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ORIGINAL RESEARCH

Evaluating the accuracy of a six-lead smartphone-based electrocardiographic device compared with standard electrocardiography in brachymorphic dogs

Giovanni Romito[1] | **Prisca Castagna**[2] | **Maria Chiara Sabetti**[3] | **Michela Ablondi**[3] | **Mario Cipone**[1]

[1]Department of Veterinary Medical Sciences, Alma Mater Studiorum—University of Bologna, Ozzano dell'Emilia, Italy

[2]Freelance Veterinary Cardiologist, Bologna, Italy

[3]Department of Veterinary Sciences, University of Parma, Parma, Italy

Correspondence
Giovanni Romito, Department of Veterinary Medical Sciences, Alma Mater Studiorum—University of Bologna, Ozzano dell'Emilia, Italy.
Email: giovanni.romito2@unibo.it

Abstract

Background: No previous study has evaluated the accuracy of a six-lead smartphone-based electrocardiographic (s-ECG) device in dogs.

Methods: This was a prospective multicentre study. Patients referred for cardiologic consultation were selected. In each patient, a 30-second electrocardiogram was simultaneously acquired with a novel six-lead s-ECG and a standard six-lead ECG machine (st-ECG). A board-certified cardiologist evaluated each recording. Nineteen ECG variables, including heart rate and rhythm, as well as quantitative and qualitative features of waves, segments and intervals, were analysed. Agreement between s-ECG and st-ECG was evaluated using Cohen's kappa coefficient and the Bland–Altman test.

Results: Seventy-five dogs were enrolled, and 140 ECG tracings were analysed. There was perfect agreement between the two methodologies for heart rate and rhythm classification, both in dogs with sinus rhythm and those with pathological rhythms. Although some disagreement was found when comparing measurements of quantitative variables obtained with the s-ECG and the st-ECG, none of the differences was of clinical relevance.

Limitations: The sample size was limited, and the interobserver variability was not analysed.

Conclusion: The six-lead s-ECG studied herein is comparable to the st-ECG for heart rate and rhythm assessment, and seems clinically acceptable for the interpretation of waves, segments and intervals in dogs.

KEYWORDS
arrhythmias, brachymorphic dogs, electrocardiogram, mean ventricular axis, somatotype, ventricular repolarisation

INTRODUCTION

The invention of the electrocardiograph (ECG) at the beginning of the last century represented a major medical advance.[1] Since then, this diagnostic method has been used with increasing frequency, becoming an important aid in modern human and veterinary cardiology.[1,2] A variety of ECG technologies have emerged over recent years to speed-up rhythm analysis and simplify interpretation of cardiac waves, segments and intervals.[3] Among the most recent ones are the smartphone-based ECG devices (s-ECGs). An advantage offered by these devices is their greater manageability compared to standard ECG machines (st-ECGs), as the former are extremely small in size and use batteries, whereas the latter are more cumbersome and usually need a continuous power supply. Additionally, not all veterinary centres have a st-ECG, whereas many people currently have a smartphone[4–7] and many veterinarians are positively predisposed to the use of modern technology, including mobile applications, in the medical field.[8–10] Finally, the digital tracings recorded by s-ECGs can be instantly shared with veterinary centres located in different cities, regions or countries for an immediate second opinion. This facilitates a rapid consultation between colleagues,[10] which, in turn, may contribute to reducing the risk of ECG misinterpretation.

Accordingly, it is not surprising that, in recent years, several studies on the feasibility and clinical utility of s-ECGs have been published in human medicine.[11–21] Conversely, to date, only three studies on this topic can be found in the canine medical literature.[22–24] It should also be noted that, in all these studies, a single-lead s-ECG was employed. Moreover, two out of three investigations simply focused on evaluating the heart rate (HR)/heart rhythm rather than assessing specific ECG measurements.[22,24] Additionally, in the only study comparing measurements obtained using the s-ECG with those obtained using the st-ECG, regrettably, only a few ECG parameters were analysed.[23] Lastly, it is interesting to note that none of these studies provided information on the breeds of the enrolled dogs.[22–24] In the authors' opinion, these shortcomings limit our current perception of the actual diagnostic utility of the s-ECGs in the clinical setting for several reasons. First, a single-lead device does not allow assessment of the mean electrical axis (MEA), which represents a key step during ECG analysis and for the precise diagnosis of conduction disturbances such as bundle branch blocks.[25] Second, the simple distinction between sinus rhythm and pathological rhythms is not enough for an adequate ECG evaluation, as it is equally important to carry out an accurate measurement of all the deflections, segments and intervals that compose an ECG tracing.[25] Third, the lack of data on breed makes it impossible to know whether the accuracy of smartphone-based devices is affected by the dog's somatotype. Indeed, dogs with extreme phenotypes, such as brachymorphic ones, may represent a diagnostic challenge during ECG recording and analysis and may show ECG peculiarities on tracings recorded by st-ECGs.[26]

Given the above, it seems important to further expand the current knowledge on the utility of s-ECGs in dogs, including those with particular chest conformations. With this aim, we sought to compare a large number of ECG variables obtained using a six-lead s-ECG with those obtained using a six-lead st-ECG in a selected population of dogs referred for cardiologic consultation. We hypothesised that the ECG findings obtained with this s-ECG device may be similar to those obtained with the st-ECG.

MATERIALS AND METHODS

Study population

This study was prospective and multicentre. The study group included client-owned French Bulldogs (FBs) and English Bulldogs (EBs) that were referred to the authors' institutions for a cardiologic consultation. These breeds were purposefully selected for three reasons. First, they represent two of the most popular brachymorphic canine breeds,[26–29] which intrinsically increases the potential clinical utility of our research. Second, they allowed investigation of the possible effect of somatotype on the ECG findings recorded by the different ECG devices by evaluating both small-sized and medium-sized brachymorphic dogs (i.e., FBs and EBs, respectively).[30] Third, they allowed testing of the feasibility and accuracy of s-ECG in one of the most challenging settings in canine medicine, as cardiologic tests are notoriously difficult in these breeds due to the relatively limited patient compliance (often influenced by the sensation of suffocation when some FBs and EBs are held in lateral recumbency due to brachycephalic obstructive airway syndrome) and the particular chest conformation.[31,32] Reasons for ECG analysis could include preoperative evaluation before surgeries or cardiologic screening in breeds known to be predisposed to heart diseases (e.g., pulmonic stenosis and arrhythmogenic cardiomyopathy in FBs[33] and EBs,[34] respectively). To be included, dogs had to be at least 1 year old and have a complete case record, including signalment, history, clinical findings and cardiac investigation. The latter had to include at least a transthoracic ECG performed according to the standard technique[35] and a 30-second six-lead ECG performed with a s-ECG device (technical details below). As all dogs were presented for cardiologic screening, no additional stress was imposed on the animals to obtain the data used in this study. Therefore, no institutional animal use approval was sought. Nevertheless, all owners were exhaustively informed about the nature of the research project and signed an informed consent form.

ECG recording

In all dogs, an ECG was conducted with the dogs positioned and manually restrained in right lateral recumbency, with the front legs placed parallel to each other and perpendicular to the long axis of the body and the hindlimbs in a neutral semi-flexed position.[25] The animals were not sedated and were allowed time to acclimatise so that the ECG could be taken from relaxed dogs. The ECG was simultaneously recorded with two different devices, namely, a commercially available st-ECG (Cube ECG, Cardioline, Caverano, Italy) and a portable six-lead s-ECG (eKuore 6 leads ECG, Chip Ideas Electronics, Valencia, Spain). The latter device consisted of a small recording body connected to ECG leads, able to record tracings and transmit wireless tracings instantaneously to a smartphone in order to carry out the ECG analysis-using a specific app (eKuore Vet). In the case of the st-ECG, four leads (i.e., the red, the yellow, the black and the green one) were attached to the skin by atraumatic flattened metallic alligator clips 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. According to the European reference system, the red negative electrode was placed on the right forelimb, the yellow positive electrode on

FIGURE 1 Electrocardiographic (ECG) recording in a French Bulldog using the six-lead smartphone-based ECG device. Although the smartphone is usually held by the vet during the ECG, in this case, it was gently placed on the dog's chest to show readers the real-time recording guaranteed by the wireless transmission

the left forelimb, the neutral black electrode on the right hindlimb and the ground green electrode on the left hindlimb.[25] In the case of the s-ECG, three leads were available (i.e., the red, the yellow and the green one). As in the case of the st-ECG, these leads were connected to atraumatic flattened metallic alligator clips. The leads of the s-ECG were connected close to the clips of the st-ECG and attached to the corresponding limb as previously described (Figure 1). In the case of both devices, alcohol was applied to maintain electrical contact with the skin. In both the st-ECG and the s-ECG, six-lead ECG tracings (i.e., leads I, II, III, aVR, aVL and aVF) were obtained for 30 seconds. In the case of the st-ECG, the ECG tracings were printed with a paper speed of 50 mm/s and a paper sensitivity of 10 mm/mV. The setting of the st-ECG included a sampling frequency of 600 Hz for acquisition, a 60 Hz low-pass filter and a 0.05 Hz high-pass filter. In the case of the s-ECG, the setting included a sampling frequency of 250 Hz for acquisition and a filter range of 0.5–40 Hz. In this case, tracings were recorded with an iPhone 13 (Apple, USA), automatically digitalised by the device with a paper speed of 50 mm/s and an amplitude of 10 mm/mV (Figure 2), archived as a PDF and printed for subsequent ECG analysis.

FIGURE 2 Smartphone display during an electrocardiographic (ECG) recording obtained with the smartphone-based ECG device used in this study. Note that all six leads (i.e., leads I, II, III, aVR, aVL and aVF) are simultaneously recorded, with a paper speed of 50 mm/s and a paper sensitivity of 10 mm/mV

ECG analysis

A board-certified cardiologist (G. R.) evaluated each ECG tracing and manually measured intervals and amplitudes using a calliper and ruler with 0.5-mm graduations. Tracings were considered acceptable for interpretation if baseline artefacts were absent for at least 80% of the recording. Initially, the cardiac rhythm was analysed and classified as sinus or pathological rhythm. Then, the HR in beats per minute (bpm) was calculated by determining the number of QRS complexes in a 3-second interval and multiplying this number by 20. For the purpose of this study, the classification of the heart rhythms/rate included[36–40]:

- sinus bradycardia: four or more successive sinus complexes at an HR less than 60 bpm;
- normal sinus rhythm: four or more successive sinus complexes at an HR of 60–180 bpm;
- sinus tachycardia: four or more successive sinus complexes at an HR greater than 180 bpm;
- supraventricular premature complexes (SvPC): a premature normal-appearing QRS complex not preceded by any P wave or conducted by a P wave with abnormal morphology;
- supraventricular tachycardia: three or more SvPCs at an HR greater than 160 bpm;

- atrial fibrillation: replacement of isoelectric baseline and sinus P waves by sequential less-defined deflections varying in amplitude, morphology and cycle length, associated with normal-appearing QRS complexes and irregular ventricular rhythm;
- ventricular premature complex (VPC): a premature wide and bizarre looking QRS complex, not associated with a P wave;
- accelerated idioventricular rhythm: three or more VPCs at an HR of 60–180 bpm;
- ventricular tachycardia: three or more VPCs at an HR greater than 180 bpm;
- second-degree atrioventricular block (AVB): a P wave without an associated QRS complex;
- third-degree AVB: evidence of P waves dissociated from QRS complexes with a ventricular rate less than 60 bpm.

Moreover, SvPCs and VPCs were also characterised as follows[38]:

- couplet: two consecutive SvPCs/VPCs;
- triplet: three consecutive SvPCs/VPCs;
- bigeminy: an SvPC/PVC following every sinus beat.

Subsequently, analysis of the main ECG variables was performed as previously described.[26,41,42] Specifically, these included the duration, amplitude and MEA in the frontal plane of the P-wave; the PQ interval duration; the duration and MEA of the QRS complex; the Q wave, R wave and S wave amplitudes; the presence/absence of ST segment deviation and its amplitude; the polarity and amplitude of the T wave; and the duration of the QT interval. Three representative consecutive beats were used to measure various ECG variables, and the results were averaged for each variable. Amplitudes and durations were measured in lead II and expressed in millivolts and milliseconds, respectively. Lead II was also used to assess the presence/absence of ST segment deviation and the T wave polarity. The MEA was calculated using the following equation: $\text{MEA} = \arctan(I_{\text{amp}}, \text{aVF}_{\text{amp}}) \times 180/\pi$.[25,26]

Statistical analysis

Statistical analysis was performed using commercially available statistical software (MedCalc Statistical Software version 19.5.1, Ostend, Belgium). All continuous variables were tested for their distribution with a Shapiro–Wilk normality test. Descriptive statistics included mean ± standard deviation for normally distributed data and median and range (minimum–maximum) for data that were not normally distributed. Cohen's kappa coefficient was used to calculate the agreement between the st-ECG and the s-ECG for 7 categorical variables: (1) heart rhythm classification (i.e., sinus rhythm, supraventricular tachycardia, atrial fibrillation, ventricular tachycardia, accelerated idioventricular rhythm); (2) in the case of sinus rhythm, HR classification (i.e., normal, bradycardia, tachycardia); (3) AVBs (i.e., absent, second degree, third degree); (4) premature complexes (i.e., absent, supraventricular, ventricular); (5) in the case of presence of premature complexes, couplets (i.e., present/absent), triplets (i.e., present/absent) and bigeminy (i.e., present/absent); (6) ST segment deviation (i.e., present/absent); and (7) T wave polarity (i.e., positive, negative, neutral). The κ coefficient was interpreted as follows: values 0.20 or greater 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 Bland–Altman test was used to calculate the agreement between the st-ECG and the s-ECG for 12 quantitative ECG parameters (i.e., those related to measurements of durations, amplitudes and MEA), and 95% limits of agreement were calculated for each of these variables. A p-value less than 0.05 was considered significant.

RESULTS

Study population

Seventy-seven dogs were initially considered for the study. Two dogs (one FB and one EB) were excluded due to artefacts recorded by both ECG devices (i.e., in both dogs, the artefacts occurred for more than 80% of the recordings obtained with both devices). Accordingly, the final study population consisted of 75 dogs (40 FBs and 35 EBs) and 140 ECG recordings (77 for each ECG device). Of the 40 FBs, 17 were females (13 entire and four spayed) and 23 were males (18 entire and five neutered). The median age and bodyweight were 2 years (1–9 years) and 11.1 kg (8.5–18 kg), respectively. Thirty-five (87.5%) had a normal echocardiographic exam, three (7.5%) had a mitral regurgitation, three (7.5%) had a pulmonic insufficiency and one (2.5%) had a mild pericardial effusion. Of the 35 EBs, 19 were females (16 entire and three spayed) and 16 were males (13 entire and three neutered). The median age and bodyweight were 2 years (1–9 years) and 26 kg (18–33 kg), respectively. Twenty-eight (80%) had a normal echocardiographic exam, six (17.1%) had a suspected arrhythmogenic cardiomyopathy and one (2.9%) had an aortic insufficiency.

Heart rate and heart rhythm

The st-ECG revealed a normal sinus rhythm in 69 of 75 (92%) dogs; the remaining dogs showed accelerated idioventricular rhythm (2/75, 2.8%), ventricular tachycardia (1/75, 1.3%), supraventricular tachycardia (1/75, 1.3%), atrial fibrillation (1/75, 1.3%) and second-degree AVB (1/75, 1.3%). Identical findings were obtained when the HR was classified according to the s-ECG ($\kappa = 1$). Among dogs with sinus rhythm, the st-ECG identified a normal sinus rhythm in 69 of 73 (94.5%) dogs, whereas the remaining four (5.5%) dogs had a sinus tachycardia. Identical findings were obtained when the HR was classified according to the s-ECG ($\kappa = 1$). Among dogs with a sinus rhythm, the st-ECG identified VPCs and SvPCs in seven (9.6%) and one (1.4%) of 73 subjects, respectively. In the seven dogs with VPCs, two showed a ventricular couplet, one a ventricular triplet and one a run of ventricular bigeminy. Identical findings were documented by the s-ECG, both in terms of number of dogs showing SvPCs and VPCs as well as of dogs showing a ventricular couplet, triplet and bigeminy ($\kappa = 1$).

ST segment deviation and T wave polarity

The st-ECG documented an ST segment deviation only in three of 75 (4%) dogs; in contrast, the s-ECG identified this ECG sign in 28 of 75 (37.3%) dogs. Consequently, there was no agreement between the two ECG devices for the assessment of the ST segment deviation ($\kappa = -0.01$). According to the st-ECG, out of 75 dogs, 32 (42.7%) had a positive T wave, 17 (22.7%) had a negative T wave and 26 (34.6%) had a neutral T wave. According to the s-ECG, out of 75 dogs, 34 (45.4%) had a positive T wave, 10 (13.3%) had a negative T wave and 31 (41.3%) had a neutral T wave. The agreement between the two ECG devices for the assessment of the T wave polarity was fair ($\kappa = 0.26$).

Measurements of durations, amplitudes and MEA

The measurement of quantitative ECG parameters obtained with the st-ECG and the s-ECG are reported in Table 1. The agreement between the two devices for each quantitative variable is reported in Table 2 and Figure 3. With both devices, most of these variables were within the generic reference intervals,[25,26,41–43] with the only exception being the QRS complex MEA, as a trend towards a left shift was observed with both devices. Indeed, with the st-ECG machine, the mean QRS complex MEA was 47.5° (0°−100°) and 31 of 75 (41.3%) dogs showed a left shift (median value of the QRS complex MEA among these subjects 32° [0°−39°]). Similar findings were documented by the s-ECG, as the mean QRS complex MEA was 45.1° (0°−90°) and 29 of 75 (38.7%) dogs showed a left shift (median value of the QRS complex MEA among these subjects 27° [0°−39°]). All dogs with a left shift of the QRS complex MEA had a normal ECG.

DISCUSSION

This study represents the first investigation into the use of a six-lead s-ECG in dogs as well as evaluating the highest number of ECG variables among the studies concerning s-ECGs in this species.[22–24]

A first interesting result is the perfect agreement between the six-lead s-ECG and the st-ECG in classifying HR. The agreement was also perfect for the classification of heart rhythms, including both sinus rhythm and pathological rhythms such as accelerated idioventricular rhythm, ventricular and supraventricular tachycardia, atrial fibrillation and second-degree AVB. Moreover, it is important to underline that the agreement remained perfect even in identifying SvPCs and VPCs and in classifying the organisation of ectopic complexes (i.e., couplets, triplets, bigeminy). Although not all types of rhythm disturbance have been identified in our study population (e.g., no dog showed sinus bradycardia or third-degree AVB), our results support the clinical utility of the s-ECG studied herein, as tachyarrhythmias and premature ectopic complexes are among the most common ECG abnormalities in dogs.[39,44–46] Additionally, it is intriguing to note that our findings agree with those previously reported for one-lead s-ECGs,[22–24] further supporting the reliability of s-ECG devices in the assessment of canine HR and heart rhythm.

Another noteworthy result regards the degree of agreement in detection of ST segment deviation and assessment of T wave polarity. Both the ST segment and the T wave represent two ECG parameters traditionally neglected in the veterinary literature, whose clinical relevance has been highlighted in small animals in recent years[47–50] and whose reference intervals have recently been documented in dogs.[41,42] The interpretation of these parameters is essential for a complete ECG analysis, as ventricular repolarisation is as important as depolarisation. Regrettably, previous studies evaluating digital ECG devices did not analyse their accuracy in the assessment of these ECG components.[22–24] Thus, this report represents the first study investigating the reliability of s-ECG in the analysis of ST segment and T wave polarity in dogs. Based on our results, the agreement between the s-ECG and the st-ECG for both variables was disappointing. This result suggests that the two ECG devices should not be used interchangeably for the assessment of the ventricular repolarisation and that the presence/absence of the ST segment and the T wave polarity should be interpreted cautiously in the light of the ECG technology employed.

An additional important result is that regarding the agreement for the quantitative ECG parameters, as some differences were found between the values obtained with the s-ECG and the st-ECG. The different settings (e.g., sampling frequencies, filters) of the two devices may have represented a source of variability. In addition, the particular somatotype of FBs and EBs may have further predisposed to differences in the calculation of some measurements. Indeed, both are brachymorphic breeds characterised by a relatively large, deep and barrel-shaped thorax.[26,30,51] Moreover, these breeds seem to be predisposed to accumulate adipose tissue around the heart,[52] which has a low electrical conductivity and may make the detection of some deflections more challenging. Therefore, the diagnostic performance of each device on such an extreme anatomic substrate can vary on the basis of the intrinsic technical characteristics. These results may not represent evidence of the diagnostic limits of the s-ECG studied herein but may be a consequence of our study design. Indeed, compared to previous canine studies on s-ECGs,[22–24] it was our declared

TABLE 1 Descriptive statistics for electrocardiographic (ECG) measurements in the study population

Variable	Mean/median	SD/min–max	RIs	References
P duration (ms)				
st-ECG	35.7	5.24	<45	26
s-ECG	40	20–40		
P amplitude (mV)				
st-ECG	0.17	0.06	<0.4	25,43
s-ECG	0.14	0.05		
P MEA (°)				
st-ECG	42.8	18.4	−18 to 90	43
s-ECG	45	14–76		
PQ duration (ms)				
st-ECG	91	14.9	60–130	25,43
s-ECG	87.8	15.6		
QRS duration (ms)				
st-ECG	52.3	8.6	≤70	25,43
s-ECG	53.4	6.8		
QRS MEA (°)				
st-ECG	47.5	21	40–100	25,43
s-ECG	45.1	21		
Q amplitude (mV)				
st-ECG	0.21	0.15	–	–
s-ECG	0.05	0–0.4		
R amplitude (mV)				
st-ECG	1.26	0.35	<3	25,43
s-ECG	0.8	0.32		
S amplitude (mV)				
st-ECG	0	0–0.6	–	–
s-ECG	0	0–0.2		
ST amplitude (mV)				
st-ECG	0	−0.1 to 0.1	−0.3 to 0.2	42
s-ECG	0	−0.2 to 0		
T amplitude (mV)				
st-ECG	0.04	0.19	−0.5 to 0.62	41
s-ECG	0.04	0.14		
QT duration (ms)				
st-ECG	190	19.3	150–250	25
s-ECG	193.5	18.8		

Abbreviations: max, maximum; MEA, mean electrical axis; min, minimum; RIs, reference intervals; SD, standard deviation; s-ECG, smartphone-based ECG device; st-ECG, standard ECG machine.

intention to study this ECG device in what is considered by many veterinary cardiologists to be one of the most challenging settings (i.e., the Bulldogs), precisely to 'stress' its diagnostic performance as much as possible. Regardless of the peculiarities of our study population, it should be considered that the presence of some differences between the st-ECG and s-ECG devices in the assessment of duration and amplitude of waves and intervals is not entirely unexpected, as has already been documented in studies involving dogs,[23] horses[53,54] and cows.[55] Additionally, it is essential to note that the mean differences found between the measurements obtained with the two ECG devices were of no clinical relevance. Indeed, as shown in Table 2, such differences were minimal; moreover, as shown in Table 1, all measurements apart from the QRS complex MEA fell within normal reference intervals with both ECG devices. This demonstrates that although each device can provide different numerical data, usually this difference is so small as to be clinically negligible.

The final finding supporting the clinical usefulness of the s-ECG studied herein concerns the only measurement diverging from the pertinent reference interval, namely, the QRS complex MEA. Specifically, according to both ECG devices, approximately 40% of

TABLE 2 Mean differences and upper and lower limits of agreement for quantitative electrocardiographic (ECG) parameters measured with the standard ECG machine (st-ECG) and the smartphone-based ECG device (s-ECG)

Variable	s-ECG versus st-ECG (95% CI)	Lower limit of agreement	Upper limit of agreement
P duration (ms)	0.2 (−1.19; 1.6)	−11.7	12.1
P amplitude (mV)	−0.03 (−0.05; −0.02)	−0.15	0.08
P MEA (°)	1 (−2.6; 4.5)	−29.2	31.2
PQ duration (ms)	−3.3 (−5.6; −0.9)	−23.5	17
QRS duration (ms)	1.1 (−0.9; 3)	−15.5	17.7
QRS MEA (°)	−2.3 (−6.7; 2)	−39.3	35.3
Q amplitude (mV)	−0.1 (−0.14; 0.08)	−0.35	0.13
R amplitude (mV)	−0.38 (−0.45; −0.3)	−1.05	0.3
S amplitude (mV)	−0.01 (−0.03; 0.01)	−0.17	0.15
ST amplitude (mV)	0.04 (−0.06; −0.03)	−0.16	0.07
T amplitude (mV)	−0.00 (−0.04; 0.03)	−0.3	0.3
QT duration (ms)	3.3 (−1.1; 7.7)	−34.4	41.1

Abbreviations: CI, confidence interval; MEA, mean electrical axis.

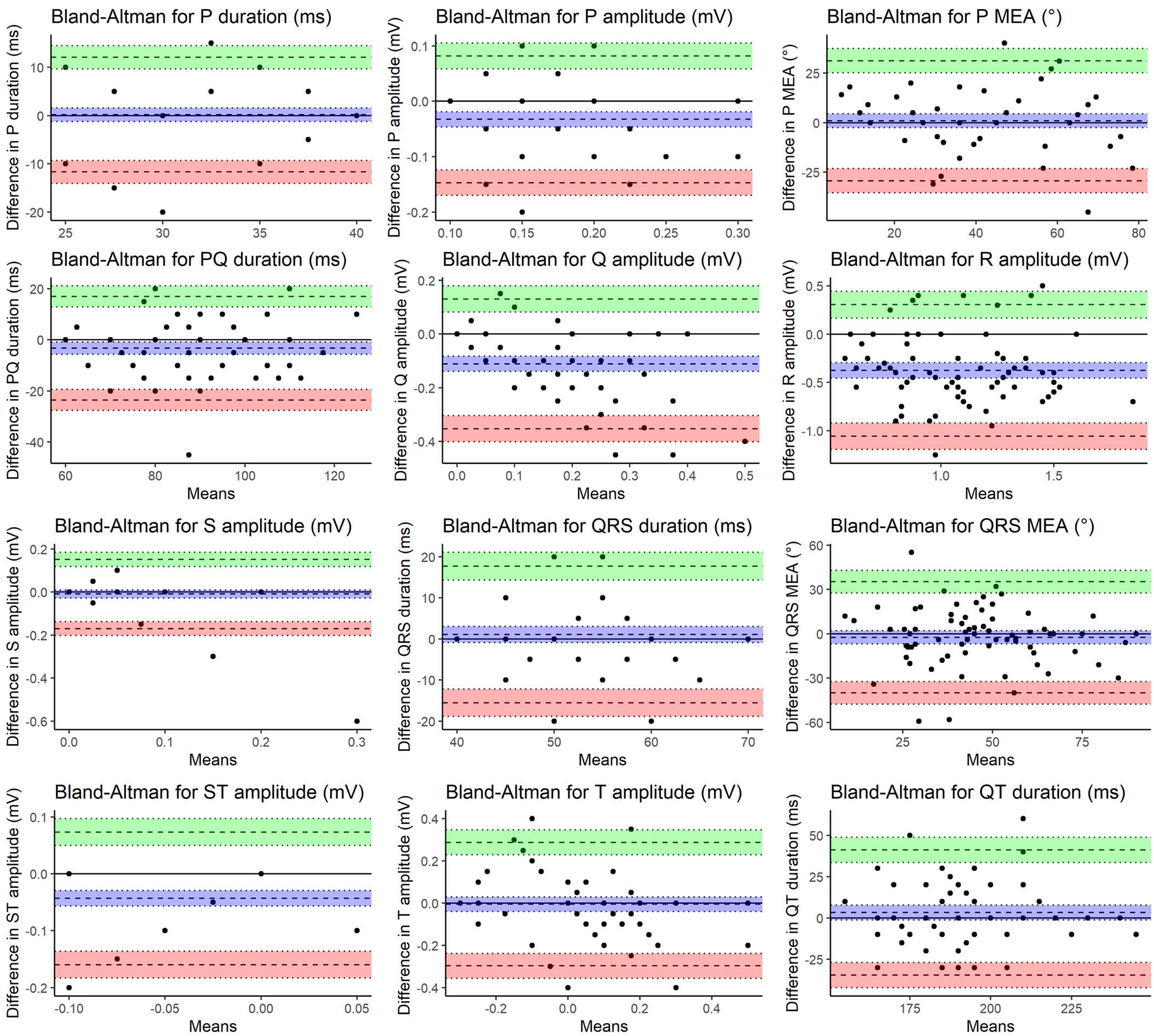

FIGURE 3 Limits of agreement (Bland–Altman) plot showing differences concerning each of the 12 continuous variables measured using a six-lead smartphone-based electrocardiographic device and a standard electrocardiographic machine. MEA, mean electrical axis

dogs had a left shift of this parameter. This result is in line with two previous investigations of the ECG features of healthy FBs and EBs that documented a left shift of the QRS complex MEA in 30% of FB[26] and 20% of EBs,[56] respectively, and assumed that such a finding was a physiological characteristic of Bulldogs related to their particular chest conformation rather than a true disturbance of ventricular conduction.[26,56] From a clinical point of view, this result suggests that this six-lead s-ECG may be able to detect breed-related ECG peculiarities similarly to the st-ECG. However, further studies are needed to demonstrate whether this device is also capable of identifying further breed-related peculiarities in breeds other than Bulldogs.

This study has some limitations. First, although the total number of subjects we enrolled was higher than that of most previous veterinary studies evaluating s-ECG devices,[22,24,53–55] only two breeds were evaluated. Moreover, the number of dogs with arrhythmias was limited, and not all rhythm disturbances were present. Therefore, additional studies enrolling a higher number of breeds, both with sinus rhythm and a wide range of pathological rhythms, are needed to further validate and expand our preliminary data. Second, our statistical analysis did not include any investigation of the role of bodyweight and body condition score on the diagnostic yield of the ECG devices. Theoretically, such an analysis could have added interesting findings as an increased amount of thoracic fat might increase the distance between the heart and electrodes, thus risking making the identification of deflections more challenging for less reliable ECG devices. Third, the ECG tracings were all interpreted by the same operator; therefore, it was impossible to evaluate the interoperator variability in the analysis of tracings obtained with the s-ECG device.

In conclusion, the six-lead s-ECG studied herein is comparable to the st-ECG for HR and heart rhythm assessment but not for the classification of ST segment deviation or T wave polarity. Although the diagnostic yield of the s-ECG device is clinically acceptable for the measurement of waves, segments and intervals, the numerical data obtained with the s-ECG and the st-ECG appear not to be interchangeable on the basis of our results.

AUTHOR CONTRIBUTIONS

Conceptualisation: Giovanni Romito. *Investigation*: Giovanni Romito and Prisca Castagna. *Resources*: Giovanni Romito, Prisca Castagna and Mario Cipone. *Data curation*: Giovanni Romito, Maria Chiara Sabetti and Michela Ablondi. *Writing*: Giovanni Romito, Maria Chiara Sabetti, Michela Ablondi and Mario Cipone. All authors have read and agreed to the published version of the manuscript.

CONFLICT OF INTEREST STATEMENT

None of the authors has any financial or personal relationships that could inappropriately influence or bias the content of this paper.

FUNDING INFORMATION

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DATA AVAILABILITY STATEMENT

The datasets generated and/or analysed during the current study are not publicly available due to the potential to compromise participant consent or confidentiality but are available from the corresponding author on reasonable request.

ETHICS STATEMENT

As all dogs were presented for routine cardiologic screening, no additional stress was imposed on the animals to obtain the data used in this study. Therefore, no institutional animal use approval was sought. Nevertheless, all owners were exhaustively informed about the nature of research project and signed an informed consent form.

ORCID

Giovanni Romito https://orcid.org/0000-0003-3927-1601
Maria Chiara Sabetti https://orcid.org/0000-0003-1902-2325
Michela Ablondi https://orcid.org/0000-0003-3700-1042
Mario Cipone https://orcid.org/0000-0002-0191-5232

REFERENCES

1. Fye WB. A history of the origin, evolution, and impact of electrocardiography. Am J Cardiol. 1994;73:937–49.
2. Buchanan JW. The history of veterinary cardiology. J Vet Cardiol. 2013;15:65–85.
3. Bansal A, Joshi R. Portable out-of-hospital electrocardiography: a review of current technologies. J Arrhythm. 2018;34:129–38.
4. Pew Research Center. Mobile Health 2012. Available from: www.pewinternet.org/wp-fontent/uploads/sites/9/media/Files/Reports/2012/PIP_MobileHealth2012_FINAL.pdf. Accessed 10 Dec 2022.
5. Krebs P, Duncan DT. Health app use among US mobile phone owners: a national survey. JMIR Mhealth Uhealth. 2015;3:e101.
6. Smith A. US Smartphone Use in 2015. Pew Research Center. Washington, DC: Pew Internet & American Life Project. Available from: www.pewinternet.org/2015/04/01/us-smartphone-use-in-2015/. Accessed 10 Dec 2022.
7. Pew Research Center. Mobile Fact Sheet. 2018. Available from: www.pewinternet.org/fact-sheet/mobile/. Accessed 10 Dec 2022.
8. Andrews CM, Bulloch L, Dennison T, Elder J, Mitchell A, Rivenbank MT, et al. Mobile technology in veterinary clinical medicine. J Vet Med Res. 2015;2:1017.
9. Huynh M. Smartphone-based device in exotic pet medicine. Vet Clin North Am Exot Anim Pract. 2019;22:349–66.
10. Wells J, Watson K, Sharma M, Davis RE, Gruszynski K, Robertson SR, et al. Application of the multi-theory model to explain veterinarians' intentions to use telehealth/telemedicine. Vet Rec. 2023;194:e2385.
11. Bruining N, Caiani E, Chronaki C, Guzik P, Van Der Velde E. Acquisition and analysis of cardiovascular signals on smartphones: potential, pitfalls and perspectives: by the Task Force of the e-Cardiology Working Group of European Society of Cardiology. Eur J Prev Cardiol. 2014;21:4–13.

12. Ferdman DJ, Liberman1 L, Silver ES. A smartphone application to diagnose the mechanism of pediatric supraventricular tachycardia. Pediatr Cardiol. 2015;36:1452–7.
13. Lowres N, Krass I, Neubeck L, Redfern J, Mclachlan AJ, Bennett AA, et al. Atrial fibrillation screening in pharmacies using an iPhone ECG: a qualitative review of implementation. Int J Clin Pharm. 2015;37:1111–20.
14. Peritz DC, Howard A, Ciocca M, Chung EH. Smartphone ECG aids real time diagnosis of palpitations in the competitive college athlete. J Electrocardiol. 2015;48:896–9.
15. Choo K-Y, Ling H-C, Lo Y-C, Yap Z-H, Pua J-S, Phan RC-W, et al. Android based self-diagnostic electrocardiogram system for mobile healthcare. Technol Health Care. 2015;23:S435–42.
16. Parimbelli E, Sacchi L, Budasu R, Napolitano C, Peleg M, Quaglini S, et al. The role of nurses in E-health: the MobiGuide project experience. Stud Health Technol Inform. 2016;225:153–7.
17. Brucal SG, Clamor GK, Pasiliao LA, Soriano JPF, Varilla LPM. Portable electrocardiogram device using Android smartphone. Annu Int Conf IEEE Eng Med Biol Soc. 2016;2016:509–12.
18. Lowres N, Mulcahy G, Gallagher R, Ben Freedman S, Marshman D, Kirkness A, et al. Self-monitoring for atrial fibrillation recurrence in the discharge period post-cardiac surgery using an iPhone electrocardiogram. Eur J Cardiothorac Surg. 2016;50:44–51.
19. Mittal S. Smartphone-based electrocardiographic and cardiac implantable electronic device monitoring. Cardiol Rev. 2017;25:12–6.
20. Chan NY, Choy CC. Screening for atrial fibrillation in 13 122 Hong Kong citizens with smartphone electrocardiogram. Heart. 2017;103:24–31.
21. Rizas KD, Freyer L, Sappler N, Von Stülpnagel L, Spielbichler P, Krasniqi A, et al. Smartphone-based screening for atrial fibrillation: a pragmatic randomized clinical trial. Nat Med. 2022;28:1823–30.
22. Kraus MS, Gelzer AR, Rishniw M. Detection of heart rate and rhythm with a smartphone-based electrocardiograph versus a reference standard electrocardiograph in dogs and cats. J Am Vet Med Assoc. 2016;249:189–94.
23. Vezzosi T, Buralli C, Marchesotti F, Porporato F, Tognetti R, Zini E, et al. Diagnostic accuracy of a smartphone electrocardiograph in dogs: comparison with standard 6-lead electrocardiography. Vet J. 2016;216:33–7.
24. Vezzosi T, Tognetti R, Buralli C, Marchesotti F, Patata V, Zini E, et al. Home monitoring of heart rate and heart rhythm with a smartphone-based ECG in dogs. Vet Rec. 2019;184:96.
25. Willis R. Electrocardiography. In: Willis R, Pedro O, Mavropoulou A, editors. Guide to canine and feline electrocardiography. Wiley-Blackwell; 2018. p. 35–56.
26. Romito G, Castagna P, Sabetti MC, Cipone M. Physiological shift of the ventricular mean electrical axis in healthy French Bulldogs: a retrospective electrocardiographic analysis of 80 healthy dogs. J Vet Cardiol. 2022;42:34–42.
27. Australia's Top Trending Dog Breeds and Names 2021. Hill's Pet Nutrition—Dog and Cat Food Transforming Lives. Available from: www.hillspet.com.au/dog-care/australias-top-trending-dog-breeds. Accessed 10 Dec 2022.
28. Leading 20 Dog Breeds in the United Kingdom (UK) in 2021, Based on Number of Registrations. 2022 Nov 28. Available from: www.statista.com/statistics/915202/top-dog-breeds-by-registered-number-united-kingdom-uk/. Accessed 10 Dec 2022.
29. American Kennel Club. Most Popular Breeds of 2021. Available from: www.akc.org/expert-advice/dog-breeds/most-popular-dog-breeds-of-2021/. Accessed 10 Dec 2022.
30. Groppetti D, Pecile A, Palestrini C, Marelli S, Boracchi P. A national census of birth weight in purebred dogs in Italy. Animals. 2017;7:43.
31. Côté E. Echocardiography: common pitfalls and practical solutions. Clin Tech Small Anim Pract. 2005;20:156–63.
32. Hostnik ET, Scansen BA, Habing AM, Chiappone GA, Layman RR, White RD. Comparison of cardiac measurements by multi-detector computed tomography angiography and transthoracic echocardiography in English bulldogs. J Vet Cardiol. 2017;19:480–91.
33. Chetboul V, Damoiseaux C, Poissonnier C, Lavennes M, Bertrand S, Borenstein N, et al. Specific features and survival of French bulldogs with congenital pulmonic stenosis: a prospective cohort study of 66 cases. J Vet Cardiol. 2018;20:405–14.
34. Holdt SL, Peckens NK, Rosenthal S, Cober R. Arrhythmogenic right ventricular cardiomyopathy in Bulldogs: evaluation of clinical and histopathologic features, progression, and outcome in 71 dogs (2004–2016). J Vet Cardiol. 2022;40:170–83.
35. Thomas WP, Gaber CE, Jacobs GJ, Kaplan PM, Lombard CW, Vet M, et al. Recommendations for standards in transthoracic two-dimensional echocardiography in the dog and cat. Echocardiography Committee of the Specialty of Cardiology, American College of Veterinary Internal Medicine. J Vet Intern Med. 1993;7:247–52.
36. Rasmussen CE, Falk T, Domanjko Petrič A, Schaldemose M, Zois NE, Moesgaard SG, et al. Holter monitoring of small breed dogs with advanced myxomatous mitral valve disease with and without a history of syncope. J Vet Intern Med. 2014;28:363–70.
37. Willis R. Sinus rhythms. In: Willis R, Pedro O, Mavropoulou A, editors. Guide to canine and feline electrocardiography. Wiley-Blackwell; 2018. p. 57–66.
38. Mavropoulou A. Ventricular rhythms. In: Willis R, Pedro O, Mavropoulou A, editors. Guide to canine and feline electrocardiography. Wiley-Blackwell; 2018. p. 169–87.
39. Romito G, Guglielmini C, Poser H, Baron Toaldo M. Lorenz plot analysis in dogs with sinus rhythm and tachyarrhythmias. Animals. 2021;11:1645.
40. Ohmori T, Matsumura Y, Yoshimura A, Morita S, Hasegawa H, Hirao D, et al. Efficacy of cilostazol in canine bradyarrhythmia. Front Vet Sci. 2022;9:954295.
41. Romito G, Castagna P, Pelle NG, Testa F, Sabetti MC, Cipone M. The canine T wave: a retrospective analysis on qualitative and quantitative T wave variables obtained in 129 healthy dogs and proposed reference intervals. J Vet Cardiol. 2022;42:52–64.
42. Romito G, Castagna P, Pelle NG, Testa F, Sabetti MC, Cipone M. Retrospective evaluation of the ST segment electrocardiographic features in 180 healthy dogs. J Small Anim Pract. 2022;63:756–62.
43. Santilli RA, Moise NS, Pariaut R, Perego M. Formation and interpretation of the electrocardiographic waves. In: Santilli RA, Moise NS, Pariaut R, Perego M, editors. Electrocardiography of the dog and cat e diagnosis of arrhythmia. 2nd ed. Edra; 2018. p. 35–70.
44. Buchanan JW. Spontaneous arrhythmias and conduction disturbances in domestic animals. Ann N Y Acad Sci. 1965;127:224–38.
45. Noszczyk-Nowak A, Michałek M, Kałuża E, Cepiel A, Pasławska U. Prevalence of arrhythmias in dogs examined between 2008 and 2014. J Vet Res. 2017;61:103–10.
46. Hellemans A, Schittekatte M, Covents M, Smets P. Diagnosis and management of arrhythmias in dogs: a cross-sectional online survey among Flemish veterinary practitioners. Vet Rec Open. 2022;9:e35.
47. Davainis GM, Meurs KM, Wright NA. The relationship of resting S-T segment depression to the severity of subvalvular aortic stenosis and the presence of ventricular premature complexes in the dog. J Am Anim Hosp Assoc. 2004;40:20–3.
48. Romito G, Fracassi F, Cipone M. Transient myocardial thickening associated with acute myocardial injury and congestive heart failure in two *Toxoplasma gondii*-positive cats. JFMS Open Rep. 2022;8:20551169221131266.
49. Romito G, Cipone M. Transient deep and giant negative T waves in dogs with myocardial injury. J Vet Cardiol. 2021;36:131–40.
50. Vila BCP, Camacho AA, Sousa MG. T-wave peak-end interval and ratio of T-wave peak-end and QT intervals: novel arrhythmogenic and survival markers for dogs with myxomatous mitral valve disease. J Vet Cardiol. 2021;35:25–41.
51. American Kennel Club. The new complete dog book: official breed standards and all-new profiles for 200 breeds. 21st ed. Lumina Media; 2014. p. 912.

52. Petite A, Kirberger R. Mediastinum. In: Schwarz T, Saunders J, editors. Veterinary computed tomography. Wiley-Blackwell; 2011. p. 249–60.
53. Alberti E, Stucchi L, Pesce V, Stancari G, Ferro E, Ferrucci F, et al. Evaluation of a smartphone-based electrocardiogram device accuracy in field and in hospital conditions in horses. Vet Rec Open. 2020;7:e000441.
54. Welch-Huston B, Durward-Akhurst S, Norton E, Ellingson L, Rendahl A, Mccue M. Comparison between smartphone electrocardiography and standard three-lead base apex electrocardiography in healthy horses. Vet Rec. 2020;187: e70.
55. Bonelli F, Vezzosi T, Meylan M, Nocera I, Ferrulli V, Buralli C, et al. Comparison of smartphone-based and standard base-apex electrocardiography in healthy dairy cows. J Vet Intern Med. 2019;33:981–6.
56. Romito G, Castagna P, Sabetti MC, Cipone M. Electrocardiographic findings in healthy Cavalier King Charles Spaniels, Pugs, and English Bulldogs. J Am Vet Med Assoc. 2023;1–8. https://doi.org/10.2460/javma.22.12.0542

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