JAVMA

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Overall good agreement of smartphone-based and standard base-apex electrocardiography in healthy sheep

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Received March 8, 2023
Accepted May 2, 2023

doi.org/10.2460/javma.23.02.0126

OBJECTIVE
To assess and compare the quality of smartphone ECG tracings to standard (base-apex) ECG tracings and assess agreement of ECG parameters between smartphone-based ECG and standard ECG.

ANIMALS
25 rams.

PROCEDURES
The rams were consecutively examined with standard ECG and smartphone-based ECG (KardiaMobile; AliveCor Inc) after physical examination. ECGs were compared for quality score, heart rate, and ECG waves, complexes, and intervals. Quality scores were based on the presence or absence of baseline undulation and tremor artifacts using a 3-point scoring system (lowest possible = 0; highest possible = 3). A lower score was indicative of a better-quality ECG.

RESULTS
Smartphone-based ECGs were interpretable in 65% of cases, while 100% of standard ECGs were interpretable. Standard ECG quality was superior to smartphone-based ECG quality, with no agreement in the quality between devices (κ coefficient, –0.0062). There was good agreement for heart rate with mean difference 2.86 beats/min (CI, –3.44 to 9.16) between the standard and smartphone ECGs. Good agreement was observed for P wave amplitude with mean difference 0.02 mV (CI, –0.01 to 0.05), QRS duration with mean difference –10.5 ms (CI, –20.96 to –0.04), QT interval with mean difference –27.14 ms (CI, –59.36 to 5.08), T wave duration with mean difference –30.00 ms (CI, –66.727 to 6.727), and T wave amplitude with mean difference –0.07 mV (CI, –0.22 to 0.08) between the 2 devices.

CLINICAL RELEVANCE
Our findings indicate good agreement between standard and smartphone ECG for most parameters, although 35% of smartphone ECGs were uninterpretable.

Smartphone technology is becoming increasingly useful in human and veterinary medicine. Its uses can be considered particularly convenient in both ambulatory practice and educational settings. Smartphone-based ECG has been investigated in several species including cats,[1] dogs,[1–3] horses,[4–8] dairy cattle,[9] water buffalo calves,[10] and goats[11] with favorable results. Currently no studies have been reported that evaluate the reliability of this technology for sheep. Additionally, to the authors' knowledge this was the first report of the use of a human smartphone-based ECG device in ruminants.

Traditional ECG equipment is expensive, and performing an ECG in the field on a large animal is more challenging than with a smartphone. The ease of accessibility of such technology could increase the number of ECGs performed by sheep practitioners and in doing so enhance "in the field" diagnostic workups. Urolithiasis and subsequent urinary obstruction is a common disease presentation in wethers and can result in hyperkalemia and associated cardiac arrythmias. Smartphone ECG, if reliable, could be particularly useful in assessment and stabilization of these patients.

The objectives of this study were to (1) assess and compare the quality of smartphone ECG tracings to standard (base-apex) ECG tracings and (2) assess agreement for heart rate (HR), P wave duration and amplitude, PR interval, QRS duration and amplitude, QT interval, T duration and amplitude, and P, QRS, and T polarity between smartphone-based ECG and standard ECG in sheep. We hypothesized that (1) smartphone-based ECG would produce tracings of similar quality to standard ECG tracings and (2) there would be good agreement of ECG parameters between smartphone-based ECG and standard ECG.

Materials and Methods

Animals

Twenty-five healthy rams were recruited from the Ross University School of Veterinary Medicine teaching flock. Using the formula $d \pm \sqrt{(3s^2/n)}$, where d is the limit, s is the standard deviation (SD), and n is the sample size, it was calculated that 20 sheep were required to estimate the limits of agreement between the 2 devices, with a 95% CI within 0.76 SDs. It was expected that ≤ 5 animals could drop out of the study for unknown reasons. Animals were newly acquired and introduced to the teaching flock and not previously well handled. Breeds included Barbados Blackbelly, Pelibüey, and St. Croix. All rams were estimated to be approximately 1 year of age on the basis of their lower incisors, and the median estimated body weight was 28 kg (range, 20 to 50 kg). The rams were dewormed with ivermectin and vaccinated with a commercial *Clostridium perfringens* type C and D and tetanus product 2 months prior to the study. All rams were screened prior to inclusion by history and physical examination and deemed healthy. The study protocol was approved by the IACUC of Ross University School of Veterinary Medicine (protocol No. 20.11.31).

Data collection

Rams were haltered and manually restrained while standing in a sheltered area of the pasture. Standard base apex ECGs were collected using a commercial device (CardEx 300 Veterinary ECG; Midmark Corp) by placing the negative electrode at the lower third of the left jugular furrow, the positive electrode at the left fifth intercostal space caudal to the olecranon, and the grounding electrode at the point of the left shoulder as previously described in dairy cattle.[9] Smartphone ECGs were collected after standard ECGs by placing the single lead bipolar device on the left thoracic wall at the level of the apex beat **(Figure 1)**. Electrodes were secured to the smartphone with adhesive tape (provided by the manufacturer), parallel to the long axis of the phone, and a base-apex lead was created by orienting the negative electrode dorsally and the positive electrode ventrally. Standard and smartphone ECGs could not be obtained simultaneously because the location of the positive electrode of the standard ECG prohibited adequate contact and correct placement of the smartphone device on the thoracic wall. An iPhone 8 (Apple Inc) was used with a commercial application (KardiaMobile; AliveCor Inc) to record the smartphone ECGs. Hair was not clipped, and 70% isopropyl alcohol was applied to the skin for improved contact. A minimum of 30 seconds of ECG tracing was recorded from each device at each location. There were approximately 60 to 90 seconds between recording the standard ECG and the smartphone ECG. The variation in time was associated with the time taken to get appropriate contact between the sheep and the device to produce a tracing. ECGs were recorded at a paper speed of 25 mm/s and amplitude of 10 mm/mV.

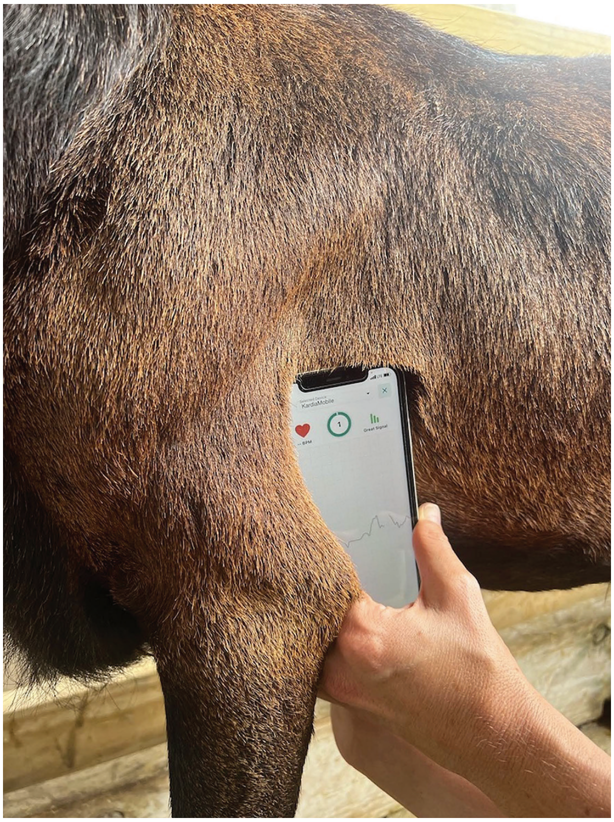

Figure 1—Placement of the smartphone on the left thoracic wall of a sheep at the level of the apex beat. ECG electrodes are secured to the back of the phone and in direct contact with the thoracic wall.

Data analysis

After collection, all tracings were masked for animal identity and reviewed by a single board-certified internist with a PhD in cardiology (KER). Heart rate was measured manually from printed ECGs for both standard and smartphone ECGs; HR as automatically calculated by the smartphone app was also recorded. Complex measurements (amplitudes and durations of all wave forms and intervals) and assessment of cardiac rhythm were performed on standard and smartphone ECGs as previously reported.[9,10] Additionally, all ECGs were quality-scored on the basis of the presence or absence of baseline undulation and tremor artifacts using a 3-point scoring system (lowest possible = 0; highest possible = 3) previously described for veterinary use **(Table 1)**.[10,12]

Table 1—ECG quality scoring system as reported by Stern et al.[12]

Score	Description
0	High-quality recording with no baseline wander or small baseline deflections
1	Intermittent, mild tremors or baseline deflections or mild baseline wander
2	Moderate tremors or baseline deflection consistent throughout the recording
3	Severe tremor artifact inhibiting the interpretation of the P and T waves

Using this whole number scoring system, a lower score was indicative of a higher-quality ECG (0 = high-quality recording with no baseline wander or small baseline deflections; 3 = severe tremor artifact inhibiting the interpretation of the P and T waves).

Statistical analysis

Commercial software (Stata version 16; StataCorp LLC) was used for statistical analysis. Data was assessed for normality using the Shapiro-Wilk test. Quantitative variables that followed the normal distribution were presented as mean and SD. Variables that did not follow the normal distribution were presented as median and IQR. Bland-Altman plots were used to evaluate agreement between the standard method, smartphone, and smartphone app for continuous variables. The corresponding 95% limits of agreement and mean difference (with 95% CI) were reported. The Cohen κ statistic was used to assess agreement between categorical variables. The κ coefficient was interpreted as follows: values ≤ 0.20 as no agreement, 0.21 to 0.40 as fair, 0.41 to 0.60 as moderate, 0.61 to 0.80 as good, 0.81 to 0.99 as very good, and 1.00 as perfect agreement. If the contingency table reported ≥ 1 value equal to 0, Cohen κ could not be calculated; therefore, in these cases, the percentage of agreement was used.

Results

Animals and feasibility

Twenty-five feral sheep were enrolled in the study. Standard and smartphone ECGs were collected in 23 sheep. One sheep was excluded due to incomplete physical examination information, and a second sheep was excluded because the animal's temperament precluded acquisition of an ECG. All 23 sheep moved during ECG collection. Standard ECG recording was feasible in all sheep despite animal motion. Smartphone ECG collection was achieved in 23 sheep; however, due to animal motion, the smartphone device had to be repositioned 1 to 3 times in each sheep to reestablish adequate contact and correct positioning on the thoracic wall.

ECG interpretation, quality, and measurements

Standard ECG tracings from 23 of 23 (100%) sheep were interpretable **(Figure 2)**; 6 of 23 (26%) sheep had normal sinus rhythm, 11 of 23 (48%) sheep had sinus arrhythmia, and 6 of 23 (26%) sheep had sinus tachycardia (HR > 90 beats/min [bpm]).[13] Smartphone ECG tracings from 15 of 23 (65%) sheep were interpretable; 9 of 15 (60%) sheep had sinus rhythm, 3 of 15 (20%) sheep had sinus arrhythmia, and 3 of 15 (20%) sheep had sinus tachycardia (HR > 90 bpm).[13] Smartphone ECG tracings from 8 of 23 (35%) sheep were not interpretable due to excessive baseline artifact associated with animal motion (eg, rapid respiration) and/or very low amplitude or undetectable wave forms. All 8 (100%) sheep had uninterpretable P waves; 3 of 8 (38%) had uninterpretable QRS complexes, 6 of 8 (75%) had uninterpretable T waves, and 3 of 8 (38%) had no interpretable waveforms. Eighteen of 23 (78%) standard ECGs were of good quality as indicated by a score of 1 or 0, while 13 of 23 (56%) smartphone ECGs had a score of 1 or 0. Five of 23 (22%) standard ECGs had a quality score of 2, and no standard ECGs had a quality score of 3. Four of 23 (17%) smartphone ECGs had a quality score of 2, and 6 of 23 (26%) smartphone ECGs had a score of 3. A κ coefficient of –0.0062 indicated no agreement between the devices in terms of quality score. Heart rates, wave form and interval measurements, and quality scores for the standard and smartphone ECGs are presented **(Table 2)**. Heart rate determination was possible for 23 of 23 (100%) standard ECGs by manual calculation, 21 of 23 (91%) smartphone ECGs by manual calculation, and 8 of 23 (35%) smartphone ECGs by the app. For manual HR calculations of the standard and smartphone ECGs, the mean difference was 2.86 bpm (CI, –3.44 to 9.16) with 95% limits of agreement of –24.81 to 30.53 **(Supplementary Figure S1)**. When manual HR of the standard ECG was compared to HR produced by the smartphone app, the mean difference was 2.5 bpm (CI, –6.12 to 11.12) with 95% limits of agreement of –18.12 to 23.12. On standard ECG, 23 of 23 (100%) sheep had a P wave duration of 40 ms. In the 15 sheep that had interpretable P waves on smartphone ECG, 14 (93%) had a P wave duration of 40 ms and 1 (7%) sheep had a P wave duration of 80 ms. P wave amplitude measured on standard ECG and smartphone ECG showed a mean difference of 0.02 mV (CI, –0.01 to 0.05) with 95% limits of agreement of –0.071 to 0.111. P wave polarity was positive in all sheep on standard ECG, and P wave polarity was positive in 14 of 15 (93%) sheep on smartphone ECG. P waves were biphasic in 1 (7%) sheep on smartphone ECG. PR interval on the 2 devices showed a

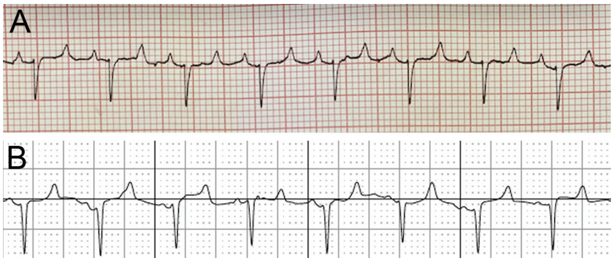

Figure 2—Examples of base apex standard (A) and smartphone (B) ECGs from a study ram. Paper speed, 25 mm/s; amplitude, 10 mm/mV.

Table 2—Base-apex ECG measurements in healthy feral sheep using a standard ECG device and a smartphone ECG device.

Parameter	Standard ECG	Smartphone ECG
Heart rate (beats/min)[1]	105.2 ± 27.8 (70, 180)	104.3 ± 25.8 (70, 160)
Heart rate app (beats/min)[1]	—	86.3 ± 14.6 (72, 105)
Quality score[1]	1.2 ± 0.49 (0, 3)	1.6 ± 0.99 (0, 3)
P duration (ms)	40[a]	40[b]
P amplitude (mV)[2]	0.1 (0.1, 0.2)	0.1 (0.1, 0.2)
PR interval (ms)[1]	107.4 ± 22.2 (70, 160)	152.5 ± 38.6 (100, 200)
QRS duration (ms)[2]	40 (40, 80)	40 (40, 120)
QRS amplitude (mV)[2]	–0.5 (–0.4, –0.8)	–0.35 (–0.1, –1)
QT interval (ms)[1]	174.8 ± 37.3 (120, 240)	205.7 ± 38.8 (160, 280)
T duration (ms)[1]	74.8 ± 30.3 (40, 160)	111.4 ± 50.1 (40, 200)
T amplitude (mV)[2]	0.2 (–0.5, 0.5)	0.1 (0.1–0.7)

[1]Mean ± SD and (min, max). [2]Median (min, max). [a]23/23 measurements were 40 milliseconds. [b]14/15 measurements were 40 milliseconds, and 1 measurement was 80 milliseconds.

mean difference of –44.38 ms (CI, –64.69 to –24.06) with 95% limits of agreement of –120.61 to 31.86. For QRS duration, there was a mean difference between the standard and smartphone ECGs of –10.50 ms (CI, –20.96 to –0.04) with 95% limits of agreement of –55.21 to 34.21. QRS amplitude measured on standard ECG and smartphone ECG showed a mean difference of 0.18 mV (CI, 0.06 to 0.29) with 95% limits of agreement of –0.31 to 0.66. QRS polarity was negative in all sheep on both devices. For QT interval, there was a mean difference between the standard and smartphone ECGs of –27.14 ms (CI, 59.36 to 5.08) with 95% limits of agreement of –138.75 to 84.47. T wave duration on the 2 devices showed a mean difference of –30.00 ms (CI, –66.727 to 6.727) with 95% limits of agreement of –157.219 to 97.219, and T wave amplitude showed a mean difference of –0.07 mV (CI, –0.22 to 0.08) with 95% limits of agreement of –0.58 to 0.44. See supplementary Figure S1 illustrating the agreement of the ECG parameters.

Discussion

The major findings of our study were that (1) smartphone ECG was feasible in healthy sheep, with some challenges; (2) interpretability and quality of the smartphone ECG tracings were inferior to standard ECG; (3) there was good agreement for HR, P wave duration and amplitude, QRS duration, T wave duration and amplitude, and QT interval between the smartphone-based ECG and standard ECG; and (4) there were clinically relevant differences for PR interval and QRS amplitude between the 2 devices.

There was good agreement between standard ECG and smartphone ECG for most ECG parameters; however, due to the temperament of the sheep (feral), motion and tachypnea appeared to affect the quality of the tracings in several cases, with 35% of smartphone ECGs being uninterpretable. These challenges appeared to be more significant in our study than what has been reported in cattle[9] and goats,[11] for which 89% and 100% of ECGs, respectively, were interpretable. In those studies, however, animal subjects had been previously well handled and were not feral. Quality scores were worse in smartphone ECGs than standard ECGs (κ coefficient, –0.0062), although it is still possible to obtain good-quality ECGs with the smartphone device (56% of sheep in this study) with repositioning of the device on the thoracic wall. Although some variability in HR was appreciated between the 2 devices, the degree of variability appears to be clinically insignificant.

Of the ECG parameters analyzed, there were clinically relevant differences for PR interval and QRS amplitude between the standard and smartphone ECGs. One potential reason for this may be that the smartphone device we used has only been validated in humans. Vera et al[8] reported that higher-quality ECGs were obtained from the veterinary smartphone device over a human smartphone device when used on horses, and so perhaps this holds true in other species. The device described in cattle,[9] water buffalo calves,[10] and goats[11] is a veterinary-specific device, and to the authors' knowledge, this was the first time that use of a human device has been described in ruminants. The veterinary device is no longer available, so the utility of available human devices needs to be explored in other species. One of the most common reasons a general practitioner may consider performing an ECG on ovine patients in the field is for urolithiasis cases. Urinary obstruction and/or bladder rupture can cause hyperkalemia and subsequent arrythmias. The ECG manifestations of hyperkalemia in cats and dogs include sinus bradycardia; tall, peaked T waves; P waves that are low amplitude, widened, and eventually absent; prolonged PR and QRS intervals and HR corrected QT interval; and generally low amplitude QRS complexes.[14] ECG alterations reported in calves with hyperkalemia include prolonged QRS durations, decreased P wave amplitude, deeper S wave, higher T wave, and higher ST segment amplitudes.[15] To the authors' knowledge, hyperkalemia-induced ECG changes have not been reported in sheep, with the exception of 1 case report[16] in which the absence of P waves was reported. In our study, PR interval and QRS amplitude in smartphone ECGs were unreliable and P waves were uninterpretable in 8 of 23 (35%) sheep. Additional studies in sheep are needed to ascertain whether these findings are repeatable.

Our study had several limitations. The output from the 2 devices differed visually, and therefore the observer was not blinded to the machine type. In addition, the ECGs were not recorded simultaneously because the location of the positive electrode of the standard ECG device prohibited adequate contact and correct placement of the smartphone device on the thoracic wall. This could have impacted HR and/or rhythm results. Although differences in HR in our study were not clinically relevant, there were notable differences in cardiac rhythm diagnoses. This limitation may be avoided in future studies by placing the electrode of the standard ECG in a more cranial location and/or utilizing a smaller smartphone. The smartphone device used was calibrated for humans, which may have impacted the quality and interpretability of the tracings. The bipolar ECG lead derived from the KardiaMobile device was the difference between 2 very closely located electrodes and as such is not ideal for detecting intervals. Only a small population of yearling rams was used for comparison of the 2 devices. In studies aiming to determine reference criteria for the KardiaMobile device, the authors suggest that a larger group with a range of ages should be used to ensure external validity. The temperament of the rams provided challenges including motion and tachypnea, so quality of smartphone tracings may be improved in sheep that are more amenable to handling. However, these challenges are realistic considerations when working with production animals; thus, this information is useful for general practitioners and may allow them to manage expectations of the utility of the device in various clinical scenarios. Standard ECG was less influenced by movement in our study than the smartphone ECG and may be preferred in sheep that are more challenging to handle.

In conclusion, smartphone ECG using the KardiaMobile device produced interpretable tracings in 65% of feral sheep while the standard ECG device produced interpretable tracings in 100% of sheep. We observed good agreement between the smartphone ECG and standard ECG for several ECG parameters; however, our findings suggest that clinicians should be cautious when interpreting PR interval and QRS amplitude on tracings produced by the smartphone ECG as the statistical differences appreciated may be clinically relevant. The smartphone ECG represents an additional practical tool for field triage of ovine cases but is not a substitute for traditional ECG. Follow-up with a traditional ECG is warranted when significant irregularities are found before making clinical decisions. Studies evaluating the KardiaMobile smartphone ECG device in other species and in animals with arrhythmias are warranted. Additionally, investigating the use of KardiaMobile in cases of hyperkalemia associated with urolithiasis in small ruminants would be of particular interest.

Acknowledgments

This study was funded by a Ross University School of Veterinary Medicine (RUSVM) intramural grant (No. 42001-2022). No third-party funding or support was received in connection with this study or the writing or publication of the manuscript. Funding sources did not have any involvement in the study design, data analysis and interpretation, or writing and publication of the manuscript.

The authors have nothing to declare.

The authors would like to thank RUSVM students Danielle Plank, Maria Chardon Suárez, and Sara Cote for their assistance in data collection.

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Supplementary Materials

Supplementary materials are posted online at the journal website: avmajournals.avma.org