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Comparison between smartphone electrocardiography and standard three-lead base apex electrocardiography in healthy horses

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Abstract

Background—Cardiac arrhythmias are commonly auscultated during routine physical examinations in horses and determining the underlying electrical abnormality using an ECG is important. The most commonly used device is a three-lead base apex system (Televet), however few practitioners carry this for routine visits. With recognition of the utility of smartphone-based ECGs in humans, dogs and ruminants, the AliveCor single-lead bipolar smartphone-based ECG has gained popularity. The objective of this study was to determine if AliveCor and Televet ECG measurements were comparable in healthy horses using multiple observers.

Methods—ECGs were performed on 15 healthy horses simultaneously using the AliveCor and Televet.

Results—There was very good to perfect interdevice and interobserver agreement for heart rate and RR interval measurement, and moderate-to-good interdevice and interobserver agreement for detection of non-pathological arrhythmias. Interdevice agreement for measurement of P-wave and QRS duration, QT, PR and T-peak to T-end interval was poor to fair. Interestingly, interobserver agreement for P-wave and QRS duration, QT, PR, and T-peak to T-end interval measurements was fair to good.

Conclusion—Overall, the AliveCor is comparable to the Televet for heart rate and RR measurement, and for the detection of non-pathogenic arrhythmias with acceptable agreement between observers.

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Competing interests None declared.

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Ethics approval All procedures were approved by the University of Minnesota IACUC committee (protocol: 1609–34123A).

Data availability statement Anonymised data are available on reasonable request to the corresponding author.

Introduction

Cardiac arrhythmias are common in horses.¹ Although there are many benign causes of arrhythmias, it is important to detect pathological arrhythmias as they can lead to poor performance² and may contribute to sudden cardiac death.³ Arrhythmias are frequently audible during routine cardiac auscultation, however identifying the underlying cause of the arrhythmia requires an ECG. The most commonly used method of ECG acquisition in the horse is a three-lead base apex system⁴ (eg, Televet 100, Rösch & Associates, Information Engineering GmbH, Mörfelder Landstraße, Frankfurt am Main, Germany (Televet)). However, the rise of the smartphone and several commercially available smartphone-based medical devices⁵ has led to the development of tools that are easily portable, simple, user friendly and cheaper than the traditional approaches.⁶ Recent studies have also demonstrated the usefulness of smartphone-based ECG devices for measuring heart rate and rhythm in humans,^{7–11} dogs,¹²¹³ ruminants¹⁴¹⁵ and horses.¹⁶¹⁷ With most equine veterinary patients being evaluated in the field, a user-friendly, inexpensive, and portable method of obtaining an ECG would be highly clinical relevant.

The only such ECG device targeted for veterinary practitioners is the AliveCor (AliveCor, San Francisco, California, USA) device. This device has been validated in several veterinary species,^{12–15} including horses,¹⁶¹⁷ however, these studies have all consisted of single observer reported measurements. Interobserver agreement is critically important for determining the usefulness of an ECG device. Therefore, the objective of this study was to determine if the AliveCor was comparable to the ‘standard’ Televet in healthy adult horses without documented cardiac abnormalities and if there was agreement between three reviewers (two ACVIM (LAIM) diplomates and one ACVIM (LAIM) resident).

Materials and methods

Animals

This was a prospective randomised single-blinded clinical method comparison study that took place in October 2017. Fifteen mares that were part of the University of Minnesota teaching were examined. The mares had a median age of 15 years (range 4–25) and were determined to be healthy based on history and physical examination. A body condition score based on the Henneke body condition scoring guidelines¹⁸ was obtained for each mare (table 1).

ECG acquisition and analysis

The ECGs were obtained in the University of Minnesota Leatherdale Equine Center’s Dudley teaching barn between 10.30 and 13.30 hours. The horses were restrained in cross ties, and the AliveCor AC-002 and Televet were used simultaneously to record three pairs of 15 s ECG tracings from each standing, unsedated and unclipped horse. A small amount of alcohol was used to optimize contact and obtain a good quality ECG signal for both methods. The Televet was applied based on the manufacturer’s instructions. Briefly, the green electrode was placed on the sternum or slightly to the right of the sternum. The red electrode was placed on the left side of the thorax about 30 cm below the top of the thorax.

The black electrode was placed approximately 10 cm above the red electrode. The yellow electrode was placed on the right side of the thorax in a similar position to the red electrode on the left. The AliveCor was held against the left chest wall caudal to the olecranon over the area where the maximum apex beat could be palpated (figure 1) and the recordings obtained on an iPad mini (Apple, One Apple Park Way, Cupertino, California, USA). The AliveECG Vet application was used to observe ECGs from the AliveCor device. The AliveCor was moved and/or rotated (horizontal, vertical or oblique) until the best contact and clearest possible tracing was achieved. All ECG recordings were recorded by the same investigators using a paper speed of 25 mm/s on a 50 Hz scale with a gain of 20 mm/mV.

For each horse, the AliveCor traces were evaluated for diagnostic quality and the best AliveCor tracing and simultaneous Televet tracing were selected for analysis. If tracings were longer than 15 seconds, then the best 15 seconds from that tracing were selected for analysis. All traces were anonymised and randomised by horse within their category (AliveCor vs Televet) using R software.¹⁹ Due to inherent differences in how each tracing was displayed, the source equipment of the tracing was not blinded (figure 2). Each tracing was evaluated for the presence of an arrhythmia or abnormal complexes. ECG variables measured from each trace included: heart rate (bpm (HR)); determined by the number of QRS complexes in the 15 seconds trace multiplied by 4); P-wave duration (seconds (P-wave)); PR interval (seconds (PR)); QRS duration (seconds (QRS)); instantaneous and mean R-R interval (seconds (RR)), Q-T interval (seconds (QT)) and T peak-T end interval (seconds (TT)). Each interval was measured for the first three complexes of each 15 seconds ECG trace and each single measurement analysed in addition to the average measurement over the three complexes. Three observers (two boarded large animal internists and a final year large animal internal medicine resident) blinded to the horse's identity performed the measurements for each trace. To standardise ECG analysis, all measurements were performed by hand without the assistance of ECG interpretation software.

Statistical analysis

For each pair of simultaneous tracings, the mean HR, P-wave and QRS durations, and PR, RR, QT and TT intervals were calculated for all observers and devices. Correlation between observers was calculated using Fleiss's kappa (κ) coefficient for categorical variables and intraclass correlation coefficients (ICC) for continuous variables. Correlation between ECG devices were determined using Cohen's κ coefficients for categorical data, and ICC between the devices were used for continuous variables. The κ coefficients and ICC were interpreted as previously described,¹³ in brief: κ /ICC 0.20, no correlation; 0.21–0.40, fair; 0.41–0.60, moderate, 0.61–0.80, good; 0.81–0.99, very good and 1 as perfect agreement.²⁰ Bland-Altman analysis was used to provide limits of agreement plots to highlight the median differences in ECG measurements for continuous variables between the AliveCor and Televet within two sds. All statistical analysis was performed using commercial software in R.¹⁹ Significance was set at $P = 0.05$ with 95 per cent CIs when applicable.

Results

All fifteen horses tolerated the ECG procedure and had at least one AliveCor tracing considered of diagnostic quality.

Heart rhythm

No pathological arrhythmias were recorded or identified by either device for any horse used in this study. Five horses (33.3 per cent) had non-pathological arrhythmias (four had sinus arrhythmia on at least one tracing (two horses identified using both devices and three on the AliveCor or Televet only) and one had second-degree atrioventricular block on the Televet only). Four of those five horses (80 per cent) were considered overweight based on the Henneke body condition score system with a body condition score (BCS) of greater than equal to six (table 1). The interdevice correlation for the detection of non-pathological arrhythmias was moderate to good depending on the observer (κ : 0.44–0.63 (table 2)). The interobserver correlation for the presence of non-pathological arrhythmias was good (κ : 0.66–0.74 (table 3)).

Heart rate

The HR was within normal limits for all horses with both devices. The median (range) HR for both devices is shown in table 4. The average correlation between the AliveCor and Televet for HR over the three observers was very good (ICC: 0.93, $P=1.49\times 10^{-32}$, 95 per cent CI: 0.90 to 0.97) (table 5). The mean HR difference between the Televet and AliveCor was 0.09 (−3.26 to 3.43), with 100 per cent of AliveCor measurements falling within 4 bpm of the corresponding Televet measurement (figure 3A). The interobserver correlation was very good for the three observers (average ICC: 0.93, $P=1.49\times 10^{-32}$, 95 per cent CI: 0.90 to 0.97 (table 6)) for the two devices (table 6).

P-wave and QRS duration

The median (range) P-wave and QRS duration for both devices are shown in table 4. No significant correlation was observed between devices for the average P-wave duration (ICC: 0.08, $P=0.23$, 95 per cent CI: −0.08 to 0.37 (table 5)). The mean P-wave difference between the Televet and the AliveCor was 0.02 seconds (−0.002 to 0.05). Fifty-three per cent of AliveCor measurements fell within 5 per cent (0.01 seconds) of the median Televet P-wave duration (0.10 seconds (figure 3C)). The interobserver correlation for the measurement of the average P-wave duration was moderate for the three observers (average ICC: 0.55, $P=0.001$, 95 per cent CI: 0.33 to 0.73) for the two devices (table 6).

No significant correlation was observed between devices for the average QRS duration (ICC: 0.34, $P=0.07$, 95 per cent CI: −0.10 to 0.70 (table 5)). The mean QRS duration difference between the Televet and the AliveCor was 0.01 seconds (−0.01 to 0.03). Sixty-seven per cent of AliveCor measurements fell within 5 per cent (0.01 seconds) of the median Televet QRS duration (0.13 seconds (figure 3E)). The interobserver correlation for the measurement of the average QRS duration was moderate for the three observers (average ICC: 0.55, $P=0.005$, 95 per cent CI: 0.17 to 0.77) for the two devices (table 6).

PR, RR, QT and TT intervals

The median (range) RR, PR, QT and TT interval for both devices is shown in table 4. Correlation between the AliveCor and Televet for measurement of the average RR interval was very good (average ICC: 0.99, $P = 0.001$, 95 per cent CI: 0.98 to 1.00 (table 5)). The mean RR difference between the Televet and AliveCor was 0.01 seconds (−0.05 to 0.07). Hundred per cent of AliveCor measurements fell within 5 per cent (0.08 seconds) of the median Televet RR interval (1.67 seconds (figure 3B)). The interobserver correlation for the measurement of the average RR interval was very good for the three observers (average ICC: >0.99 , $P=1.15 \times 10^{-69}$, 95 per cent CI: >0.99 to 1.00) for the two devices (table 6).

No significant correlation was observed between devices for the average PR interval (ICC: 0.02, $P=0.47$, 95 per cent CI: −0.54 to 0.53 (table 5)). The mean PR interval difference between the Televet and the AliveCor was 0.001 seconds (−0.09 to 0.09). Forty-seven per cent of AliveCor measurements fell within 5 per cent (0.01 seconds) of the median Televet PR interval (0.25 seconds (figure 3D)). The interobserver correlation for the measurement of the average PR interval duration was moderate for the three observers (average ICC: 0.41, $P=0.05$, 95 per cent CI: 0.02 to 0.734 for the two devices (table 6).

No correlation was observed between devices for the average QT interval (ICC: 0.20, $P=0.16$, 95 per cent CI: −0.11 to 0.57 (table 5)). The mean QT difference between the Televet and the AliveCor was 0.04 seconds (−0.01 to 0.08). Sixty per cent of AliveCor measurements fell within 5 per cent (0.03 seconds) of the median Televet QT interval (0.51 seconds (figure 3F)). The interobserver correlation for the measurement of the average QT interval was very good for the three observers (average ICC: 0.87, $P=2.15 \times 10^{-10}$, 95 per cent CI: 0.76 to 0.94) for the two devices (table 6).

No correlation was observed between devices for the average TT interval (ICC: −0.10, $P=0.80$, 95 per cent CI: −0.27 to 0.24). The mean TT difference between the Televet and the AliveCor was 0.02 seconds (−0.01 to 0.05). Seven per cent of AliveCor measurements fell within 5 per cent (0.004 seconds) of the median Televet TT interval (0.07 seconds (figure 3G)). The interobserver correlation for the measurement of the average TT interval was very good for the three observers (average ICC: 0.87, $P=2.41 \times 10^{-11}$, 95 per cent CI: 0.76 to 0.93) for the two devices (table 6).

Discussion

Visualising the underlying electrical activity of the horse heart using an ECG is essential for determining the type of arrhythmia present. Handheld ECG devices are affordable, user friendly and highly portable making them appealing for general practitioners. The authors demonstrate that 1) the AliveCor-002 handheld smartphone ECG device was well tolerated by all horses; 2) at least 15 seconds of interpretable ECG tracing could be obtained from the AliveCor by recording the ECG for up to 45 seconds and visualised using the AliveECG application on an iPad mini; 3) there was moderate to good correlation between the AliveCor and Televet, and good correlation between observers correlation for the identification of the presence of benign arrhythmias; 4) correlation between the AliveCor and Televet varied from no correlation to very good, while correlation between observers

was moderate to very good for the measurement of HR, P-wave and QRS duration, and PR, RR, QT and TT intervals; 5) 100 per cent of AliveCor HR measurements were within one measurement (4 bpm) of the median Televet HR and 6) 50 per cent–100 per cent of AliveCor P-wave and QRS duration, RR and QT interval measurements were within 5 per cent of the corresponding median Televet measurement; and 47 per cent and 7 per cent of AliveCor PR and TT interval measurements, respectively were within 5 per cent of the corresponding median Televet measurement. Overall, this suggests that the AliveCor is a useful ECG device in normal healthy horses, with the exception of TT interval and there is good inter-observer correlation for the AliveCor and Televet.

The correlation between the AliveCor and Televet was moderate to good for detection and classification of benign arrhythmias (sinus arrhythmia and second degree atrioventricular block). Interestingly, the correlation between observers was better than the correlation between devices. As expected, given that the horses used were apparently healthy teaching horses, no pathological arrhythmias were detected. Therefore, to determine the utility of the AliveCor for detecting pathological arrhythmias a further study using horses with pathologic arrhythmias will need to be performed.

The correlation between the AliveCor and Televet for HR and RR interval was very good depending on the observer and the agreement was excellent. This shows that the AliveCor is useful for measuring the HR and measuring the RR interval in healthy horses. The mean difference between the AliveCor and Televet was minimal for the HR and RR interval (<1 bpm and <0.01 seconds, respectively) and would likely not be considered clinically significant. The mean difference in this study (0.09 seconds) is less than reported in cattle (3 seconds),¹⁵ but similar to a previous report in healthy horses (0.2 seconds).¹⁶ This, combined with all AliveCor HR and RR interval measurements falling within 1 hour measurement (4 bpm) or within 5 per cent of the median Televet RR interval, respectively adds to the literature supporting the utility of the AliveCor for HR measurement in humans,⁹¹¹ dogs,¹²¹³ ruminants¹⁴¹⁵ and horses.¹⁶¹⁷²¹ The interobserver agreement across both devices was very good for measurement of the HR and RR interval. This is an important observation as it suggests that different observers are likely to agree on the interpretation of both the AliveCor and Televet HR and RR measurements.

Despite the AliveCor having minimal correlation with the Televet for the measurement of the P-wave and QRS duration and QT interval, most (>52 per cent) of the AliveCor measurements still fell within 5 per cent of the median Televet P-wave or QRS duration or QT interval respectively. This suggests, that the AliveCor may still be useful for measuring the P-wave and QRS duration as well as QT interval, as the difference between the AliveCor and Televet in most cases is unlikely to be clinically significant. However, AliveCor duration and interval measurements should be interpreted with caution and followed up with the Televet if there are concerns about alterations in the these areas of the waveform. Similarly, there was minimal correlation between the AliveCor and Televet for the measurement of the PR and TT interval, respectively. Forty-seven per cent of the AliveCor PR interval measurements still fell within 5 per cent of the median Televet PR interval, however, only one AliveCor TT interval fell within 5 percent of the median Televet TT interval. This suggests that the AliveCor is less useful for measuring the PR and TT intervals in this

population of horses. The AliveCor has been used successfully in humans,²² adult dairy cows¹⁵ and horses¹⁶ for measuring the QT interval. The mean difference (0.04 seconds) between the AliveCor and Televet for QT measurement in this study was greater than that reported previously in horses (0.0008 seconds)¹⁶ and cattle (0.004 seconds),¹⁵ but the reason for this is not clear. The mean difference in P-wave (0.02 seconds) and QRS (0.01 seconds) duration was similar to a previous comparison of the AliveCor and Televet that reported a mean difference of 0.01 seconds in the P-wave and QRS durations. Interestingly, despite the poor correlation between devices for the PR interval, the mean difference here (0.001 seconds) between the two devices was better than the previously reported mean difference of 0.02 seconds for the PR interval. Previous studies using the AliveCor in dogs,¹²¹³ ruminants¹⁴¹⁵ and horses¹⁶¹⁷²¹ did not evaluate the TT interval and so no comparison can be made.

Based on feedback from the observers, the main challenge with the P-wave, PR, QT and TT interval measurements was identifying where the P-wave and T-wave started and ended due to undulation in the baseline of both devices. This is similar to findings in studies performed by Kruse and others and Vera and others where polarity¹⁷ and visibility²¹ of the waveform demonstrated some degree of variability between observer and device. Despite this, the interobserver agreement for measurement of these parameters across both devices was moderate to very good. Given the lack of correlation between the AliveCor and Televet for the measurement of these intervals, this is a surprising finding and would suggest that the observers estimated the beginning of the P-wave and end of the T waves differently between the two devices, but consistent with how the other observers estimated the intervals. Further investigation using a larger number of horses is necessary to interpret these findings and to establish if they are repeatable.

One disadvantage of the AliveCor was that although the ECG tracing could be observed in real time, it Continued could not be adjusted, nor could measurements be taken without first converting it to a PDF document. Furthermore, the polarity of the tracing on the smartphone-based reader frequently did not match the Televet. This is likely due to the authors' attempts to orientate the AliveCor to give the best possible tracing. It was elected not to standardise the orientation of the AliveCor beyond starting at the apex beat because it was very difficult to obtain a tracing of diagnostic quality in certain horses without adjusting the position of the device. In dogs, it has been hypothesised that body condition could influence the quality of the tracing due to the increased electrical impedance of higher body fat content.¹² The authors were not able to investigate if this was the case in this study due to the uniformity of the study population described here. While body condition score may have affected the quality of tracing in these horses, an additional challenge in the horse was the degree of musculature around and behind the shoulder, which affected device positioning and may have played a role in the interpretation of the ECG measurements. An additional challenge to collecting the ECG measurements was that any movement led to major artefacts on the trace. While this was consistent across devices, the AliveCor frequently disconnected when the horse moved so the ECG tracing was lost, and the device needed to be repositioned to initiate an entirely new recording. This delayed obtaining a diagnostic ECG trace but was not the case for the Televet, where the recording was interpretable virtually as soon as the horse stopped moving.

Conclusion

This study demonstrates that interobserver correlation for ECG measurements using the AliveCor and Televet is very good and that there was excellent agreement between the AliveCor and Televet for measurement of HR and RR interval. This would suggest that the AliveCor is a useful device for the measurement of HR and RR intervals by different observers. Given the many advantages of the AliveCor over the Televet, in particular the relatively cheap and portable nature requiring no special equipment or training, these results suggest that the AliveCor is likely a useful device for initial ECG examination in the horse. The utility of the AliveCor for measurement of P-wave and QRS duration, PR, QT and TT intervals, and detection of pathological arrhythmias requires further study.

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Figure 1.
Placement of AliveCor sensors in a vertical orientation over the apex beat and two of four Televet leads on left chest wall.

Figure 2.
Different appearance of simultaneous Televet (a) and AliveCor (b) tracings from the same horse.

Figure 3.

Bland-Altman plots showing differences between the AliveCor (AC) and Televet (TV) for measurements averaged over the three measurements and three observers for heart rate (HR) (a), RR interval (b), P-wave duration (c), PR interval (d), QRS duration (e), QT interval (f) and TT interval (g). The limits of agreement are represented by dotted lines.

Table 1

Arrhythmia identification and body condition score in 15 healthy horses

Horse ID	Arrhythmia (yes/no)	Type*	Device Televet (TV) AliveCor (AC)	Observer(s)	Body condition score
1	No	n/a	TV, AC	OBS1, OBS2, OBS3	6
2	No	n/a	TV, AC	OBS1, OBS2, OBS3	6
3	No	n/a	TV, AC	OBS1, OBS2, OBS3	5
4	Yes	Sinus arrhythmia	TV, AC	OBS1, OBS2, OBS3	6
5	No	n/a	TV, AC	OBS1, OBS2, OBS3	7
6	No	n/a	TV, AC	OBS1, OBS2, OBS3	3
7	No	n/a	TV, AC	OBS1, OBS2, OBS3	4
8	Yes	Second-degree AV block	TV	OBS1, OBS2, OBS3	6
9	Yes	Sinus arrhythmia	TV	OBS1, OBS2, OBS3	4
10	No	n/a	TV, AC	OBS1, OBS2, OBS3	6
11	Yes	Sinus arrhythmia	AC	OBS1, OBS2, OBS3	6
12	No	n/a	TV, AC	OBS1, OBS2, OBS3	7
13	No	n/a	TV, AC	OBS1, OBS2, OBS3	7
14	No	n/a	TV, AC	OBS1, OBS2, OBS3	7
15	Yes	Sinus arrhythmia	TV, AC	OBS2, OBS3	6

* n/a used when no arrhythmia observed.

Table 2

Cohen's kappa agreement between two methods of obtaining ECGs for categorical variables by each observer (OBS1, OBS2 and OBS3) for all 15 horses

Variable	Kappa	P value
Arrhythmia (OBS1)	0.63	0.01
Arrhythmia (OBS2)	0.44	0.08
Arrhythmia (OBS3)	0.44	0.08
Arrhythmia type (OBS1)	0.44	0.02
Arrhythmia type (OBS2)	0.46	0.05
Arrhythmia type (OBS3)	0.46	0.04

Table 3

Fleiss's kappa agreement between three observers for categorical variables over all measurements, and either the smartphone-based method (AliveCor (AC)) or gold standard base-apex method (Televet (TV)) for all 15 horses

Variable	Kappa	P value
Arrhythmia (yes/no) (both)	0.71	<0.001
Arrhythmia (yes/no) (AC)	0.66	<0.001
Arrhythmia (yes/no) (TV)	0.74	<0.001
Arrhythmia type (both)	0.80	0
Arrhythmia type (AC)	0.85	<0.001
Arrhythmia type (TV)	0.76	<0.001

Table 4

Median (range) of the mean values across observers with the Televet (TV) and AliveCor (AC) ECG traces from all 15 horses

Parameter	TV median (range)	AC median (range)
HR (bpm)	36 (27–43)	36 (28–43)
P-wave duration (seconds)	0.10 (0.09–0.14)	0.08 (0.07–0.10)
PR interval (seconds)	0.25 (0.21–0.33)	0.24 (0.19–0.32)
QRS duration (seconds)	0.13 (0.12–0.14)	0.12 (0.10–0.14)
RR interval (seconds)	1.67 (1.46–2.58)	1.64 (1.42–2.57)
QT interval (seconds)	0.51 (0.48–0.56)	0.47 (0.43–0.51)
TT interval (seconds)	0.07 (0.05–0.09)	0.05 (0.04–0.07)

Table 5

Intraclass correlation coefficient (ICC) agreement between two methods of ECG obtainment in continuous variables for each observer (OBS1, OBS2 and OBS3) and averaged over the three observers for all 15 horses

Variable	ICC	P value	95% CI
Heart rate (average—bpm)	0.93	<0.001	0.81 to 0.98
Heart rate (OBS1)	0.89	<0.001	0.71 to 0.96
Heart rate (OBS2)	0.91	<0.001	0.74 to 0.97
Heart rate (OBS3)	0.94	<0.001	0.84 to 0.98
P-wave duration 1 (average—seconds)	−0.01	0.52	−0.18 to 0.30
P-wave duration 1 (OBS1)	−0.15	0.71	−0.61 to 0.38
P-wave duration 1 (OBS2)	−0.27	0.88	−0.57 to 0.22
P-wave duration 1 (OBS3)	−0.06	0.73	−0.20 to 0.23
P-wave duration 2 (average—seconds)	0.09	0.23	−0.09 to 0.40
P-wave duration 2 (OBS1)	0.17	0.24	−0.28 to 0.59
P-wave duration 2 (OBS2)	0.00	0.50	−0.12 to 0.25
P-wave duration 2 (OBS3)	0.06	0.25	−0.07 to 0.33
P-wave duration 3 (average—seconds)	0.08	0.25	−0.09 to 0.37
P-wave duration 3 (OBS1)	0.00	0.51	−0.31 to 0.41
P-wave duration 3 (OBS2)	−0.02	0.57	−0.24 to 0.33
P-wave duration 3 (OBS3)	0.03	0.39	−0.11 to 0.29
Average P-wave (average—seconds)	0.08	0.23	−0.08 to 0.37
Average P-wave (OBS1)	0.07	0.38	−0.30 to 0.50
Average P-wave (OBS2)	−0.02	0.59	−0.16 to 0.24
Average P-wave (OBS3)	0.05	0.27	−0.06 to 0.27
PR interval 1 (average—seconds)	0.13	0.32	−0.44 to 0.60
PR interval 1 (OBS1)	0.10	0.34	−0.38 to 0.56
PR interval 1 (OBS2)	0.01	0.48	−0.41 to 0.48
PR interval 1 (OBS3)	0.26	0.16	−0.26 to 0.67
PR interval 2 (average—seconds)	−0.06	0.59	−0.60 to 0.47
PR interval 2 (OBS1)	0.00	0.50	−0.47 to 0.49
PR interval 2 (OBS2)	0.09	0.35	−0.35 to 0.54
PR interval 2 (OBS3)	−0.20	0.76	−0.66 to 0.35
PR interval 3 (average—seconds)	0.05	0.43	−0.51 to 0.55
PR interval 3 (OBS1)	0.14	0.30	−0.37 to 0.59
PR interval 3 (OBS2)	−0.03	0.55	−0.47 to 0.45
PR interval 3 (OBS3)	−0.05	0.57	−0.59 to 0.48
Average PR (average—seconds)	0.02	0.47	−0.54 to 0.53
Average PR (OBS1)	0.09	0.37	−0.39 to 0.55
Average PR (OBS2)	0.02	0.47	−0.40 to 0.49
Average PR (OBS3)	−0.06	0.58	−0.58 to 0.47

Variable	ICC	P value	95% CI
QRS duration 1 (average—seconds)	0.34	0.07	−0.12 to 0.71
QRS duration 1 (OBS1)	0.21	0.23	−0.36 to 0.65
QRS duration 1 (OBS2)	0.21	0.23	−0.36 to 0.65
QRS duration 1 (OBS3)	0.23	0.13	−0.13 to 0.61
QRS duration 2 (average—seconds)	0.37	0.08	−0.11 to 0.74
QRS duration 2 (OBS1)	0.21	0.21	−0.29 to 0.63
QRS duration 2 (OBS2)	0.46	0.03	−0.01 to 0.77
QRS duration 2 (OBS3)	0.17	0.17	−0.11 to 0.53
QRS duration 3 (average—seconds)	0.22	0.16	−0.20 to 0.61
QRS duration 3 (OBS1)	0.07	0.40	−0.49 to 0.56
QRS duration 3 (OBS2)	−0.11	0.65	−0.63 to 0.43
QRS duration 3 (OBS3)	0.14	0.23	−0.18 to 0.52
Average QRS (average—seconds)	0.34	0.07	−0.10 to 0.70
Average QRS (OBS1)	0.37	0.09	−0.19 to 0.74
Average QRS (OBS2)	0.37	0.07	−0.13 to 0.73
Average QRS (OBS3)	0.10	0.23	−0.11 to 0.43
RR interval 1 (average—seconds)	0.99	<0.001	0.98 to >0.99
RR interval 1 (OBS1)	0.98	<0.001	0.96 to 0.96
RR interval 1 (OBS2)	>0.99	<0.001	0.99 to >0.99
RR interval 1 (OBS3)	0.99	<0.001	0.98 to >0.99
RR interval 2 (average—seconds)	0.86	<0.001	0.65 to 0.95
RR interval 2 OBS1)	0.78	<0.001	0.48 to 0.92
RR interval 2 (OBS2)	0.81	<0.001	0.54 to 0.93
RR interval 2 (OBS3)	0.88	<0.001	0.69 to 0.96
RR interval 3 (average—seconds)	0.98	<0.001	0.94 to 0.99
RR interval 3 (OBS1)	0.94	<0.001	0.92 to 0.99
RR interval 3 (OBS2)	0.98	<0.001	0.94 to 0.99
RR interval 3 (OBS3)	0.98	<0.001	0.95 to 0.99
Average RR (average—seconds)	0.99	<0.001	0.98 to >0.99
Average RR (OBS1)	0.99	<0.001	0.97 to >0.99
Average RR (OBS2)	0.99	<0.001	0.98 to >0.99
Average RR (OBS3)	>0.99	<0.001	0.99 to >0.99
QT interval 1 (average—seconds)	0.20	0.15	−0.13 to 0.57
QT interval 1 (OBS1)	0.15	0.24	−0.23 to 0.55
QT interval 1 (OBS2)	−0.02	0.56	−0.19 to 0.29
QT interval 1 (OBS3)	0.31	0.09	−0.11 to 0.68
QT interval 2 (average—seconds)	0.16	0.17	−0.12 to 0.53
QT interval 2 (OBS1)	0.13	0.27	−0.26 to 0.55
QT interval 2 (OBS2)	0.02	0.44	−0.18 to 0.35

Variable	ICC	P value	95% CI
QT interval 2 (OBS3)	0.12	0.22	−0.13 to 0.47
QT interval 3 (average—seconds)	0.23	0.16	−0.10 to 0.62
QT interval 3 (OBS1)	0.37	0.09	−0.11 to 0.74
QT interval 3 (OBS2)	0.19	0.17	−0.10 to 0.56
QT interval 3 (OBS3)	0.21	0.15	−0.11 to 0.58
Average QT (average—seconds)	0.20	0.16	−0.11 to 0.57
Average QT (OBS1)	0.20	0.15	−0.15 to 0.58
Average QT (OBS2)	0.07	0.27	−0.11 to 0.37
Average QT (OBS3)	0.24	0.14	−0.12 to 0.62
T peak-end interval 1 (average—seconds)	−0.17	0.84	−0.41 to 0.26
T peak-end interval 1 (OBS1)	−0.13	0.79	−0.34 to 0.26
T peak-end interval 1 (OBS2)	−0.07	0.67	−0.30 to 0.30
T peak-end interval 1 (OBS3)	−0.01	0.51	−0.37 to 0.44
T peak-end interval 2 (average—seconds)	−0.12	0.76	−0.36 to 0.28
T peak-end interval 2 (OBS1)	0.06	0.35	−0.18 to 0.41
T peak-end interval 2 (OBS2)	−0.05	0.64	−0.27 to 0.31
T peak-end interval 2 (OBS3)	−0.30	0.87	−0.69 to 0.229
T peak-end interval 3 (average—seconds)	−0.03	0.63	−0.16 to 0.23
T peak-end interval 3 (OBS1)	0.09	0.24	−0.11 to 0.41
T peak-end interval 3 (OBS2)	−0.04	0.67	−0.19 to 0.24
T peak-end interval 3 (OBS3)	−0.09	0.70	−0.34 to 0.31
Average T peak-end interval (average—seconds)	−0.10	0.80	−0.27 to 0.24
Average T peak-end interval (OBS1)	−0.09	0.74	−0.28 to 0.26
Average T peak-end interval (OBS2)	−0.07	0.74	−0.23 to 0.24
Average T peak-end interval (OBS3)	−0.14	0.77	−0.43 to 0.29

Table 6

Intraclass correlation coefficient (ICC) between three observers for continuous variables over all measurements, and either the smartphone-based method (AliveCor (AC)) or gold standard base-apex method (Televet (TV)) for all 15 horses

Variable	ICC	P value	95% CI
Heart rate (both—bpm)	0.93	<0.001	0.90 to 0.97
Heart rate (AC)	0.93	<0.001	0.85 to 0.97
Heart rate (TV)	0.96	<0.001	0.91 to 0.99
P-wave duration 1 (both—seconds)	0.37	<0.001	0.15 to 0.59
P-wave duration 1 (AC)	0.18	0.11	−0.09 to 0.53
P-wave duration 1 (TV)	0.25	0.03	−0.01 to 0.57
P-wave duration 2 (both—seconds)	0.57	<0.001	0.36 to 0.75
P-wave duration 2 (AC)	0.58	<0.001	0.28 to 0.81
P-wave duration 2 (TV)	0.34	0.01	0.03 to 0.65
P-wave duration 3 (both—seconds)	0.46	<0.001	0.24 to 0.67
P-wave duration 3 (AC)	0.34	0.01	0.04 to 0.67
P-wave duration 3 (TV)	0.22	0.04	−0.03 to 0.54
Average P-wave (both—seconds)	0.55	<0.001	0.33 to 0.73
Average P-wave (AC)	0.48	0.001	0.16 to 0.76
Average P-wave (TV)	0.30	0.02	0.01 to 0.62
PR interval 1 (both—seconds)	0.14	0.06	−0.1 to 0.39
PR interval 1 (AC)	0.19	0.05	−0.01 to 0.52
PR interval 1 (TV)	0.12	0.06	−0.01 to 0.40
PR interval 2 (both—seconds)	0.20	0.04	−0.01 to 0.50
PR interval 2 (AC)	0.27	0.03	−0.00 to 0.64
PR interval 2 (TV)	0.18	0.04	−0.01 to 0.50
PR interval 3 (both—seconds)	0.22	0.04	−0.01 to 0.53
PR interval 3 (AC)	0.33	0.02	0.01 to 0.70
PR interval 3 (TV)	0.16	0.05	−0.01 to 0.47
Average PR (both—seconds)	0.41	0.05	−0.02 to 0.74
Average PR (AC)	0.52	0.02	0.01 to 0.84
Average PR (TV)	0.35	0.04	−0.01 to 0.73
QRS duration 1 (both—seconds)	0.28	0.004	0.07 to 0.52
QRS duration 1 (AC)	0.33	0.02	0.02 to 0.66
QRS duration 1 (TV)	0.18	0.07	−0.05 to 0.50
QRS duration 2 (both—seconds)	0.08	0.21	−0.10 to 0.31
QRS duration 2 (AC)	0.18	0.13	−0.12 to 0.54
QRS duration 2 (TV)	−0.01	0.51	−0.13 to 0.25
QRS duration 3 (both—seconds)	0.05	0.30	−0.12 to 0.28
QRS duration 3 (AC)	−0.05	0.60	−0.29 to 0.33

Variable	ICC	P value	95% CI
QRS duration 3 (TV)	0.12	0.13	−0.07 to 0.44
Average QRS (both—seconds)	0.55	0.005	0.17 to 0.77
Average QRS (AC)	0.69	0.004	0.26 to 0.89
Average QRS (TV)	0.36	0.12	−0.24 to 0.74
RR interval 1 (both—seconds)	0.97	<0.001	0.99 to >0.99
RR interval 1 (AC)	0.99	<0.001	0.98 to >0.99
RR interval 1 (TV)	>0.99	<0.001	>0.99 to >0.99
RR interval 2 (both—seconds)	0.95	<0.001	0.90 to 0.97
RR interval 2 (AC)	0.93	<0.001	0.84 to 0.97
RR interval 2 (TV)	0.97	<0.001	0.92 to 0.99
RR interval 3 (both—seconds)	>0.99	<0.001	1.00 to >0.99
RR interval 3 (AC)	0.99	<0.001	0.98 to >0.99
RR interval 3 (TV)	>0.99	<0.001	0.99 to >0.99
Average RR (both—seconds)	>0.99	<0.001	>0.99 to >0.99
Average RR (AC)	>0.99	<0.001	>0.99 to >0.99
Average RR (TV)	>0.99	<0.001	>0.99 to >0.99
QT interval 1 (both—seconds)	0.60	<0.001	0.40 to 0.77
QT interval 1 (AC)	0.67	<0.001	0.40 to 0.86
QT interval 1 (TV)	0.42	0.001	0.1 to 0.73
QT interval 2 (both—seconds)	0.55	<0.001	0.34 to 0.74
QT interval 2 (AC)	0.53	<0.001	0.22 to 0.79
QT interval 2 (TV)	0.31	0.01	0.03 to 0.63
QT interval 3 (both—seconds)	0.61	<0.001	0.37 to 0.78
QT interval 3 (AC)	0.43	0.002	0.13 to 0.72
QT interval 3 (TV)	0.45	0.002	0.13 to 0.74
Average QT (both—seconds)	0.87	<0.001	0.76 to 0.94
Average QT (AC)	0.83	<0.001	0.60 to 0.94
Average QT (TV)	0.80	<0.001	0.44 to 0.91
T peak-end interval 1 (both—seconds)	0.55	<0.001	0.34 to 0.73
T peak-end interval 1 (AC)	0.40	0.004	0.10 to 0.70
T peak-end interval 1 (TV)	0.45	0.002	0.14 to 0.74
T peak-end interval 2 (both—seconds)	0.53	<0.001	0.32 to 0.72
T peak-end interval 2 (AC)	0.26	0.04	−0.022 to 0.60
T peak-end interval 2 (TV)	0.53	0.001	0.21 to 0.79
T peak-end interval 3 (both—seconds)	0.69	<0.001	0.51 to 0.82
T peak-end interval 3 (AC)	0.32	0.01	0.03 to 0.64
T peak-end interval 3 (TV)	0.57	<0.001	0.26 to 0.81
Average T peak-end interval (both—seconds)	0.87	<0.001	0.76 to 0.93
Average T peak-end interval (AC)	0.66	0.005	0.23 to 0.88

Variable	ICC	P value	95% CI
Average T peak-end interval (TV)	0.84	<0.001	0.60 to 0.94

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