Original Article

Reliability of a smartphone electrocardiogram device in dogs: comparison with standard 6-lead electrocardiography

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Abstract

A prospective, multicenter, single-blind study was conducted in 166 dogs to assess the reliability of a smartphone electrocardiogram (ECG) device in evaluating heart rhythm and ECG measurements. 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 with 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, with a 100% sensitivity and 97.9% specificity. The smartphone ECG provides tracings that are adequate for analysis in most dogs with a reliable assessment of heart rate, heart rhythm, atrioventricular blocks or ectopic beats. The smartphone device represents an additional tool in the management of dogs with arrhythmias, but does not substitute a 6-lead ECG. Arrhythmias identified by the smartphone device should be followed up with a standard ECG before taking clinical decisions.

Keywords: Alivecor; Canine; Electrocardiography; iPhone; Mobile

Introduction

Many arrhythmias have paroxysmal presentation, while others require frequent monitoring due to the risk of progression. In these settings, serial electrocardiograms (ECG) are crucial for correct diagnosis and management. Clinical electrocardiography has thus undergone a continuous technological evolution since its invention by Willem Einthoven in 1903, leading to the development of Holter monitoring, telemetry systems and loop recorders (Kennedy, 2013).

One of the latest innovations is the 1-lead ECG recorded by smartphone devices using specific applications (Bruining et al., 2014; Walsh et al., 2014; Baquero et al., 2015). In human medicine there are many studies highlighting the accuracy of smartphone ECG tracings to measure the heart rate (HR) and evaluate heart rhythm (Lau et al.,2013; Ho et al., 2014; Haberman et al., 2015). Other studies have shown the good performances of smartphone ECG devices for diagnosing supraventricular tachycardia in pediatrics (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 signs associated with myocardial ischemia (Wong, 2013). To the best of our knowledge only one preliminary study has been performed comparing a smartphone ECG device to standardized ECG tracings in dogs (Kraus et al., 2013). The aim of the present study was therefore to assess the use and reliability 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 anesthesia. The study was prospective, multicenter and single-blind. Dogs were recruited over a one-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 (permission number 39/2015).

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 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 hindlimbs, as previously described (Tilley, 1992). Rubbing alcohol was applied to maintain electrical contact with the skin. A sampling frequency of 1000Hz for standard ECG acquisition was used, with a 100 Hz low-pass filter and a 0.5 Hz high-pass filter to decrease respiratory artifact, as previously published (Hinchcliff, et al. 1997).

A smartphone ECG tracing was simultaneously recorded, starting and ending at the same time of the 6-lead ECG, using a single-lead bipolar ECG recorder (AliveCor Veterinary Heart Monitor, AliveCor, Inc.) and its application (AliveECG Vet, AliveCor, Inc.). Three operators (TV, CB, FM) recorded the smartphone ECGs with an iPhone 4S (Apple Inc.). The smartphone ECG was recorded placing it on the left precordial area of all the dogs. 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 the 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 the long-haired dogs, a small amount of alcohol was placed after shaving the left precordial area in order to acquire the same high-quality signal. Smartphone ECG recordings were automatically digitized by the device, sent via email 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 analyzed. 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. For all ECG tracings, the same operator evaluated the rhythm and performed ECG measurements. Measurements were achieved using the lead II of the standard ECG and using the only available lead of the smartphone ECG.

In each case, the following measurements were performed: mean HR (beats per min, bpm); P wave amplitude (mV) and duration (ms); PQ interval duration (ms); R wave amplitude (mV); QRS complex duration (ms) and QRS polarity. The mean HR was calculated as the number of QRS complexes recorded in the 1 min ECG tracings (bpm). Other measurements were achieved as previously described (Kittleson and Kienle, 1998). The QRS polarity of the smartphone ECG traces was compared with lead II of the standard ECG. Finally, the mean HR calculated automatically by the smartphone application (App HR) was noted. Heart rate was classified as normal if between 70 and 160 bpm, bradycardia if < 70 bpm and tachycardia if > 160 bpm, as previously described (Kittleson and Kienle, 1998).

Statistical analysis

The analysis was performed only with paired ECG tracings that were considered acceptable for interpretation, as defined by the operator, and the standard ECG was set as the reference method. Cohen's kappa (κ) test was used to calculate the agreement between the smartphone ECG and standard ECG for HR classification (normal, bradycardia or tachycardia), heart rhythm (sinus rhythm, atrial fibrillation, ventricular rhythm, supraventricular rhythm), atrioventricular blocks (AVB) (absent, first-degree AVB, second-degree AVB, third-degree AVB), premature complexes (absent, ventricular, supraventricular), polarity of QRS complex (positive, negative). The kappa 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, positive and negative predictive values of the smartphone ECG to detect arrhythmia were calculated. In addition, the median and range of differences between the standard ECG and smartphone ECG were calculated for HR, amplitude of the P and R waves, for the duration of the P wave, PQ interval, QRS complex. Bland-Altman plots were used to show the differences between smartphone and standard ECG for numerical data. The Pearson or Spearman correlation coefficients were used to study correlations between HRs measured with the standard ECG and the smartphone ECG using values calculated either by the operator or automatically. The Shapiro-Wilk test was used to determine the normality of the datasets..

Statistical analysis was performed with a commercial software (GraphPad Prism 5). $P < 0.05$ was considered as significant.

Results

Animals and feasibility

A total of 166 dogs were enrolled in the study, of which 84 were males and 82 were females. The median age was nine years (ranging between 0.3 to 17 years) and median body weight was 25 kg (55.1 lb) with a range of 2.1 to 75 kg (4.6 to 165.3 lb). The majority of dogs (71/166, 43%) had cardiac diseases, both congenital or acquired; 32/166 (19%) dogs had neoplastic diseases, 30/166 (18%) were in the intensive care unit because of renal, respiratory, gastro-intestinal or neurologic diseases, and 33/166 (20%) were healthy dogs evaluated for pre-anesthesia assessment prior to elective surgeries.

The blinded operator judged 162/166 (97.6%) of the smartphone ECG tracings as acceptable for interpretation (Fig. 2, 3 and 4). In 4/166 (2.4%) cases the traces were deemed as non-interpretable; all 4 of the traces deemed uninterpretable were obtained from patients weighing <10kgs.

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 digitized tracings (Table 1). A strong positive correlation was found between the HR values manually measured on standard ECGs and smartphone ECG tracings ($r^2 = 0.99$; $P < 0.0001$; Fig. 5). Median paired differences between the HR manually measured on standard ECG and smartphone ECG was 0 bpm (-10, +20 bpm; Table 2 and Fig. 6).

A strong positive correlation was also found between the App HR values and those manually measured on standard ECG tracings ($r^2 = 0.923$; $P < 0.0001$; Fig. 7). However, the App HR was less accurate than the manually measured HR on digitized 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; (-31, +20 bpm; Fig. 8). However in only 4/162 (2.5%) cases, was there a misclassification of HR with the smartphone application. According to App HR, two dogs with tachycardia were classified as normal HR, one dog with normal HR was classified as bradycardia, and one dog with bradycardia was classified as normal HR. The greatest disagreement was found in a dog with severe bradycardia (40 bpm) secondary to a third-degree AVB in which the App HR read the P waves as QRS complexes, thus erroneously yielding an 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; 7/162 (4%) dogs had ventricular rhythm or ventricular arrhythmias; 6/162 (4%) dogs had different types of AVBs.

Very good agreement (κ=0.94) was found in the evaluation of the heart rhythm. Disagreement was found in only 3/162 (1.9%) cases, in which the sinus rhythm was erroneously classified as atrial rhythm 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) on the smartphone ECG trace (Table 3). In 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 (-0.4; +0.1 mV). The analysis of the P wave duration showed a median difference between the two methods of 0 ms (-20, +0 ms).

Considering all the arrhythmias taken together, the smartphone ECG had 100% sensitivity and 97.9% specificity in differentiating between sinus rhythm versus non sinus rhythm, with a positive predictive value of 87.5%, and a negative predictive value of 100%.

QRS complex analysis

A good agreement (κ=0.65) was found in the polarity of the QRS complexes between the smartphone ECG and lead II of the standard 6-lead ECG (Fig. 2, 3, 4). The same 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 tracing showed a negative QRS. In one case with negative polarity of the QRS complex in lead II, the smartphone tracing showed a positive QRS. The evaluation of the QRS duration showed a median difference of 0 ms (-20, +10 ms). Lastly, the smartphone ECG underestimated the amplitude of R wave in 121/162 (74.7%), with a median difference of -0.5 mV (-2.1; +1 mV), compared to the standard ECG.

Ectopic beats

A perfect agreement (κ=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. In addition a perfect agreement was found regarding the polarity of ventricular premature complexes on the smartphone ECG tracings compared with lead II of the standard 6-lead ECG.

Atrioventricular blocks

A perfect agreement (κ=1) between the smartphone ECG and standard ECG was found in the AVB diagnosis, including two cases with first-degree AVB, one with second-degree AVB and three cases with third-degree AVB. The PQ interval analysis using smartphone tracings was reliable in comparison to the standard ECG, with a median difference of 0 ms (range -20, +20 ms).

Discussion

In our investigation the smartphone ECG was easily performed in all dogs and 96.7% of tracings were deemed as interpretable. These results are in line with findings in human medicine 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 artifacts are common, which likely accounted for the fact that the tracings were not readable.

In our study, the smartphone ECG was excellent in the HR evaluation in dogs. This is in accordance with a preliminary study in dogs, where a good agreement was found between smartphone ECG and reference ECG in the evaluation of instantaneous and mean HR (Kraus et al., 2013). In our investigation, the greatest reliability was found when the HR was manually measured on digitized tracings. Conversely the App HR was less reliable, since lower agreement was found between the HR values obtained by the smartphone device and the standard ECG. As the QRS complexes on smartphone ECG tracings had a low amplitude in most dogs, we hypothesize that the App HR may underestimate the HR due to the fact that some QRS complexes are not correctly interpreted by the instrument. In a few dogs, the App HR was totally unreliable. However, in only one case the disagreement was of a real clinical value: in a dog with severe bradycardia secondary to third-degree AVB, the App HR read the P waves as QRS complexes, thus erroneously resulting in a normal HR.

The smartphone ECG was very reliable in evaluating heart rhythm in dogs, as it showed 100% sensitivity and 97.9% specificity in the detection of arrhythmias. All cases of atrial fibrillation were correctly diagnosed, without false negatives. This result is similar to findings in humans 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 humans, 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. In a few cases, however, the P waves were difficult to recognize and it was hard to determine between a sinus arrhythmia and atrial fibrillation. Consequently, two out of 141 cases of sinus rhythm were incorrectly classified as atrial fibrillation. In a small breed dog, the P waves had negative polarity on the smartphone ECG leading to the incorrect diagnosis of an atrial ectopic rhythm. 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 our cranio-caudal orientation (Stromberg and Kvart, 2015). It might be that in some small breed dogs, the orientation of the smartphone case should be individually adjusted to correctly visualize 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 humans, 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; Lowres et al., 2015b Haberman et al., 2015; Peritz et al. 2015;). Early diagnosis of atrial fibrillation is difficult in dogs. Our results show that the smartphone ECG may become a promising tool for frequent monitoring of dogs predisposed to atrial fibrillation. It could also be beneficial 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-hour Holter monitoring is expensive and necessitates the owner's 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 a good reliability 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. In comparison to the standard ECG however, the smartphone device underestimated the R wave amplitude. In fact, wave amplitudes are extremely dependent on the electrocardiographic derivation method. Further studies are needed to establish reference values of wave amplitudes on smartphone ECG tracings.

In our opinion, smartphone tracings should not be used to assess the amplitude of ECG waves as a substitute for standard electrocardiograms and as a diagnostic method in the detection of chamber enlargement.

The smartphone ECG was highly reliable 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). It could thus be useful in screening or monitoring dogs with cardiomyopathies associated with ventricular arrhythmias.

With regard to the reliability of the smartphone ECG for AVBs, a good agreement with the standard ECG was found both in the evaluation of the PQ interval and in the identification of the type of block. One study in humans described a higher percentage of false positives and negatives during the evaluation of AVBs compared to our results (Haberman et al., 2015). The authors reported motion artifacts (arm movement, muscle tension and tremor) as the main difficulties in AVB evaluation. None of the smartphone ECG tracings recorded motion artifacts that led to misdiagnosing AVBs. Thus, the agreement between devices was perfect, suggesting that the smartphone ECG can be helpful in the interpretation of AVBs in dogs.

Our investigation has some limitations. First, the study group was large but the number of dogs with arrhythmias was relatively low. 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 these cases the smartphone ECG was consistent in diagnosing the arrhythmia. Second, the smartphone tracings were acquired by three operators but inter-operator variability in the quality of ECG recording was not evaluated.

Conclusion

In conclusion, 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, AVBs and ectopic beats.

The smartphone device does not substitute the 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 has any financial or personal relationships that could inappropriately influence or bias the content of the paper.

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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 to 0.97)	Good

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

Table 2

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

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

Median difference and range are reported.

App HR, heart rate automatically measured by smartphone application; Manual HR, heart rate manually measured on printed ECG tracings.

Table 3

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

	Smartphone ECG				
Standard ECG	**S**	**AF**	**SV**	**V**	**Total**
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.

Figure legends

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

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 AVB with standard ECG (A) and with smartphone ECG (B) in the same dog. Paper speed = 50 mm/s; 5 mm = 1 mV.

Fig. 5. Pearson test showing a strong positive correlation between the HR values manually measured on standard ECGs and smartphone ECG tracings ($r^2 = 0.99$; $P < 0.0001$).

Fig. 6. Bland-Altman plot showing differences between HR values manually measured on standard ECG and smartphone ECG tracings.

Fig. 7. Pearson test showing a strong positive correlation between the HR values manually measured on standard ECGs and HR values produced by the smartphone application ($r^2 = 0.92$; $P < 0.0001$).

Fig. 8. Bland-Altman plot showing diffences between the HR values manually measured on standard ECGs and HR values produced by the smartphone application.