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# Diagnostic accuracy of a smartphone electrocardiograph in dogs: Comparison with standard 6-lead electrocardiography

T. Vezzosi [a,*], C. Buralli [a], F. Marchesotti [b], F. Porporato [b], R. Tognetti [a], E. Zini [b,c,d], O. Domenech [b]

[a] Department of Veterinary Science, University of Pisa, via Livornese lato monte, 56122 San Piero a Grado, Pisa, Italy
[b] Istituto Veterinario di Novara, Strada Provinciale 9, 28060 Granozzo con Monticello, Novara, Italy
[c] Clinic for Small Animal Internal Medicine, Vetsuisse Faculty, University of Zurich, Winterthurerstrasse 260, CH-8057, Zurich, Switzerland
[d] Department of Animal Medicine, Production and Health, University of Padova, Viale dell'Universita' 16, 35020 Legnaro, Padova, Italy

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ABSTRACT

The diagnostic accuracy of a smartphone electrocardiograph (ECG) in evaluating heart rhythm and ECG measurements was evaluated in 166 dogs. A standard 6-lead ECG was acquired for 1 min in each dog. A smartphone ECG tracing was simultaneously recorded using a single-lead bipolar ECG recorder. All ECGs were reviewed by one blinded operator, who judged if tracings were acceptable for interpretation and assigned an electrocardiographic diagnosis. Agreement between smartphone and standard ECG in the interpretation of tracings was evaluated. Sensitivity and specificity for the detection of arrhythmia were calculated for the smartphone ECG. Smartphone ECG tracings were interpretable in 162/166 (97.6%) tracings. A perfect agreement between the smartphone and standard ECG was found in detecting bradycardia, tachycardia, ectopic beats and atrioventricular blocks. A very good agreement was found in detecting sinus rhythm versus non-sinus rhythm (100% sensitivity and 97.9% specificity). The smartphone ECG provided tracings that were adequate for analysis in most dogs, with an accurate assessment of heart rate, rhythm and common arrhythmias. The smartphone ECG represents an additional tool in the diagnosis of arrhythmias in dogs, but is not a substitute for a 6-lead ECG. Arrhythmias identified by the smartphone ECG should be followed up with a standard ECG before making clinical decisions.


## Introduction

Many cardiac arrhythmias are paroxysmal, while others require frequent monitoring due to the risk of progression. In these settings, serial electrocardiographic (ECG) tracings facilitate correct diagnosis and management, and clinical electrocardiography has evolved with the development of Holter monitoring, telemetry systems and loop recorders (Kennedy, 2013).

Recently, one-lead ECGs recorded with smartphone devices using specific adaptors and software have been developed (Bruining et al., 2014; Walsh et al., 2014; Baquero et al., 2015). Studies in human patients have highlighted the accuracy of smartphone ECG tracings in measuring heart rate (HR) and in evaluating heart rhythm (Lau et al., 2013; Ho et al., 2014; Haberman et al., 2015). Other studies have demonstrated the suitability of smartphone ECG devices in diagnosing supraventricular tachycardia in children (Wackel et al., 2014; Ferdman et al., 2015; Nguyen et al., 2015), for detecting atrial fibrillation (Lau et al., 2013; Lee et al., 2013; McManus et al., 2013; Saxon, 2013; Orchard et al., 2014; Lowres et al., 2015a) and for identifying ECG changes associated with myocardial ischaemia (Wong, 2013; Muhlestein et al., 2015). Kraus et al. (2013) previously compared a smartphone ECG device to standardised ECG tracings in dogs and cats. Therefore, we sought to assess the utility and accuracy of a smartphone ECG to evaluate heart rhythm and ECG measurements in dogs.

### Materials and methods

*Animals*

The study group included client-owned dogs that were referred to the Department of Veterinary Science of the University of Pisa or the Department of Cardiology of the Istituto Veterinario di Novara for a cardiologic consultation or assessment prior to anaesthesia. The study was prospective, multicentre and single-blinded. Dogs were recruited over a 1 year period (December 2014–December 2015). Each case underwent a cardiac evaluation, including physical examination, standard 6-lead ECG and echocardiogram. The study protocol was reviewed and approved by the Institutional Welfare and Ethics Committee of the University of Pisa (approval number 39/2015; date of approval 17 December 2015).

*ECG acquisition and analysis*

A standard 6-lead ECG (Elan 1100 ECG system, Cardioline; MAC 800 ECG system, GE Healthcare) was acquired for 1 min in conscious, unsedated dogs positioned in

* Corresponding author.
*E-mail address:* tommaso.vezzosi@vet.unipi.it (T. Vezzosi).

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**Fig. 1.** Cranio-caudal orientation of the smartphone in a dog. The camera side of the smartphone was located caudally.

right lateral recumbency. Surface electrodes made of flattened alligator clips were attached to the skin at the level of the olecranon on the caudal aspect of the forelimb, and over the patellar ligaments on the cranial aspect of the hind limbs (Tilley, 1992). Rubbing alcohol was applied to maintain electrical contact with the skin. A sampling frequency of 1000 Hz for standard ECG acquisition was used, with a 100 Hz low-pass filter and a 0.3–0.5 Hz high-pass filter to decrease respiratory artefact (Hinchcliff et al., 1997).

A smartphone ECG tracing was simultaneously recorded, starting and ending at the same time as the 6-lead ECG, using a single-lead bipolar ECG (AliveCor Veterinary Heart Monitor, AliveCor) and its software interface (AliveECG Vet, AliveCor). Three operators (TV, CB, FM) recorded the smartphone ECG tracings with an iPhone 4S (Apple) by placing the recorder over the left precordial area. A cranio-caudal orientation of the smartphone case was used in each dog, with the camera side of the smartphone located caudally (Fig. 1). In short-haired dogs, a small amount of alcohol was placed on the left precordial area in order to obtain a good quality smartphone ECG signal. In long-haired dogs, a small amount of alcohol was placed after shaving the left precordial area. Smartphone ECG recordings were automatically digitised by the device, sent via e-mail and stored as a PDF file. For each dog, ECG tracings obtained with the two methods were printed at a paper speed of 50 mm/s with a gain of 10 mm/mV. The last 30 s of each ECG tracing were analysed. Dogs with a smartphone ECG trace lasting < 30 s were excluded from the study.

All ECG tracings were reviewed by a board-certified veterinary cardiologist (OD), in a blinded fashion, who judged whether the tracings were acceptable for interpretation. The same operator evaluated the rhythm and performed ECG measurements on all tracings. Electrocardiographic complexes were measured in lead II of the standard ECG and using the only available lead of the smartphone ECG.

The following variables were measured from both ECGs in each dog: mean HR (beats per min, bpm), calculated as the number of QRS complexes recorded in 30 s and multiplied by two; P wave amplitude (mV) and duration (ms); PQ interval duration (ms); R wave amplitude (mV); QRS complex duration (ms) and QRS polarity. The minute HR (beats per min, bpm) was calculated from the reference ECG as the number of QRS complexes recorded in 1 min. Other ECG variables were measured as previously described (Kittleson and Kienle, 1998). The QRS polarity of the smartphone ECG traces was compared with lead II of the standard ECG. The mean HR calculated automatically by the smartphone application (App HR) was recorded. Heart rate was classified as normal if from 70 to 160 bpm, bradycardia if < 70 bpm and tachycardia if > 160 bpm (Kittleson and Kienle, 1998).

### Statistical analysis

The analysis was performed only with paired ECG tracings that were considered to be acceptable for interpretation, as defined by the operator, and the standard ECG was set as the reference method. Cohen's κ test was used to calculate the agreement between the smartphone ECG and standard ECG for HR classification (normal, bradycardia, tachycardia), heart rhythm (sinus rhythm, atrial fibrillation, ventricular rhythm, supraventricular rhythm), atrioventricular blocks (absent, first-degree, second-degree, third-degree), premature complexes (absent, ventricular, supraventricular), polarity of QRS complex (positive, negative). The κ coefficient was interpreted as follows: values ≤ 0.20 as no agreement, 0.21–0.40 as fair, 0.41–0.60 as moderate, 0.61–0.80 as good, 0.81–0.99 as very good and 1 as perfect agreement. The sensitivity, specificity, and positive and negative predictive values of the smartphone ECG to detect arrhythmia were calculated. Additionally, the median and range of differences between the standard ECG and smartphone ECG were calculated for HR, amplitude of the P and R waves, duration of the P wave, PQ interval and QRS complex. Limits of agreement plots were created to show the differences between smartphone and standard ECG for numerical data. Statistical analysis was performed with commercial software (GraphPad Prism 5). $P < 0.05$ was considered to be significant.

## Results

### Animals and feasibility

The study included 166 dogs (84 males and 82 females). The median age was 9 years (range 0.3–17 years) and the median body weight was 25 kg (range 2.1–75 kg). Cardiac disease (congenital or acquired) was present in 71/166 (43%) dogs; 32/166 (19%) had neoplasia, 30/166 (18%) were in the intensive care unit because of renal, respiratory, gastro-intestinal or neurological diseases, and 33/166 (20%) were healthy dogs evaluated during pre-anaesthesia assessment prior to elective surgeries.

The blinded cardiologist (OD) judged 162/166 (97.6%) of the smartphone ECG tracings to be acceptable for interpretation (Figs. 2–4). In 4/166 (2.4%) cases, all from dogs weighing <10 kg, the tracings were judged to be non-interpretable.

### Heart rate

According to the standard 6-lead ECG, 133/162 (82%) dogs had a normal HR, 20/162 (12%) had tachycardia and 9/162 (6%) had bradycardia. A perfect agreement (κ = 1) between the smartphone and standard ECG was found in the classification of HR when it was manually measured on digitised tracings (Table 1). The median paired difference between the HR measured manually on standard ECG and smartphone ECG was 0 bpm (–10, +20 bpm; Table 2 and Fig. 5).

The App HR was less accurate than the manually measured HR on digitised standard ECG tracings (κ = 0.91). In 103/162 (63.6%) cases, the App HR underestimated the actual HR, with a median difference of –3 bpm; (range –31 to +20 bpm; Fig. 6). HR was misclassified with the smartphone application in 4/162 (2.5%) cases. According to App HR, two dogs with tachycardia were classified as having a normal HR, one dog with a normal HR was classified as bradycardic and one dog with bradycardia was classified as having a normal HR. The greatest disagreement was found in a dog with

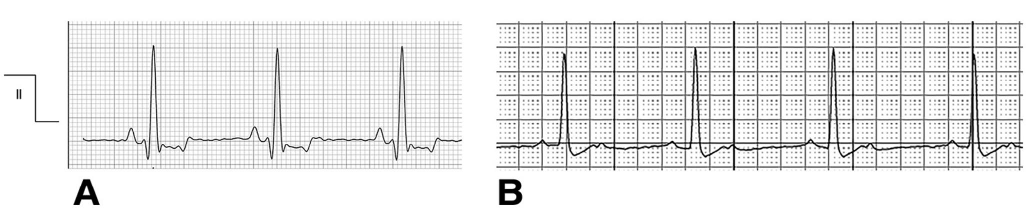


**Fig. 2.** Sinus rhythm with standard ECG (A) and with smartphone ECG (B) in the same dog. Paper speed = 50 mm/s; 10 mm = 1 mV.


**Fig. 3.** Atrial fibrillation with standard ECG (A) and with smartphone ECG (B) in the same dog. Paper speed = 50 mm/s; 10 mm = 1 mV.


**Fig. 4.** Third-degree atrioventricular block with standard ECG (A) and with smartphone ECG (B) in the same dog. Paper speed = 50 mm/s; 5 mm = 1 mV.

severe bradycardia (40 bpm) because of a third-degree atrioventricular block, in which the App HR interpreted the P waves as QRS complexes, thus erroneously calculating a HR of 140 bpm.

*Heart rhythm*

The majority of dogs (141/162, 87%) had sinus rhythm or sinus arrhythmia; 14/162 (9%) dogs had supraventricular arrhythmias and 7/162 (4%) dogs had ventricular rhythm or ventricular arrhythmias; 6/162 (4%) dogs had different types of atrioventricular blocks. Very good agreement (κ = 0.94) was found in the evaluation of the heart rhythm. Disagreement was found in 3/162 (1.9%) cases, in which the sinus rhythm was erroneously classified on the smartphone ECG tracing as a supraventricular arrhythmia due to the negative polarity of the P waves (one case), or as a slow atrial fibrillation due to non-observable P waves (two cases; Table 3). In

**Table 1**
Agreement (κ) between smartphone ECG and standard 6-lead ECG.

| Type of analysis | κ | 95% CI | Agreement |
|---|---|---|---|
| Manual HR | 1 | | Perfect |
| App HR | 0.91 | 0.81–0.99 | Very good |
| Heart rhythm | 0.94 | 0.86–1 | Very good |
| AVBs | 1 | | Perfect |
| Ectopic beats | 1 | | Perfect |
| QRS polarity | 0.65 | 0.34–0.97 | Good |

CI, confidence interval; Manual HR, heart rate manually measured on printed ECG tracings; App HR, HR automatically measured by smartphone application; AVBs, atrioventricular blocks.

**Table 2**
Differences between smartphone ECG and standard ECG in the evaluation of electrocardiographic parameters.

| Parameter | Difference | Range |
|---|---|---|
| Manual HR (bpm) | 0 | –10 to +20 |
| App HR (bpm) | –3 | –31 to +20 |
| P (ms) | 0 | –20 to +0 |
| P (mV) | –0,1 | –0,4 to +0,1 |
| PQ (ms) | 0 | –20 to +20 |
| QRS (ms) | 0 | –20 to +10 |
| R (mV) | –0,5 | –2,1 to +1 |

Median difference and range are reported.
CI, confidence interval; Manual HR, heart rate manually measured on printed ECG tracings; App HR, HR automatically measured by smartphone application; AVBs, atrioventricular blocks.

128/141 (90.7%) cases of sinus rhythm, the smartphone ECG underestimated the amplitude of the P wave, with a median difference of –0.1 mV (range –0.4 to +0.1 mV). The analysis of the P wave duration showed a median difference between the two methods of 0 ms (range –20 to +0 ms). Overall, the smartphone ECG had 100%

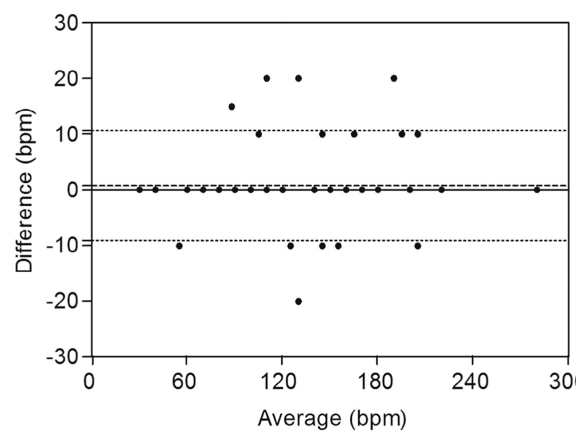


**Fig. 5.** Limits of agreement (Bland–Altman) plot showing differences between heart rate (HR) values manually measured on standard ECG and smartphone ECG tracings.

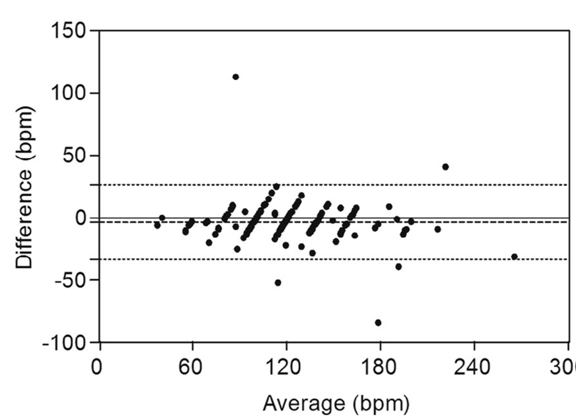


**Fig. 6.** Limits of agreement (Bland–Altman) plot showing differences between heart rate (HR) values manually measured on standard ECGs and HR values produced by the smartphone application.

**Table 3**
Agreement between smartphone ECG and standard 6-lead ECG in heart rhythm identification in 162 dogs.

| Standard ECG | Smartphone ECG | | | | Total |
|---|---|---|---|---|---|
| | S | AF | SV | V | |
| S | 138 | 2 | 1 | 0 | 141 |
| AF | 0 | 12 | 0 | 0 | 12 |
| SV | 0 | 0 | 2 | 0 | 2 |
| V | 0 | 0 | 0 | 7 | 7 |
| Total | 138 | 14 | 3 | 7 | 162 |

AF, atrial fibrillation; S, sinus rhythm; SV, supraventricular rhythm; V, ventricular rhythm.

sensitivity and 97.9% specificity in differentiating between sinus rhythm and non-sinus rhythm, with a positive predictive value of 87.5% and a negative predictive value of 100%.

*QRS complex analysis*

A good agreement ($\kappa = 0.65$) was found in the polarity of the QRS complexes between the smartphone ECG and lead II of the standard 6-lead ECG (Figs. 2–4). Identical QRS polarity was found in 158/162 (97.5%) cases. In three cases with positive polarity of the QRS complex in lead II, the smartphone ECG tracing showed a negative QRS. In one case with negative polarity of the QRS complex in lead II, the smartphone ECG tracing showed a positive QRS. The evaluation of the QRS duration showed a median difference of 0 ms (range –20 to +10 ms). The smartphone ECG underestimated the amplitude of R wave in 121/162 (74.7%) dogs, with a median difference of –0.5 mV (range –2.1 to +1 mV), compared to the standard ECG.

*Ectopic beats*

Perfect agreement ($\kappa = 1$) between the smartphone ECG and standard ECG was found in the identification and classification of ectopic beats, including 16 cases with ventricular premature complexes, three cases with supraventricular premature complexes and four cases with both supraventricular and ventricular ectopic beats. Perfect agreement was found in identification of the polarity of ventricular premature complexes on the smartphone ECG tracings compared with lead II of the standard 6-lead ECG.

*Atrioventricular blocks*

Perfect agreement ($\kappa = 1$) between the smartphone ECG and standard ECG was found in the diagnosis of atrioventricular blocks, including two cases with first-degree, one with second-degree and three cases with third-degree atrioventricular block. The PQ intervals measured on smartphone ECG tracings agreed with those measured on the standard ECG, with a median difference of 0 ms (range –20 to +20 ms).

## Discussion

In our investigation, the smartphone ECG could be used easily in all dogs and 96.7% of tracings were deemed to be interpretable. These results are in line with findings in human patients, where smartphone ECG tracings were interpretable in 87–99% of patients (Saxon, 2013; Nguyen et al., 2015; Tarakji et al., 2015). The few tracings judged as non-interpretable were all recorded in small breed dogs, where motion artefacts are common, which is likely to have accounted for the poor tracing quality.

In our study, the smartphone ECG was excellent in measuring HR in dogs, similar to the findings of the study of Kraus et al. (2013), in which perfect agreement was found between smartphone and reference ECGs in the evaluation of instantaneous and mean HR. We observed the greatest accuracy when the HR was manually measured on digitised tracings. However, the App HR proved less accurate than manual measurement, with poorer agreement between the mean HR obtained by the smartphone device and that measured from the standard ECG. Since the QRS complexes on smartphone ECG tracings had low amplitudes in most dogs, we hypothesise that the App HR underestimated the HR because some QRS complexes are not correctly interpreted by the software. In a few dogs, the App HR was totally unreliable. However, in only one case was the disagreement of clinical relevance; this was in a dog with severe bradycardia secondary to third-degree atrioventricular block, in which the App HR identified the P waves as QRS complexes, erroneously reporting a normal HR.

The smartphone ECG was very accurate in evaluating heart rhythm in dogs, with 100% sensitivity and 97.9% specificity in the detection of arrhythmias. All cases of atrial fibrillation were correctly identified. This is similar to findings in human beings, where the sensitivity and specificity of the smartphone ECG in detecting atrial fibrillation were 94–100% and 90–97%, respectively (Lau et al., 2013; Haberman et al., 2015; Tarakji et al., 2015). In human beings, most false diagnoses of atrial fibrillation are due to small voltage P waves. Our results showed that the smartphone ECG underestimates the amplitude of the P wave. Despite this, the P waves remained clearly visible in the majority of dogs with sinus rhythm. However, in a few cases the P waves were difficult to recognise and it was hard to differentiate between a sinus arrhythmia and atrial fibrillation. Consequently, 2/141 (0.14%) cases of sinus rhythm were incorrectly classified as atrial fibrillation. In one small breed dog, the negative polarity of the P waves on the smartphone ECG lead to an incorrect diagnosis of a supraventricular arrhythmia. A preliminary study in cats recommended positioning the smartphone case parallel to the long axis of the heart, with a more base-apex orientation in comparison to the cranio-caudal orientation of human beings (Stromberg and Kvart, 2015). In some small breed dogs, the orientation of the smartphone case may have to be individually adjusted to correctly visualise the P waves.

Atrial fibrillation is common in dogs with severe cardiac disease and increases the risk of cardiac-related death in those with myxomatous mitral valve degeneration and dilated cardiomyopathy (Calvert et al., 1997; Jung et al., 2016). Likewise, in human beings, atrial fibrillation increases the chance of morbidity or mortality, and recent studies have highlighted the utility of the smartphone ECG in screening for this arrhythmia (Lau et al., 2013; Lee et al., 2013; McManus et al., 2013; Saxon, 2013; Orchard et al., 2014; Haberman et al., 2015; Lowres et al., 2015b; Peritz et al., 2015). Early diagnosis of atrial fibrillation is difficult in dogs. Our results show that the smartphone ECG could become a tool for frequent at-home monitoring of dogs predisposed to atrial fibrillation. It could also be of benefit for dogs with atrial fibrillation that receive drugs to control HR. Holter monitoring is an essential tool for evaluating HR and in treating atrial fibrillation in dogs. However, 24 h Holter monitoring is expensive and necessitates owner compliance; hence, its use may not always be practical. In the light of its ease and cost effectiveness, the smartphone ECG could represent a complementary tool for HR evaluation at home in dogs with atrial fibrillation.

The smartphone ECG showed good agreement in the analysis of the QRS complex, in assessing both duration and polarity. In most dogs, QRS complexes displayed the same polarity on smartphone tracings and lead II of the 6-lead ECG, with a similar polarity in all cases of ventricular ectopic beats. However, in comparison with the standard ECG, the smartphone device underestimated the R wave amplitude. Further studies are needed to establish reference values of wave amplitudes using the smartphone ECG. In our opinion, smartphone tracings should not be used to assess the amplitude of ECG waves as a substitute for standard electrocardiograms or as a diagnostic method for detection of chamber enlargement.

The smartphone ECG was highly accurate in the identification of ectopic beats. Ventricular premature complexes, accelerated idioventricular rhythms and ventricular tachycardias were easily identified in all cases with the smartphone ECG. One recent investigation used it as the sole electrocardiographic method in the identification of ventricular premature complexes in the screening of Doberman pinschers for occult dilated cardiomyopathy (Gordon et al., 2015). Our findings suggest that the smartphone ECG might be useful in screening or monitoring dogs with cardiomyopathies associated with ventricular arrhythmias.

Regarding the reliability of the smartphone ECG for atrioventricular blocks, we found good agreement with the standard ECG both in the evaluation of the PQ interval and in the identification of the type of atrioventricular block. One study in human beings described a higher percentage of false positives and negatives during the evaluation of atrioventricular blocks than we observed in dogs (Haberman et al., 2015). The authors reported motion artefacts (arm movement, muscle tension and tremor) as the main difficulties in atrioventricular block evaluation. None of the smartphone ECG tracings in our study recorded motion artefacts that led to misdiagnosis of atrioventricular blocks. Thus, the agreement between devices was perfect, suggesting that the smartphone ECG can be helpful in the diagnosis of atrioventricular blocks in dogs.

Our investigation has some limitations. The study group was large, but the number of dogs with arrhythmias was relatively small. A larger number of rhythm disturbances might have revealed a lower reliability of the smartphone ECG. However, most common types of canine arrhythmias were included in our study and, in all of these cases, the smartphone ECG tracing permitted a diagnosis of the arrhythmia. In addition, the smartphone tracings were acquired by three operators, but inter-operator variability in the quality of ECG recording was not evaluated.

## Conclusions

The smartphone ECG can rapidly and simply record a single-lead ECG of good diagnostic quality in dogs. Tracing analysis performed by cardiologists reliably evaluated HR, heart rhythm, atrioventricular blocks and ectopic beats. The smartphone device is not a substitute for 6-lead ECG or Holter monitoring, but does represent an additional tool in the management of dogs with arrhythmias or in monitoring dogs at risk for heart rhythm disturbances. Therefore, any arrhythmia identified by the smartphone device should be followed by a standard 6-lead ECG and treatment decisions based upon smartphone ECG only are not recommended. Further studies are needed to assess the diagnostic value of the smartphone ECG recorded by owners in a home setting.

## Conflict of interest statement

None of the authors of this paper have a financial or personal relationship with other people or organisations that could inappropriately influence or bias the content of the paper.

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