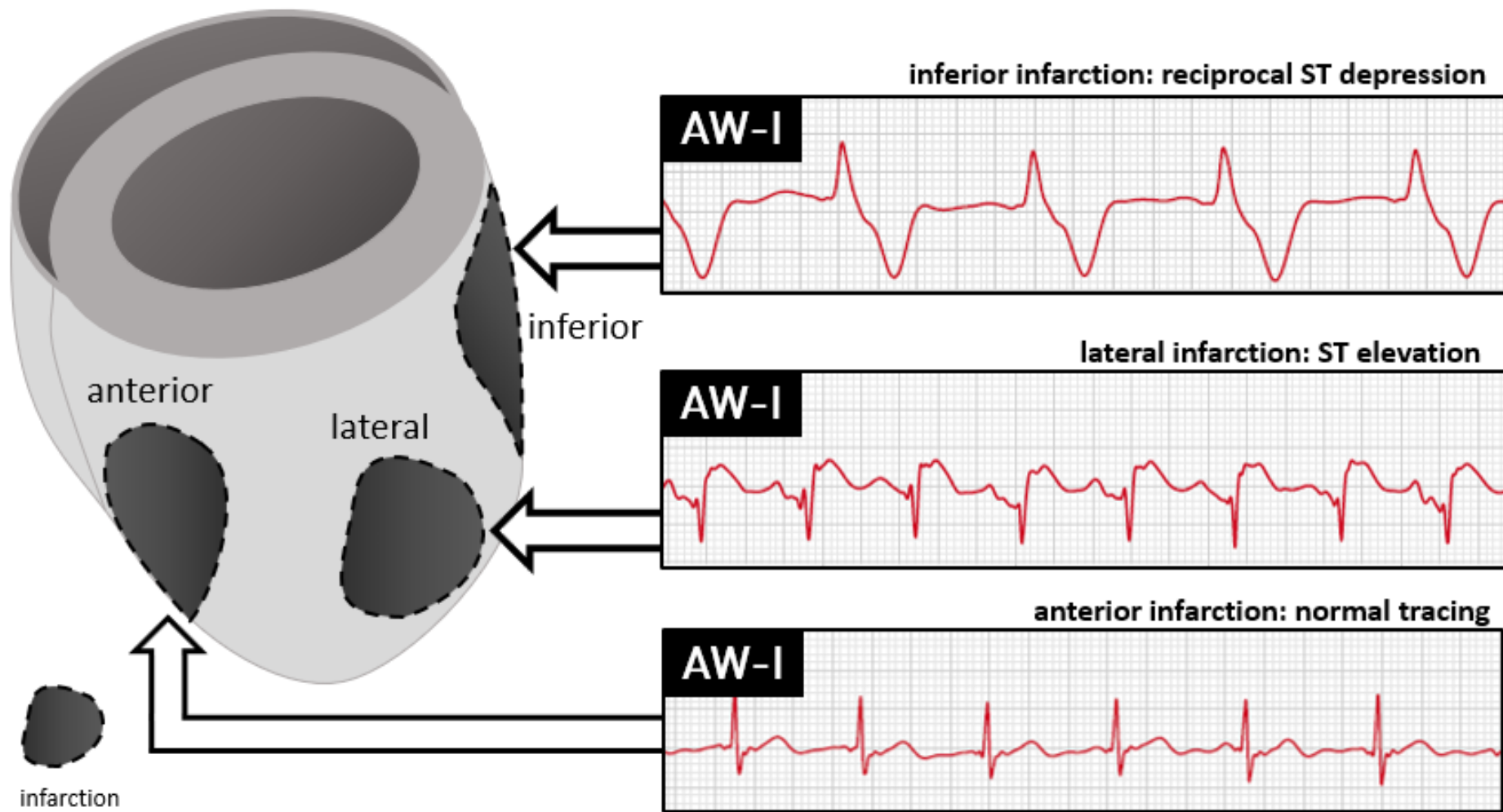


Figure 7. Typical examples of ST-elevation myocardial infarctions in different coronary distributions with corresponding AW-I tracings.

## Table

Table 1: Prevalence of abnormalities diagnosed on 12-lead ECGs

<b>12-LEAD ECG DIAGNOSIS</b>	<b>PREVALENCE</b>
any abnormality	189 (73%)
<b>1. BRADYCARDIA (&lt;55 BPM)</b>	<b>40 (15%)</b>
sinus bradycardia	27 (10%)
3 <sup>rd</sup> degree atrioventricular block	10 (4%)
2 <sup>nd</sup> degree atrioventricular block	3 (1%)
<b>2. ATRIAL ARRHYTHMIA</b>	<b>62 (24%)</b>
atrial fibrillation	49 (19%)
atrial flutter/tachycardia	13 (5%)
<b>3. BUNDLE BRANCH BLOCK</b>	<b>42 (16%)</b>
left bundle branch block	18 (7%)
right bundle branch block	20 (8%)
intraventricular conduction delay	4 (1%)
<b>4. ISCHEMIC HEART DISEASE</b>	<b>67 (26%)</b>
abnormal ST-segment or T-wave	38 (15%)
abnormal Q-waves	15 (6%)
both abnormal ST/T-waves and Q-waves	14 (5%)
<b>5. RARE ABNORMALITIES</b>	<b>6 (2%)</b>
ventricular tachycardia (2), brugada type 1 pattern (2), ventricular pre-excitation (2)	

III. ARTICLE II

# Validating QT-interval measurement using the Apple Watch ECG to enable remote monitoring during the COVID-19 pandemic

**Short Title:** Validating the Apple Watch for QT measurement

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**Word count:** 800

**Key Words:** Apple watch, QT-interval, ECG, QT monitoring, COVID-19



Screening and monitoring for QT prolongation when initiating certain medications is routinely performed to avoid arrhythmic complications. However, the novel coronavirus disease (COVID-19) pandemic and its proposed treatments – including hydroxychloroquine and azithromycin, which are known to prolong the QT-interval(21) – raise logistical and safety concerns with established QT-monitoring strategies. Recently, the American College of Cardiology made recommendations for QT-monitoring in outpatients with COVID-19 on hydroxychloroquine/azithromycin, suggesting that the use of direct-to-consumer mobile devices, such as the Apple Watch 1-lead ECG, could be considered in cases of resource constraints or quarantines.(22) The Apple Watch ECG is FDA-cleared for detecting atrial fibrillation but has not been studied for QT-monitoring. Lead I (the lead recorded by the Apple Watch) may be suboptimal for measuring this interval; however, other leads can be reproduced by placing the smartwatch on the left ankle or chest.(16) We therefore sought to validate the use of the Apple Watch for QT measurement, including using non-standard smartwatch positions, in an unselected outpatient population.

The data from this study are available from the corresponding author upon reasonable request. Between December 2019 and January 2020, 100 consecutive patients in sinus rhythm were enrolled from outpatient or emergency departments. The study was approved by our institutional review committee and the subjects gave informed consent. Standard 12-lead ECGs were performed, followed by smartwatch ECG recordings using the Apple Watch Series 4® (Apple Inc, Cupertino, CA). After a brief demonstration, patients recorded 30-second Apple Watch ECG equivalents of lead I (AW-I, watch on left wrist), lead II (AW-II, watch on left ankle), and a simulated lead V6 (AW-LAT, watch on left lateral chest) (Figure A). Using commercially available software (EP Calipers, EP studios Inc., Louisville, KY), a cardiologist measured three RR and QT-intervals to calculate the corrected QT-interval (QTc) using Bazett's formula (Figure B). A QTc >480 ms was considered "high risk". Agreement between 12-lead and Apple Watch QTc measurements was calculated using median absolute error and Bland-Altman analyses. To measure interobserver variability, all AW-I QTc measurements were repeated by a second blinded cardiologist and the intraclass correlation coefficient (ICC) was calculated based on a two-way random absolute agreement model with single measurements. Agreement on whether a tracing was interpretable was assessed using Cohen's kappa ( $\kappa$ ) statistic. T-wave amplitude was measured to evaluate its association with QTc measurement accuracy.

The mean age was  $67 \pm 7$  years, 59% were male, and 35% had diagnosed cardiac disease. Heart rates were similar on 12-lead and Apple Watch recordings ( $69 \pm 11$  versus  $70 \pm 13$  bpm, respectively,  $P=0.2$  paired student t-test). QTc-intervals ranged from 336 to 530 ms on 12-lead ECGs. Eight patients were identified as high risk, all of whom were similarly identified by the smartwatch. QTc-measurements could not be performed in 15 patients (15%) using AW-I, in 31 patients (31%) using AW-II, and in 15 patients (15%) using AW-LAT due to low T-wave amplitude, baseline artifact, or both. Repositioning the smartwatch to a different location often yielded an adequate tracing (Figure C); however, in six patients (6%), none of the three smartwatch positions allowed for an adequate measurement.

There was excellent agreement between cardiologists on whether recordings were acceptable for QTc measurements ( $\kappa=0.92$ ). Interobserver agreement for QTc measurements was similarly high with a median absolute error of 9 ms (interquartile range [IQR] 5–15 ms) and an ICC of 0.92 (95% confidence interval 0.85–0.95). Compared with the 12-lead ECG, the median

absolute error in QTc was 18 ms for AW-I (IQR 9–35 ms), 20 ms for AW-II (IQR 8–33 ms), and 16 ms for AW-LAT (IQR 8–27 ms). There were no significant differences in absolute offset between smartwatch positions. Bland-Altman analyses revealed a bias of -5 ms (95% limits of agreement [LoA] -65 to +54) with AW-I, -9 ms with AW-II (95% LoA -67 to +50), and -11 ms (95% LoA -60 to +37) with AW-LAT. The negative bias suggests that using the smartwatch slightly overestimated the QTc-interval. T-waves were significantly higher in AW-LAT than in AW-I and AW-II (0.28 versus 0.20 and 0.19 mV, respectively, ANOVA  $p < 0.001$ ). Tracings with T-wave amplitudes  $> 1$  mV demonstrated lower absolute errors in AW-I ( $21 \pm 16$  ms vs  $30 \pm 25$  ms,  $p = 0.03$ , unpaired t-test).

In our study, Apple Watch ECG tracings allowed for adequate QT measurements when the smartwatch was worn on the left wrist in 85% of patients. This figure increased to 94% when the smartwatch was moved to alternative positions. Performance depends on factors such as ECG tracing quality and T-wave amplitude, therefore identifying the best smartwatch position (i.e. “T-wave mapping”) at baseline may improve accuracy. Other ECG systems were not evaluated but may be similarly valuable,<sup>(23,24)</sup> such as the Kardia 6L system (AliveCor, Mountain View, CA), which has received FDA clearance for QT measurement. Overall, this technology has the potential to facilitate remote QT-monitoring, including among quarantined outpatients on QT-prolonging treatments.

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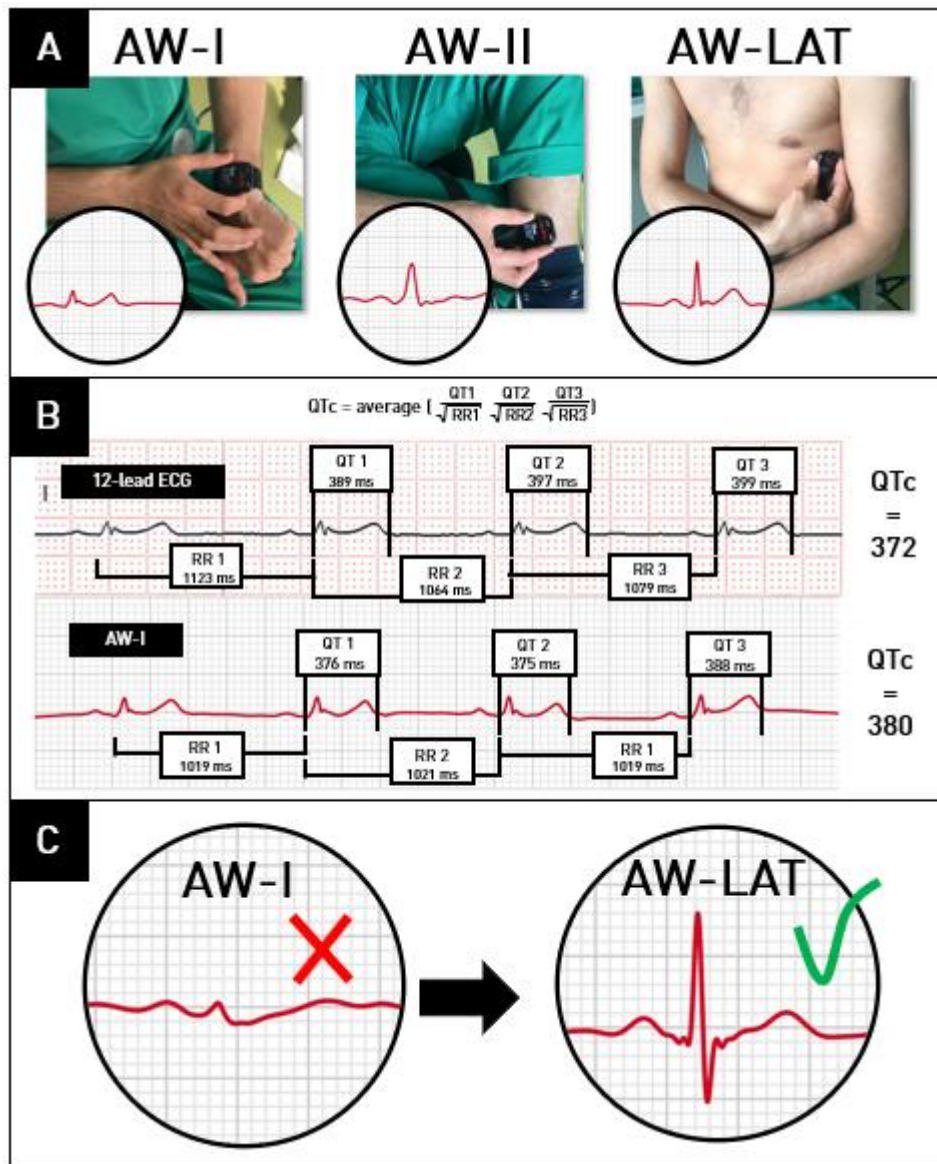
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Figure



**Figure 1. Apple Watch ECG recordings, QT interval measurements, and impact of recording tracings from non-standard smartwatch positions.** A. Recording Apple Watch ECG equivalents of lead I (AW-I, watch on left wrist), lead II (AW-II, watch on left ankle), and a simulated lead V6 (AW-LAT, watch on left lateral chest). B. Corrected QT interval (QTc) measurements from a 12-lead ECG and an Apple Watch lead I ECG (AW-I). QTc using the 12-lead ECG is 372 ms, QTc using AW-I is 380 ms (absolute difference of 8 ms and a bias of -8 ms). C. Repositioning the Apple Watch may improve signal quality and measurement of the QT interval. Example of two smartwatch ECG recordings from the same patient. Measurement of the QT interval was deemed impossible in lead II (AW-II) due to low T-wave amplitude ( $\leq 0.1$  mV). After moving the smartwatch to the left lateral chest wall (AW-LAT), the T-wave amplitude increased to 2 mV, markedly facilitating the measurement of the QT-interval. Note the similar increase in QRS complex amplitudes.

# Validating QT-interval measurement using the Apple Watch ECG to enable remote monitoring during COVID-19 pandemic

**Short Title:** Validating the Apple Watch for QT measurement

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## Abstract

### Background

Experimental treatments for the novel coronavirus disease (COVID-19) include QT-prolonging medications, which raise concerns for arrhythmic complications. The American College of Cardiology (ACC) has suggested that the Apple Watch could be used for outpatient QT monitoring during periods of quarantine or resource constraints.

### Objectives

We sought to validate the use of the Apple Watch for monitoring the QT-interval

### Methods

One hundred patients in sinus rhythm underwent simultaneous recordings of 12-lead and Apple Watch ECGs of lead I (AW-I, watch on left wrist), lead II (AW-II, watch on left ankle), and lead V6 (AW-V6, watch on left lateral chest). QT-intervals were measured using digital calipers and corrected for heart rate (QTc). T-wave amplitudes were similarly quantified. AW-I QTc measurements were repeated by a blinded observer to assess inter-observer variability.

### Results

QT-interval could not reliably be measured in 15% of patients using AW-I, 32% using AW-II, 15% using AW-V6, and 6% using any lead due to small T-waves or baseline wander. Compared to 12-lead ECGs, the absolute difference in QTc measurements was 23 ms using AW-I, 24 ms using AW-II, and 21 ms using AW-V6. Variations in T-wave amplitude influenced measurement accuracy. All 8 patients with QTc >480 ms were correctly identified using the smartwatch. Inter-observer match was excellent ( $r=0.94$ ).

### Conclusions

Measuring the QT-interval with an Apple Watch is feasible in most patients and agrees well with the 12-lead ECG. In case of small T-waves, moving the smartwatch to another position can improve accuracy. QT-monitoring with Apple Watch is therefore possible.

**Key Words:** Apple watch, QT-interval, ECG, QT-monitoring, COVID-19



## Introduction

The ongoing coronavirus disease (COVID-19) pandemic is claiming a remarkable number of lives, causing considerable morbidity, and straining healthcare systems around the world. As frontline healthcare workers and the global medical research community move with unprecedented urgency to control its spread and to identify effective treatments, some candidate therapies are already being used despite the absence of conclusive data of their benefits or risks for COVID-19. Among the most commonly advocated therapy is hydroxychloroquine alone or in combination with azithromycin(25) , which has/have been suggested to be of potential benefit in *in vitro* and preliminary clinical studies. These drugs have long been used for other clinical indications, where they have been shown to be associated with QT prolongation, thus raising concerns of potentially lethal arrhythmias such as polymorphic ventricular tachycardia, when used for COVID-19. Accordingly, ensuring adequate monitoring of the QT interval among patients with COVID-19 while on such treatments is an increasing clinical concern.

Inpatient or in-person QT monitoring poses unique problems during the COVID-19 outbreak: it represents a patient encounter during which healthcare providers (or others) could be exposed to the virus, thus requiring them to use of personal protective equipment, which may be a limited resource that could be rationed for other encounters. Methods to remotely monitor the QT intervals of patients well enough for outpatient therapy could therefore be valuable. Recently, the American College of Cardiology (ACC) made recommendations for outpatient QT monitoring of patients with COVID-19 on hydroxychloroquine/azithromycin. These include performing a baseline ECG (using a corrected QT [QTc] cut-off of 480 ms as a relative contraindication to these agents) and repeating an ECG 2-3 hours after dosing on day 3 of therapy, if feasible, or considering alternative methods to assess patients' QT intervals and arrhythmia risk depending on quarantine or resource constraints. Proposed alternative methods to monitor the QT interval include the use of direct-to-consumer mobile devices, such as the Apple Watch 1-lead ECG (22).

The Apple Watch ECG is FDA-approved for detecting atrial fibrillation, but has not yet been validated for QT measurements. Measuring the QT interval in a single lead can pose important challenges. For instance, it may be difficult to accurately determine the onset of the QRS complex and the end of the T-wave, particularly if tracings are of poor quality. Furthermore, based on 12-lead ECG studies, lead I, which is the standard lead registered by the Apple Watch, may be suboptimal for measuring the QT.(26) Notably, however, Einthoven limb leads can be reproduced using the Apple Watch by placing the smartwatch on the left ankle and precordial leads can be simulated by placing it on the chest.

We therefore sought to validate the use of the Apple Watch for monitoring the QT interval, including using non-standard smartwatch positions to generate alternate limb and precordial lead tracings, in an unselected outpatient population.

## Methods

Between December 2019 and January 2020, 100 patients with or without a history of cardiovascular disease who presented to our hospital outpatient and emergency departments were prospectively enrolled for this study. All patients provided informed consent. Participants had a standard 12-lead ECG performed followed immediately by three

smartwatch ECG recordings using the Apple Watch Series 4® (Apple Inc, Cupertino, CA, USA) while at rest. Patients were shown how to record ECG tracings using the smartwatch, and we included the first complete 30-second tracings for analysis. Figure 1 shows the three positions of the smartwatch which were used to acquire the registrations. Einthoven lead I was recorded with the watch on the left wrist and the right index finger on the crown (AW-I), Einthoven lead II was recorded with the watch on the left ankle or lower left abdomen and the right index finger on the crown (AW-II), and Wilson chest lead V6 was simulated by placing the smartwatch on the left lateral chest over the fifth intercostal space in left midaxillary line and the right index finger on the crown (AW-V6).

### Measurement of QT intervals

All recorded ECGs were digitally stored using the Health application of an iPhone Series 7 smartphone (Apple Inc, Cupertino, CA, USA). Using the “Export a PDF for Your Doctor” function, a PDF file of each single-lead tracing was saved for anonymization and offline analysis. The Apple Watch ECG application does not include automated QT interval measurements, therefore commercially available software (EP Calliper, EP studios) was used to perform all measurements digitally. This software was chosen because it is moderately priced, supports multiple operating systems, allows one to import 12-lead and Apple Watch single-lead ECG PDF files, and readily allows for ECG calibration and RR and QT interval measurements. All tracings were maximally expanded and three beats were selected to calculate RR and QT intervals. QT intervals were corrected using the preceding RR interval as per Bazett’s formula ( $QTc = \frac{QT}{\sqrt{RR}}$ ), where RR is measured in seconds.(27) Patients with a QTc >480 ms in any lead were classified as “high risk”. To measure inter-observer variability, all QTc measurements from AW-I were repeated by a second blinded observer. The impact of T-wave amplitude (in millivolts) on QTc measurement accuracy was examined in all Apple Watch tracings.

### Statistical analysis

Normal distributions of variables were confirmed before analysis. Continuous variables are reported as mean ± standard deviation and categorical variables as *n* (%). Agreement between 12-lead and Apple Watch QTc measurements was calculated using average absolute offset and Bland-Altman analyses. Inter-method variability and inter-observer variability are expressed as correlation coefficients estimated by a Pearson correlation test and the intra-class correlation coefficient (ICC) for single and averaged measurements based on a two-way mixed absolute agreement model.(28) The inter-observer agreement in qualifying a tracing as interpretable for QT measurement was expressed by calculating Cohen’s kappa ( $\kappa$ ) statistic. The paired Student *t*-test and ANOVA was used to compare mean values between groups. For all statistical tests, a two-tailed *p*-value <0.05 was considered statistically significant. Statistical analyses were performed using SPSS for Windows, version 19.0 (SPSS, Inc., Chicago, IL, USA).

## Results

A total of 100 subjects in sinus rhythm underwent simultaneous 12-lead ECG and Apple Watch ECG recordings (leads I, II and V6) were included in the analysis. The mean age was 67 ± 7 years and 59 % were male. 35% of patients were previously known with cardiac disease. The mean heart rate was similar on 12-lead and Apple Watch recordings (69 versus 70 bpm,

respectively,  $P=NS$ ). Based on 12-lead ECG measurements, QTc intervals ranged from 336 ms to 530 ms (5<sup>th</sup>-95<sup>th</sup> percentile: 383-488 ms).

Examples of QTc measurements from a 12-lead ECG and from the Apple Watch worn on the left wrist (AW-I) is shown in Figure 2. Based on 12-lead ECGs, 8 patients were identified as being high-risk based on a QTc of >480 ms, all of whom were also identified as high risk by the smartwatch. In one of the eight patients, AW-I was considered of insufficient quality to measure the QTc, but a QTc >480 ms was measured using other smartwatch locations (AW-II and AW-V6), thus correctly classifying the patient. QTc measurements were possible for all patients using 12-lead ECGs but was deemed impossible in 15 patients (15%) using AW-I, in 31 patients (31%) using AW-II, and in 15 patients (15%) using AW-V6. In six patients, none of the three smartwatch positions allowed for an adequate QTc measurement. Cases in which the QT could not be properly measured were due to low T-wave amplitude in 40% of cases and due to baseline artifact in 60% of cases. Repositioning the smartwatch to another location to record a different ECG lead often yielded an adequate tracing (Figure 3).

### Inter-observer variability

Observers 1 and 2 demonstrated high levels of agreement when deciding whether recordings were acceptable for QT measurements ( $\kappa = 0.92$ ). Inter-observer agreement on measuring the QTc interval in AW-1 was very high with an average absolute difference of 11 ms, a Pearson's correlation coefficient of 0.94, and an ICC of 0.96.

### Inter-method variability

Compared with the 12-lead ECG, the average absolute offset in QTc was 25 ms for AW-I, 24 ms for AW-II, and 21 ms for AW-V6 (Table 1). There were no significant differences in absolute offset between smartwatch positions. Bland-Altman analysis revealed a bias of -5 ms for AW-I, -9 ms for AW-II, and -11 ms for AW-V6 and standard deviations of 30 ms for AWI, 30 ms for AWII and 25 ms for AW-V6 (Figure 4). The negative bias shows that for all Apple Watch recordings, there was a slight overestimation of the QTc-interval of 5 ms (AW-I) to 11 ms (AW-V6). On average, T-waves were significantly higher in AW-V6 than in AW-I and AW-II (T-wave amplitude 0.28 mV versus 0.20 mV and 0.19 mV, respectively,  $P<0.05$ ). The amplitude of the T-waves was associated with accuracy of the QTc measurement as registrations with T-waves >1 mV demonstrated lower average absolute difference for all smartwatch locations (Table 2).

## Discussion

Drug-induced QT prolongation is a well-recognized phenomenon that is commonly encountered in clinical practice. Screening and monitoring for QT prolongation, particularly when initiating certain medications that are known to prolong the QT interval, is routinely performed to minimize the risk of arrhythmic complications. However, the ongoing COVID-19 pandemic and proposed treatments for this viral illness – namely hydroxychloroquine and azithromycin, which are known to prolong the QT interval – raise logistical and safety concerns with established QT monitoring strategies. Use of the Apple Watch has been proposed as a potential alternative method to monitor the QT interval among patients with COVID-19, particularly among quarantined outpatients. We report that in 85% of patients in our study, the Apple Watch yielded ECG tracings that allowed for adequate QT measurements and that

could be used to correctly identify patients who would be considered at high risk for QT prolongation, when the smartwatch was worn on the left wrist. This figure increased to 94% when the smartwatch was moved to alternative positions, such as the left ankle or left lateral chest wall. There was excellent inter-observer agreement in smartwatch-based QTc measurements and in classifying uninterpretable recordings. Overall, the Apple Watch therefore allows for accurate measurement of the QT interval, although its performance depends on factors such as ECG tracing quality and T-wave amplitude.

### Measuring the QT-interval

Recognizing an abnormal QT interval is key to estimating a patient's risk of malignant arrhythmias when initiating or continuing QT-prolonging therapies. However, measuring the QT interval can be challenging and when done incorrectly, can adversely impact a patient's treatment plan or expose them to arrhythmic risks.<sup>(29)</sup> Measuring the QT interval using single-lead smartwatch ECGs poses potentially even more challenges. Whether the QT interval in a single lead (lead I in case of the Apple Watch), accurately reflects ventricular depolarization and/or repolarization measures in a given patient is questionable. When using 12-lead ECGs, lead II is generally considered to be the most accurate with respect to QT interval measurements. Thus, we attempted to record lead II-analogous tracings with the Apple Watch by positioning the smartwatch electrode on patients' left ankles and having them press the crown with their right index fingers. However, in our analysis of smartwatch recordings, lead II tracings did not yield more accurate QT interval measurements and, in fact, yielded more uninterpretable recordings. It is possible that the body positioning required to record lead II tracings with the Apple Watch contributed to their suboptimal quality and lower T-wave amplitudes.

### Clinical Perspectives

As the COVID-19 pandemic progresses, the public health push to encourage physical distancing, the limited pool of available healthcare workers, and concerns regarding the availability of personal protective equipment render monitoring the QT interval among infected outpatients challenging. This is particularly problematic given that widely used candidate therapies for COVID-19 include QT-prolonging medications. In light of these extraordinary circumstances, the ACC recently recommended that as yet unvalidated methods to monitor the QT interval could be considered, particularly among outpatients with COVID-19 on such treatments. Such methods include the use of direct-to-consumer mobile devices, such as the Apple Watch. Our results demonstrate that this approach may not be unreasonable from a technical standpoint. Using the Apple Watch, patient-initiated single-lead ECG tracings could be recorded and digitally sent to a physician for interpretation. QTc measurements could be performed in most cases and agreed well with measurements using standard 12-lead ECGs, although Apple Watch measurements slightly overestimated the QTc. Our results suggest that if the Apple Watch is to be used for QT monitoring, careful inspection of the T-wave during the first recordings is important. If the tracing is found to be suboptimal, moving the Apple Watch to another position may significantly improve QRS complex and T-wave morphologies, thus improving the accuracy of QTc measurements. In our experience, a simple rule of thumb to prompt non-experts to suspect a suboptimal tracing is if one cannot fit a "small square" (1 mm x 1 mm) within the T-wave. Various smartwatch positions can be trialed across the limbs or the chest to search for a pronounced T-wave (and QRS-complex).

Based on our data, the V6 position may be a logical alternative to the left wrist, but patient-specific factors are likely to influence this. Identifying the best smartwatch position for QT measurements (i.e. performing “T-wave mapping”) at baseline, ideally before initiating QT prolonging agents, may improve accuracy and clinical value.

#### Limitations

A limitation of our study is that we did not study the use of Apple Watch for QT measurements in patients with significant drug-induced QT prolongation (e.g. during sotalol loading) or with known genetic predispositions to QT prolongation. However, our study sample did include patients with prolonged QT intervals as evidenced by the wide range in QT intervals (spread of >200 ms) and the finding of 8% with QTc intervals >480 ms. Another limitation is that we did not attempt to recreate additional lead tracings, such as lead III or precordial leads V1-V5. We omitted these steps for study logistical reasons, but it is possible that one or more of these could prove valuable.

#### Conclusion

Measuring the QT interval using the Apple Watch is feasible in most patients and agrees well with measurements from 12-lead ECGs. In cases of low T-wave amplitudes, moving the smartwatch to alternative positions can improve accuracy. This technology has the potential to facilitate remote QT monitoring, including among quarantined outpatients on QT-prolonging treatments.

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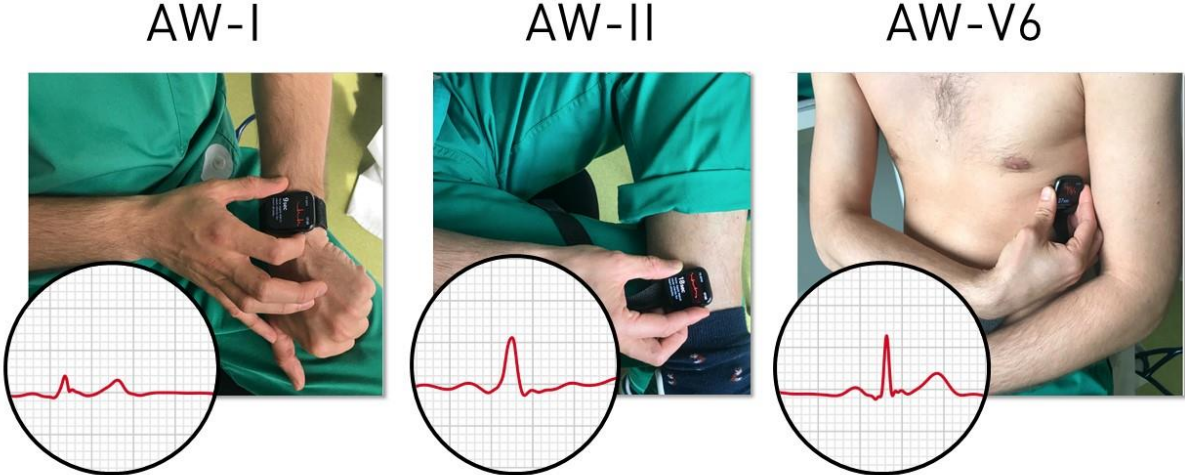
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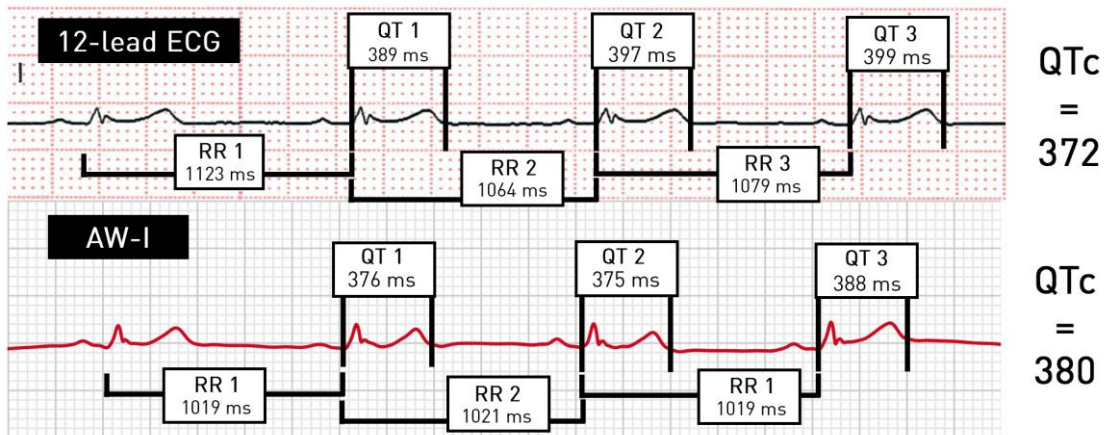


Figures



**Figure 1. Smartwatch positions used for the validation study.** AW-I is the standard position with the watch on the left wrist and the right index finger on the crown (lead I). AW-II is an alternative position with the watch placed on the left limb and the right index finger on the crown (lead II). AW-V6 is an alternative position with the watch placed on the left lateral chest at the position one would place at the Wilson chest lead V6 position (lead V6).

$$QTc = \text{average} \left( \frac{QT1}{\sqrt{RR1}} \quad \frac{QT2}{\sqrt{RR2}} \quad \frac{QT3}{\sqrt{RR3}} \right)$$



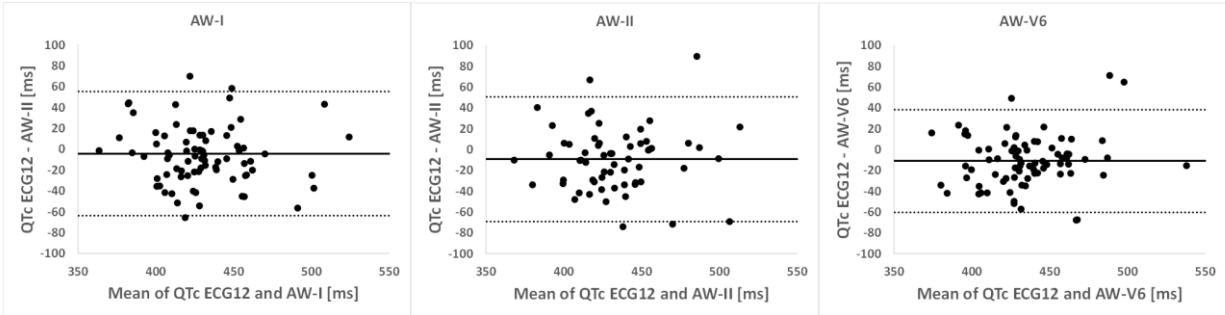
**Figure 2. QTc measurements from a 12-lead ECG and an Apple Watch lead I ECG (AW-I).** QTc using the 12-lead ECG is 372 ms, QTc using AW-I is 380 ms (absolute difference of 8 ms and a bias of -8 ms).



**Figure 3. Repositioning the Apple Watch may improve signal quality and measurement of the QT interval.** Example of two smartwatch ECG recordings from the same patient. Measurement of the QT interval was deemed impossible in lead I (AW-I) due to low T-wave

amplitude (<0.1 mV). After moving the smartwatch to the V6 position (AW-V6), the T-wave amplitude increased to 2 mV, markedly facilitating the measurement of the QT-interval. Note the similar increase in QRS complex amplitudes.

### Bland-Altman plot



**Figure 4. Bland-Altman analyses.** Bland-Altman plots of three smartwatch ECG locations (AW-I, AW-II, and AW-V6) compared to the 12-lead ECG (ECG12). Bland-Altman analysis shows slight negative biases, indicating QTc overestimation (solid black line), and narrower limits of agreement for AW-V6 (dashed lines).

**Table 1. Inter-method variability.** Average of the absolute differences (ms) and Bland-Altman results are shown for comparisons between 12-lead ECG and Apple Watch recordings (AW-I, AW-II and AW-V6).

	12-lead ECG vs AW-I	12-lead ECG vs AW-II	12-lead ECG vs AW-V6
Average absolute difference [ms]	23	24	21
Bias [ms]	-5	-9	-11
Standard deviation [ms]	30	30	25
Limits of agreement [ms]	-63 : 54	-67 : 50	-60 : 37

**Table 2. Impact of T-wave amplitude.** Average absolute differences between smartwatch leads I, II and V6 and the 12-lead ECG stratified by T-wave amplitude.

Position	Average absolute difference		
	T-wave $\leq$ 1 mV	T-wave $>$ 1 mV	
Lead I	29 ms (n=39)	21 ms (n=61)	P<0.05
Lead II	27 ms (n=41)	23 ms (n=53)	P<0.05
Lead V6	26 ms (n=19)	21 ms (n=75)	P<0.05

## IV. Conclusion

### 1-Discussion des résultats

L'objectif de ces études est d'évaluer les capacités de l'AppleWatch pour différents diagnostics de troubles du rythme, de la conduction et de la repolarisation.

Dans l'article I- *Accuracy of a smartwatch-derived ECG to detect various electrocardiographic abnormalities*, nous avons pu établir les capacités et les limites de l'Apple Watch selon les différentes anomalies présentes à l'ECG 12D. Pour une seule dérivation D1, la montre reconnaît les ECG normaux avec une bonne sensibilité (de 96%) mais une spécificité faible (80%). Cependant la valeur prédictive positive est faible : 63%, mais ce résultat est directement en corrélation avec une prévalence élevée d'anomalies ECG dans notre série. En effet, elle reconnaît parfaitement le rythme sinusal (régularité, bonne visibilité des ondes P : sensibilité 93%, spécificité 98%), les bradycardies (sensibilité et spécificité de 100%) et les tachycardies supraventriculaires (sensibilité 98%, spécificité 95%). Mais elle ne permet pas de distinguer les blocs indifférenciés, les hémiblocs, les séquelles ischémiques ou les ECG de cardiopathies (Sensibilités < 35%).

Ces résultats sont attendus et sont directement liés à l'exploration d'un seul territoire par la montre. Il s'agit de la même limite que la surveillance par un scope en service de soins ; S'il est aisé pour un praticien de diagnostiquer un rythme sinusal, une bradycardie, une FA, il est plus compliqué de faire la différence entre une tachycardie atriale, un flutter commun ou une TJ. Idem pour les anomalies de la repolarisation qui ne sont pas explorées par une seule dérivation. Nous avons donc enregistré des dérivations complémentaires (DII, V1 et V6) qui permettent d'améliorer la détection des troubles de la repolarisation (sensibilité de 25 à 64%), améliorer le diagnostic de flutter (25 à 69%) et de préciser de manière efficace la présence d'un bloc de branche droit ou gauche (respectivement 90 et 91% de sensibilité).

Le diagnostic de bradycardie est aisé mais la différence entre un bloc sino-atrial et un BAV n'est pas toujours évident, ce d'autant plus que les tracés de bradycardies ont été parfois enregistrés chez des patients symptomatiques, la qualité du tracé en étant impactée.

La reproductibilité est bonne avec des Kappa de Cohen supérieurs à 0,8 dans les deux études.

Nous avons montré dans l'article II- *Validating QT-Interval Measurement Using the Apple Watch ECG to Enable Remote Monitoring During the COVID-19 Pandemic*, la possibilité de mesurer et monitorer l'intervalle QT. La faisabilité a été estimée de 85 à 94%. Nous retrouvons une différence inter-méthodes de 25ms sur le D1. Nous nous attendions à une amélioration significative de la performance avec les dérivations latérales ou il est conseillé de mesurer le QT (30) ce qui n'a pas été retrouvé dans notre série. Cependant, l'augmentation du nombre de dérivations permet une amélioration de la faisabilité. De plus, il faut cibler les dérivations où l'amplitude de T est la plus grande, permettant une mesure plus adaptée.

Nous avons collecté plus de 1500 tracés avec divers troubles du rythme et de la conduction. Il s'agit de projets innovants car à notre connaissance aucune étude n'a été réalisée sur l'interprétation des tracés AppleWatch hors FA et RS. Himmelreich and al (3) ont réalisé une étude avec schéma similaire avec

inclusion de 214 patients. N'est réalisé qu'un seul tracé D1 par le Kardia mobile et l'expert classe en « FA ou flutter », « tout trouble du rythme » ou « tout trouble de la conduction ».

Contrairement à notre étude, l'expert fait un choix sommaire là où nous notre expert doit réaliser un diagnostic précis. De plus l'ajout de tracés complémentaires n'avait pas été évalué dans ce cadre.

La réalisation de nouvelles dérivations a été validée par Samol and al (6). L'intérêt a déjà été évoqué par Avila et al (31) dans le cadre d'un ST+ : ils nous présentent 2 cas de STEMI inférieurs bien discriminés par 3 tracés réalisés par l'Apple Watch : DI, DII et DIII.

## 2- Implications

Pour le clinicien l'intérêt de connaître les possibilités et limites des montres connectées est double :

-Premièrement, lorsqu'un patient réalise un tracé spontanément, il va pouvoir interpréter avec sérénité la fréquence cardiaque de celui-ci, diagnostiquer une tachycardie ou une bradycardie et évaluer le caractère sinusal du rythme. Il connaîtra aussi les limites inhérentes à un tracé 1 dérivation.

-Deuxièmement il pourra éventuellement se servir de cet outil dans une démarche diagnostique. L'évaluation de palpitations ou bien le monitoring du QT sont les indications privilégiées.

Dans le bilan de palpitations, les recommandations préconisent la réalisation d'un ECG per-critique (32). Actuellement, l'outil le plus utilisé est le holter ECG. Giada et al nous rappelle dans une revue de la littérature, les contraintes inhérentes au holter : temps d'enregistrement court et gêne pour les activités habituelles. ((33) Les holters-ECG dit longue durée sont souvent mal tolérés au vu de la pénibilité à porter. Les alternatives par des enregistreurs externes une piste ont déjà été étudiées.

Déjà en 1996, Kinlay et al compare le holter 48h et un enregistreur d'évènements et met en évidence une meilleure rentabilité diagnostique. (34)

En 2014, *De Asmundis et al*, compare le holter 24H à l'Omron chez des patients sans cardiopathies présentant palpitations ou lipothymies. Le holter ne va diagnostiquer que 2% des patients contre 89% avec l'Omron sur une période de 15j (35)

*Wasserlauf and al* ont récemment évalué la capacité de l'AppleWatch avec le bracelet Kardia à faire le diagnostic de FA en comparant aux données d'un dispositif implantable type REVEAL Linq. Ils mettent en évidence une excellente sensibilité de la montre. ((36))

## 3-Limites

La principale limite de l'article II- *Accuracy of a smartwatch-derived ECG to detect various electrocardiographic abnormalities* est l'hétérogénéité des troubles du rythme étudiés avec pour certains un effectif très faible (notamment pour les cardiopathies structurales et l'ischémie).

L'autre limite est la comparaison des tracés Apple Watch avec des tracés 12 dérivations sortis de leur contexte. Les experts interprétant les tracés Apple Watch et 12D ne connaissant pas le motif d'entrée et l'historique du patient.

Nous avons pu mettre en évidence différentes faiblesses limitantes aussi l'utilisation de l'Apple Watch.

- Ergonomie difficile
  - en termes de hardware d'abord avec sa petite couronne nécessaire à lancer le tracé. Celle-ci peut être difficile à maintenir.
  - En termes de software avec des menus complexes et peu intuitifs, le tout rendant son utilisation difficile chez les personnes âgées ou présentant des difficultés motrices.

- Manque de précision en termes de repolarisation avec un filtrage important de l'onde T et une faible amplitude rendant difficile les diagnostics de troubles de la repolarisation.
- Leurs utilisations est aussi restreintes par la nécessité d'une mise en route active du tracé. On passe donc à côté de toutes les possibilités de monitoring d'un patient asymptomatique.

Le plethysmographe permet en principe de corriger cela avec la surveillance de la fréquence cardiaque et l'alerte selon le profil. *Tison and al*, ont entraîné un réseau neuronal pour détecter la FA via des données de photoplethysmographie enregistrées par une AW. Ils utilisent comme population une cohorte connectée (plus de 6000participants). Ils valident une très bonne sensibilité et spécificité sur une population de patient devant subir une cardioversion (37).

Actuellement la mesure de la fréquence sert donc pour le dépistage de l'arythmie asymptomatique et le tracé ECG pour le diagnostic. L'ajout d'une électrode sur un bracelet au poignet controlatéral à celui qui porte la montre pourrait permettre un enregistrement permanent comme un holter.

#### 4-Conclusion

Nous avons montré la possibilité de réaliser avec une bonne sensibilité et spécificité les diagnostics de rythme sinusal, de tachycardie, bradycardie, FA ainsi que de reconnaître un bloc de branche. L'ajout de nouvelles dérivations améliore le diagnostic des troubles de la repolarisation mais avec une sensibilité qui reste faible. Nous avons montré aussi la possibilité de mesurer un QT avec une fiabilité correcte.

En 2018, l'AppleWatch s'est vendu à plus de 11millions d'exemplaire. L'ECG devient à la portée du grand public. La technologie pourra être encadré à des fins médicales mais sera surtout aussi utilisée par des utilisateurs non familiers avec la cardiologie. Les praticiens risquent d'être suscité pour des avis sur de nombreux tracés hors contexte symptomatique.

C'est dans ce cadre que plusieurs projets ont été créés :

- le livre *Apprendre à lire un ECG avec une montre connectée : cas cliniques basés sur des tracés Apple Watch*, qui reprend les bases électrocardiographiques de plusieurs pathologies cardiaques et leur possibilités diagnostiques sur un ECG de smartwatch.

Déjà commercialisé, il est destiné aux professionnels de la santé ou toutes personnes témoignant d'un intérêt pour la technologie ECG embarquée dans une montre connectée.

- le site *applewatchecg.com* qui comprendra prochainement une base de formation et d'entraînement à la lecture des tracés applewatch pour tout public.

-Etudes de la pertinence des tracés de smartwatch dans des contextes cliniques. Des travaux sur l'apport d'un ECG par montre connectée en pré médical dans le cadre de symptômes doivent être effectués. Nous travaillons actuellement sur la douleur thoracique tout venant au SAU et sa capacité a détecté des anomalies.

Au total, les montres connectées sont un outil d'avenir. Elles sont performantes dans la détection de troubles du rythme et de la conduction.

Pour l'instant peu utilisée par les praticiens, ces études permettent de valider leurs pertinences cliniques pratiques.



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