## Manuscript Details

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| **Manuscript number** | JEVS_2018_29_R1 |
| **Title** | Evaluation of a smartphone electrocardiograph in healthy horses: comparison with standard base-apex electrocardiography |
| **Article type** | Research paper |

**Abstract**

A good diagnostic accuracy of smartphone-based electrocardiography in the evaluation of heart rate, heart rhythm and ECG measurements has been reported in humans, dogs and cats. The aim of this study was to assess the feasibility of smartphone-based electrocardiography in horses. Fifty healthy adult horses were enrolled. Standard base-apex ECG and smartphone ECG were simultaneously recorded in each horse. All ECGs were reviewed by one blinded operator, who judged whether tracings were acceptable for interpretation and performed electrocardiographic measurements. Agreement between smartphone and standard base-apex ECG in the analysis of tracings was evaluated. Smartphone ECG tracings were interpretable in 48/50 (96%) cases. A perfect agreement between smartphone and standard ECG tracings was found in the assessment of heart rate. Heart rate automatically measured by the smartphone application was not reliable. In terms of electrocardiographic waves and interval duration, minimal differences of no clinical value were found between smartphone and standard ECG. Agreement was found for QRS complex polarity evaluation, but not for P wave polarity. Baseline artefacts were rare but significantly higher in the smartphone ECG tracings compared to standard ECG. The smartphone ECG can record single-lead ECG tracings of an adequate quality for interpretation in horses. The smartphone ECG could represent an additional tool for the electrocardiographic evaluation of horses, but is not a substitute for the standard base-apex ECG.

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| **Keywords** | Equine; Cardiology; Electrocardiography; Smartphone; Validation |

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| **Suggested reviewers** | Josefa Fernandez-del Palacio, Oriol Domenech, ALBERTO TARDUCCI |

## Submission Files Included in this PDF

**File Name  [File Type]**

Vezzosi et al., Cover letter post revision.docx  [Cover Letter]

Answers to reviewers.docx  [Response to Reviewers]

Vezzosi et al., Highlights.docx  [Highlights]

Vezzosi et al., main text_revised.docx  [Manuscript File]

Fig. 1.tiff  [Figure]

Fig. 2.tif  [Figure]

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Fig. 4 A and B.tif  [Figure]

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Vezzosi et al. Ethical Statment.docx  [Ethical Statement]

Pisa, 4th March 2018

To

Editor-in-Chief

*Journal of Equine Veterinary Science*

Dear Editor,

here is our paper titled "**Evaluation of a smartphone electrocardiograph in horses: comparison with standard base-apex electrocardiography**", authored by Vezzosi et al. and revised according to the reviewers' comments and suggestions (JEVS_2018_29).

This study was approved by the Ethical Committee (N. 45965/2016), University of Pisa and totally supported by funds from the University of Pisa. The manuscript has not been published or submitted for publication elsewhere. Authors' contribution to the manuscript is equally distributed and no conflict of interest exists. All the authors have been approved the manuscript.

If further information is needed or you have any questions or requires, please do not hesitating to contact me.

Yours sincerely,

Dr. Tommaso Vezzosi

**REPLIES TO REVIEWERS**

The authors (AU) would like to thank the reviewers (RW) for taking the time to review this manuscript. We found the comments appropriate and very useful. All the points have been addressed and corrections have been made to the manuscript accordingly. The changes to the manuscript are highlighted in yellow.

The replies to the reviewers' comments are reported below.

**Reviewer 1 (yellow)**

RW: Change the title adding "healthy"

**AU: Done (see line 1).**

RW: "Specify in which period of the year the ECG recording was performed…"

**AU: Done (see lines 72-73).**

RW: "Did the authors use ECG filters"?

**AU: Done (see lines 90-91).**

RW: "…How did you choose the position? Do you always used the same intercostal space?"

**AU: Done (see lines 96-97).**

RW: Line 146. Remove references from the results.

**AU: Removed.**

RW: Line 182. Modify in "QRS complex duration measured on standard and smartphone ECG tracings showed a bias of…".

**AU: Done (see lines 189-190).**

RW: Line 162. Would you consider if these results would have been different in case the amplitude used in the study would have been 10 mm=1 mV rather than 20mm=1mV for the Smartphone ECG?

**AU: Thank you very much for your interesting comment. During the study design we decide to use the 20mm/mV setting because using 10mm/mV the amplitude of the QRS complexes was very low on the smartphone screen in most horses and the application did not display the heart rate in these cases. If the application does not detect the heart rate, it does not record the ECG. Thus, we decided to record all ECG at 20 mm/mV to standardize the recording in the study and to obtain the recording in most horses.**

RW: Line 236: please modify "The smartphone ECG can record single-lead ECG tracings of a good quality in healthy horses".

**AU: Done (see line 244).**

RW: Fig. 1: The P wave polarity in this image seems to be negative…".

**AU: In our opinion, the P wave in the figure 1 shows both a negative (beginning) and a positive (ending) component. So, it can be defined as "biphasic". It is not completely "negative". The P wave had this biphasic morphology in most smartphone ECG tracings (75%). Thus, we choose to show this figure in the manuscript.**

RW: Fig. 2: Please provide the ECG tracing with a paper speed = 25mm/sec as it has been described in Materials and Methods.

**AU: Thank you very much for your comment. The paper speed of figure 2 is at 25 mm/sec as reported in the M&M. There was a mistake in the figure caption. We modified accordingly (see line 328).**

**Reviewer 2 (green)**

RW: Introduction. Line 67: ... and ECG measurements compared with conventional ECG.

**AU: The sentence has been added to the main text (see line 67).**

RW: Material and methods. Line 70: Were all the horses owned by the university or the owners of the department?

**AU: Yes, all the horses were property of the Department of Veterinary Sciences, University of Pisa.**

RW: Line 80-81: How were the electrodes of conventional ECG placed on the skin? Please, indicate whether they were alligator clips, discs….

**AU: The placement of the electrodes has been better clarified in the text (see line 82).**

RW: Line 98-99: I suggest to move this sentence after line 83.

**AU: The sentences have been reorganized (see lines 87-89 and 103-104).**

RW: How were the ECG recordings synchronized with both methods? And, ECG measurements? How did you select the same cardiac cycles for measurements? Please indicate. It is not clear.

**AU: As indicated at lines 92-93, the smartphone ECG tracing was simultaneously recorded, starting and ending at the same time as the standard ECG. This was possible because the smartphone ECG started storing the tracing when the applications began to show the HR on the screen, thus at that time a second operator began to store the tracings on the standard ECG machine. Using this technique, we were sure that both recordings were stored simultaneously.**

RW: Line 117: normal range is most appropriate for HR than "normal".

**AU: Modified accordingly (see lines 124-126).**

RW: Results. Line 186. It would be interesting for readers to include a figure of the most common artifacts recorded by smartphone. Also, a figure of two tracings obtained by conventional ECG and smartphone showing different polarity of P waves.

**AU: Thanks for the suggestion. We added both the images requested (see figures 3 and 4).**

RW: Line 187. A question: You have attempted to improve the contact of the electrodes of the smartphone in horses in which they have obtained artefacts? Please clarify.

**AU: Yes. In cases with many artefacts we tried to improve the contact of the electrodes and the quality of ECG signal on the smartphone using more alcohol or slight modifying the orientation of the smartphone. However, these attempts were not useful in most cases since the artefacts were due to skin or limb movements.**

**HIGHLIGHTS**

1) The aim was to assess the feasibility of smartphone electrocardiography in horses.
2) The smartphone device could record good quality ECG tracings in 96% of horses.
3) Reliable heart rate was obtained when manually measured on digitized tracings.
4) The smartphone device was reliable for measurement of ECG wave and intervals.
5) The smartphone ECG can be useful for electrocardiographic screening in horses.

# Evaluation of a smartphone electrocardiograph in healthy horses: comparison with standard base-apex electrocardiography

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**Abstract**

A good diagnostic accuracy of smartphone-based electrocardiography in the evaluation of heart rate, heart rhythm and ECG measurements has been reported in humans, dogs and cats. The aim of this study was to assess the feasibility of smartphone-based electrocardiography in horses.

Fifty healthy adult horses were enrolled. Standard base-apex ECG and smartphone ECG were simultaneously recorded in each horse. All ECGs were reviewed by one blinded operator, who judged whether tracings were acceptable for interpretation and performed electrocardiographic measurements. Agreement between smartphone and standard base-apex ECG in the analysis of tracings was evaluated.

Smartphone ECG tracings were interpretable in 48/50 (96%) cases. A perfect agreement between smartphone and standard ECG tracings was found in the assessment of heart rate. Heart rate automatically measured by the smartphone application was not reliable. In terms of electrocardiographic waves and interval duration, minimal differences of no clinical value were found between smartphone and standard ECG. Agreement was found for QRS complex polarity evaluation, but not for P wave polarity. Baseline artefacts were rare but significantly higher in the smartphone ECG tracings compared to standard ECG.

The smartphone ECG can record single-lead ECG tracings of an adequate quality for interpretation in horses. The smartphone ECG could represent an additional tool for the electrocardiographic evaluation of horses, but is not a substitute for the standard base-apex ECG.

**Keywords**: Equine; Cardiology; Electrocardiography; Smartphone; Validation.

## Introduction

In equine species, surface electrocardiography (ECG) is the gold standard for the diagnosis of arrhythmias, both at rest and during exercise [1]. In horses, a standard ECG is usually performed at rest using the base-apex lead placement [2]. The procedure requires an electrocardiographic machine, cables and electrodes. Therefore, a standard ECG is not always practical in emergency and sports medicine. Telemetric systems and Holter monitoring are used in horses for ECG recordings during and post exercise [3]. However, this technology can be expensive and requires the use of cables and electrodes, and a recorder is usually fixed on the horse with bandages or dedicated vests. A wireless, smartphone-based technology for ECG recording could be an attractive complementary tool for electrocardiographic screening in horses.

In humans, smartphone devices recording a one-lead ECG tracing have been developed using specific adaptors and software [4-10]. Several studies have highlighted the accuracy of smartphone ECG tracings in measuring heart rate (HR), evaluating heart rhythm [11-18] and detecting ECG changes associated with myocardial ischemia [19,20].

Similarly, smartphone ECG technology can provide adequate tracings, with an accurate assessment of HR and heart rhythm in dogs and cats [21,22].

To the best of the authors' knowledge, no studies on the use of smartphone ECG in the horse have been performed. The present study thus assessed the feasibility of smartphone-based electrocardiography in horses, and its accuracy to evaluate HR and ECG measurements compared with conventional ECG.

## Materials and methods

*Animals*

A total of 50 healthy horses owned by the Department of Veterinary Sciences of the University of Pisa, were enrolled in this study. The study period was from March 2016 to November 2017. The research protocol was approved by the Institutional Animal Care and Use Committee of the University of Pisa (45965/2016). All the horses were considered healthy based on history, physical examination, electrocardiography and echocardiography.

*ECG acquisition and analysis*

After the horses had been familiarized with the examination room, a standard base-apex ECG (MAC 1600 ECG system, GE Healthcare, USA) was acquired for 30 seconds in conscious, non-sedated horses in standing position. Surface electrodes were attached to the skin by alligator clips. The left arm electrode (positive) was positioned at the cardiac apex, the right arm electrode (negative) was placed two thirds of the way down the right jugular groove, and the third electrode was placed at any site remote from the heart. Lead I was selected to record the ECG [23].

No clipping was performed, and only alcohol was rubbed on the skin to maintain electrical contact. The same operator (C.B.) always recorded the standard ECG. For each horse, the ECG tracings obtained with the standard base-apex method were printed at a paper speed of 25 mm/s with a gain of 5 mm/mV. A sampling frequency of 1000 Hz for standard ECG acquisition was used, with a 100 Hz low-pass filter and a 0.3–0.5 Hz high-pass filter.

A smartphone ECG tracing was simultaneously recorded, starting and ending at the same time as the standard ECG, using a single-lead bipolar ECG (AliveCor Veterinary Heart Monitor, AliveCor, USA) and its software interface (AliveECG Vet, AliveCor, USA), as previously described [22]. The smartphone ECG tracings were recorded with an iPhone 5S (Apple, USA). The smartphone device was placed on the left chest wall at the level of the olecranon (precordial area). A dorso-ventral orientation with a 30° cranial inclination of the smartphone case was used in each horse, with the camera side of the smartphone located ventrally (Fig. 1). A small amount of alcohol was rubbed on the left precordial area to obtain a good quality smartphone ECG signal. Smartphone ECG recordings were automatically digitized by the device, sent via email and stored as a PDF (Fig. 2). The same operator (M.P.) recorded all the smartphone ECGs. The same operator (M.P.) recorded all the smartphone ECGs.

For each horse, the ECG tracings obtained with the standard base-apex method were printed at a paper speed of 25 mm/s with a gain of 5 mm/mV, while the ECG tracings obtained with the smartphone ECG, were printed at a paper speed of 25 mm/s with a gain of 20 mm/mV.

In a blinded fashion, all smartphone ECG tracings were reviewed by one expert operator (T.V.) to judge whether the tracings were acceptable for interpretation. Tracings were considered acceptable for interpretation if baseline artifacts were absent for at least 80% of each tracing. Baseline artifacts were defined as ECG segments in which P waves and/or QRS complexes could not be identified.

The same operator (T.V.) performed ECG measurements on all tracings, using lead I of the standard ECG and the only available lead of the smartphone ECG.

The following variables were measured from both ECG tracings for each horse: HR (bpm), duration of P wave (ms), PR interval (ms), QRS complex (ms), and QT interval (ms). Each wave or interval duration was calculated using three randomly selected heartbeats and the mean of the three measurements was used for statistical analysis. The mean HR was calculated as the mean value of three independent HR calculations from three different areas on the ECG tracings. The number of QRS complexes was counted over six seconds and multiplied by ten to calculate the HR per minute (bpm). The mean HR calculated automatically by the smartphone application (App HR) was also recorded. The normal range for HR was defined as between 28 and 44 bpm [2]. Bradycardia was defined when the HR was below 28 bpm, and tachycardia when the HR was greater than 44 bpm [2]. P wave and QRS complex polarity were evaluated. Presence (yes, no) and duration (ms) of baseline artifacts were assessed.

*Statistical analysis*

The analysis was performed only with paired ECG tracings that were acceptable for interpretation, and the standard ECG was set as the reference method. Cohen's κ test was used to calculate the agreement between the smartphone ECG and standard ECG for HR classification (normal, bradycardia, tachycardia), P wave (positive, negative, biphasic) and QRS polarity (positive, negative). The κ coefficient was interpreted as follows: values ≤ 0.20 as no agreement, 0.21–0.40 as fair, 0.41–0.60 as moderate, 0.61–0.80 as good, 0.81–0.99 as very good, and 1 as perfect agreement. If the contingency table reported one or more values equal to zero, Cohen's kappa could not be calculated, thus in these cases the percentage of agreement was used. Baseline artifact duration was measured in ms, and expressed as median (range). Differences in the prevalence of baseline artifacts on smartphone and standard ECG tracings were evaluated using Fisher's exact test. Using the Bland-Altman test, bias and 95% limits of agreement were calculated for HR, duration of the P wave, PR interval, QRS complex and QT interval to analyze the differences between the smartphone and standard ECG.

Statistical analyses were performed with commercial software (Microsoft Excel, 2011; GraphPad Prism 6, USA). A *P* value of $<0.05$ was considered significant.

## Results

### *Animals and feasibility*

Thirty-two out of 50 horses were mares (64%), 15/50 (30%) were stallions, and 3/50 (6%) were geldings, with a median age of 5 years (range: 2-29 years), median body weight of 474 kg (range: 300-652 Kg) and median BCS of 3/5 (range: 3-4/5). The horses were of different breeds: 34/50 were Trotters (68%), 6/50 Thoroughbreds (12%), and 10/50 Standardbreds (20%).

On standard ECG tracings, all horses enrolled in this study showed sinus rhythm. Among smartphone ECG tracings, 48/50 (96%) were judged acceptable for interpretation. The two smartphone ECG tracings considered inadequate for interpretation showed baseline artifacts in most of the tracings, and were excluded from the analysis.

### *Heart rate*

According to the standard ECG, 34/48 (71%) horses had a normal HR, 14/48 (29%) had tachycardia, and no horses showed bradycardia. A perfect agreement ($\kappa = 1$; 95% CI: -1, 1) between the smartphone and standard ECG was found in the HR classification when it was manually measured on digitized tracings. The bias between the HR manually measured on standard ECG and smartphone ECG was 0.2 bpm (95% CI: -6.0, 6.4 bpm).

The App HR was less accurate in detecting actual HR, with only a fair level of agreement compared to the standard ECG (κ = 0.24; 95% CI: -0.1, 0.4). The bias between App HR and HR manually measured on standard ECG tracings was -27.1 bpm (95% CI: -105.1, 51.0 bpm). In most cases (22/48, 46%), the App HR overestimated the HR measured on standard ECG.

*P wave, PR interval, and QT interval duration*

P wave duration measured on standard and smartphone ECG tracings showed a bias of 11.2 ms (CI 95%: -16.6, 39.1 ms), PR duration had a bias of 24.4 ms (CI 95%: -18.4, 67.1 ms), and QT duration showed a bias of 0.8 ms (CI 95%: -54.0, 55.6 ms). On the standard ECG tracings, the P polarity was positive in 31/48 (65%) cases and biphasic in 17/48 (35%). On the smartphone ECG tracings, the P polarity was positive in 12/48 (25%) and biphasic in 36/48 (75%) cases. No agreement was found between the two methods in the P polarity evaluation (κ = -0.05; 95% CI -0.3, 0.1).

*QRS complex analysis*

The QRS complexes showed a negative polarity on standard ECG in all 48 analyzed cases (100%). On the smartphone ECG tracings, the QRS polarity was negative in 46/48 (96%) cases and positive in 2/48 (4%). Hence, the resulting agreement between the two methods in the QRS polarity evaluation was high (percentage of agreement: 96%). The QRS complex duration measured on standard and smartphone ECG tracings showed a bias of 6.5 ms (CI 95%: -23.4, 36.3 ms).

*Artefacts*

Of the 48 smartphone ECG tracings judged as interpretable, 11/48 (23%) presented baseline artifacts. The median duration of baseline artifacts on smartphone ECG tracings was 1480 ms (range: 960-3680 ms), corresponding to a median of 5% of the total duration of each ECG tracing. On the relative standard ECG tracings, only 1/48 horse (2%) had baseline artifacts (duration: 560 ms). The presence of artifacts was significantly higher in the smartphone ECG tracings than in standard ECG tracings (P=0.0037).

## Discussion

In our investigation, the smartphone ECG tracings were interpretable in 96% of cases. These results are in line with findings in humans where smartphone ECG tracings were interpretable in 87-99.6% of patients [8,9,17,24] and in dogs where traces were considered interpretable in 97.6% [22]. Only two smartphone ECG tracings were judged as non-interpretable due to the presence of too many baseline artefacts. In the other smartphone ECG tracings, 23% had short segments of baseline artefacts, compatible with motion or muscle tremor artifacts, however they did not hinder the assessment of mean HR and measurement of the electrocardiographic waves and intervals.

In our study, the smartphone ECG was reliable in measuring HR in horses, similar to findings in dogs, where a perfect agreement was found between smartphone and standard ECG in the evaluation of HR [22]. We observed the greatest accuracy when the HR was manually measured on digitized tracings. The accuracy of App HR was very poor in comparison to manually measured HR on digitized tracings.

Furthermore, the App HR in horses proved less accurate than has been found in dogs [22]. In most smartphone ECG tracings, the App HR overestimated the real HR possibly because the App HR frequently interpreted tall T waves as QRS complexes. In a few horses, the App HR was totally unreliable.

Regarding the evaluation of the ECG waves and interval durations, the smartphone ECG was reliable, with minimal differences of no clinical value from the standard ECG. A good agreement in the analysis of the QRS complex polarity was also found, and in most horses, the QRS complexes showed the same polarity on smartphone ECG and standard ECG tracings. This result is in line with a previous study in dogs, in which the smartphone ECG showed a good agreement in the analysis of the QRS complex, in assessing both duration and polarity [22].

No agreement in the analysis of P wave polarity was found between the two methods. To the authors' knowledge, no previous studies in veterinary medicine have been carried out on the agreement between standard ECG and smartphone ECG in P polarity evaluation, thus our results cannot be compared with the literature.

Our investigation has some limitations. Firstly, no significant arrhythmias were detected in this study, thus no statistical analysis was performed in order to assess the diagnostic accuracy of the smartphone ECG in detecting cardiac arrhythmias. However, this is the first study to evaluate the feasibility of the smartphone ECG in recording good quality tracings in horses. Further studies are needed to evaluate the diagnostic accuracy of smartphone ECG in detecting arrhythmias in horses. Moreover, the smartphone tracings were acquired by only one operator and another blinded operator judged whether or not they were acceptable for interpretation. Inter-operator variability in the quality of ECG recording and interpretation was not evaluated.

## Conclusions

The smartphone ECG can record single-lead ECG tracings of a good quality in healthy horses. It is reliable in the evaluation of HR and in the measurement of electrocardiographic waves and intervals. Smartphone ECG technology could represent a reliable additional tool in the electrocardiographic evaluation of horses, however it is not a substitute for standard base-apex ECG. Further studies are needed to assess the diagnostic value of the smartphone ECG in the diagnosis of arrhythmias in horses.


## Funding

This study was totally supported by funds from the University of Pisa.


## References


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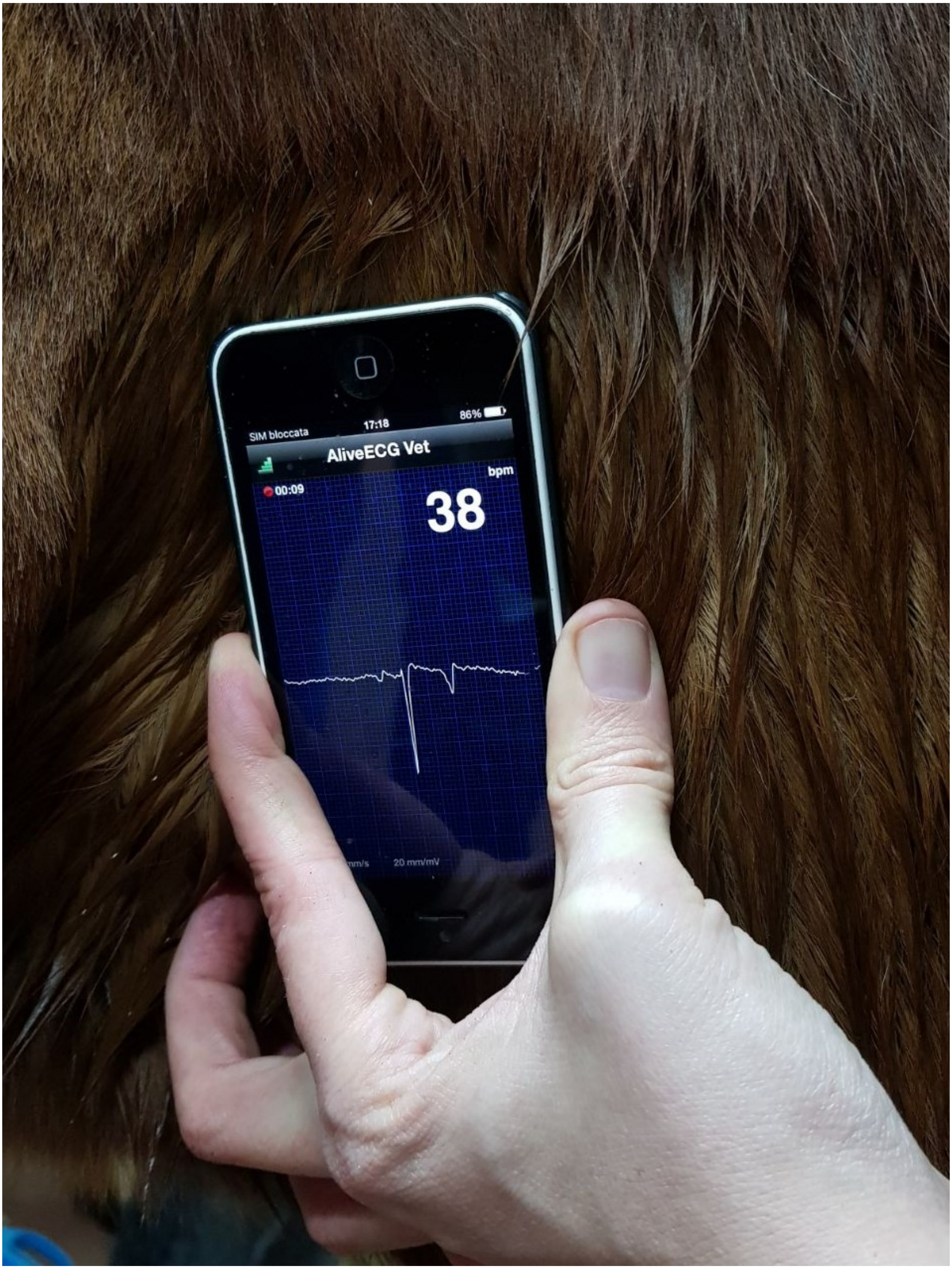
## Figure legends

Fig. 1. Dorso-ventral orientation with a 30° cranial inclination of the smartphone, with the camera side of the smartphone located ventrally.

Fig. 2. Smartphone ECG tracing showing sinus rhythm in a horse. Paper speed = 25 mm/s; 20 mm/mV.

Fig. 3. Smartphone ECG tracing showing baseline artifacts in a horse. Paper speed = 25 mm/s; 20 mm/ mV.

Fig. 4. Standard ECG (A) and smartphone ECG (B) tracings showing different P wave polarity in a horse. Paper speed = 25 mm/s (A and B); 5 mm/mV (A) and 20 mm/mV (B).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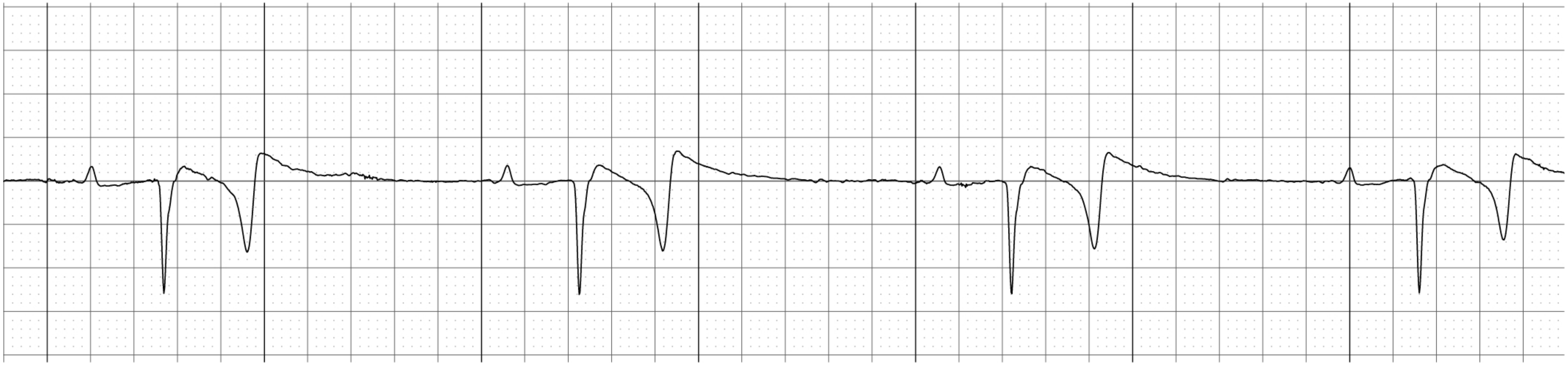

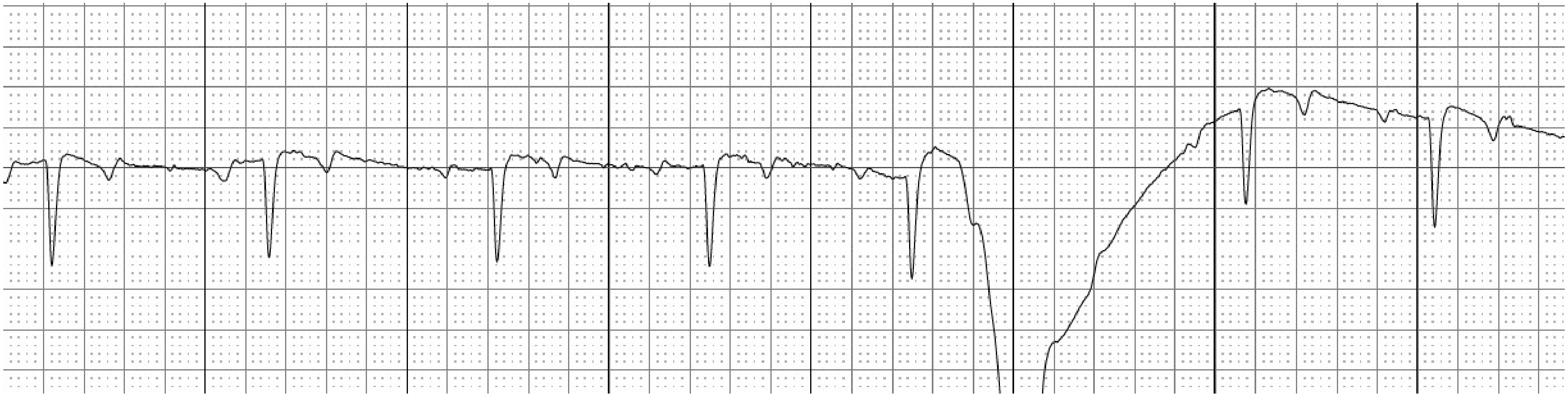


A
B

**CONFLICT OF INTEREST**

Dear Editor,

The Authors' contribution to the manuscript is equally distributed and no conflict of interest exists.

Yours sincerely,

Dr. Tommaso Vezzosi

**ETHICAL STATEMENT**

Dear Editor,

this *in vivo* study was approved by the Institutional Animal Care and Use Committee of the University of Pisa (D.R. prot. N. 45965/2016). The University of Pisa owned the horses included in the study.

Yours sincerely,

Dr. Tommaso Vezzosi