Evaluation of the performance of smartphone-based ECG devices in white rhinoceroses (*Ceratotherium simum*)

Master's thesis

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Abstract

Monitoring cardiac activity during immobilisation of white rhinoceroses (*Ceratotherium simum*) helps identifying potential immobilisation-related complications, such as dysrhythmias and hypoxemia. However, the use of conventional electrocardiogram (ECG) equipment in the field is often limited by logistical constraints. Smartphone-based ECG devices, such as the KardiaMobile (AliveCor, USA), have been shown to offer a portable and affordable alternative in various domesticated species, but their reliability in white rhinoceroses has not yet been evaluated.

This study aimed to assess the comparability and agreement between a modified version of the KardiaMobile and the more conventional Televet 100 (Televet, Germany) ECG devices in white rhinoceroses under field conditions. The ECG tracings were recorded simultaneously with both devices during routine dehorning operations. 13 rhinoceroses were included in the analysis based on signal quality and the ability to synchronize tracings. Heart rate, durations of the P wave, QRS complex, PR, QT, and RR intervals, as well as amplitudes of the P wave, QRS complex, and T wave, were measured and analysed.

Heart rate, P waves, QRS complexes, and PR interval durations were found to be similar between methods, and good agreement without systematic bias was found. In contrast, QT and RR intervals showed significant differences between devices. Amplitude measurements (P, QRS, and T waves) also differed significantly, suggesting systematic variation related to device characteristics. These results indicate that the modified KardiaMobile device provides comparable measurements to the Televet 100 for heart rate and duration-based ECG parameters in white rhinoceroses but shows reduced reliability for amplitude and specific interval measurements.

The device's portability, low cost, and ease of use make it a valuable tool for basic cardiac monitoring during field immobilisations. However, it should be regarded primarily as a screening or monitoring device rather than a diagnostic alternative to more conventional ECG systems such as Televet 100. Further studies with larger sample sizes and more standardised protocols are recommended to confirm these findings.

Contents

1. Introduction

The white rhinoceros (*Ceratotherium simum*) is one of Africa's most iconic species. Once almost brought to extinction due to the illegal poaching driven by the lucrative rhino horn trade, large-scale conservation efforts have led to a significant recovery in their numbers. The combined efforts of translocation, reintroduction programs and dehorning operations have played a critical role in these successes (Amin *et al.*, 2006; Chimes *et al.*, 2025; Chanyandura *et al.*, 2021). However, the immobilisation of white rhinoceroses for these operations is not without risks. The cardiovascular effects of the drugs commonly used for immobilisation of rhinoceroses can lead to serious complications, including hypoxemia and dysrhythmias (Buss *et al.*, 2015; Buss *et al.*, 2016; Mosing *et al.*, 2020; Nasr *et al.*, 2021).

Electrocardiograms (ECG) are widely used for monitoring heart rhythm during anaesthesia in both human and veterinary medicine. The use of ECG allows for early detection of dysrhythmia and thereby helps to decrease the risks of anaesthetic procedures (Flegal *et al*., 2009). Applying this technology on rhinoceros during immobilisation would therefore reduce the risks associated with these operations and consequently contribute to the success of conservation efforts. However, logistical challenges, such as the remote and inaccessible locations where rhinoceros immobilisations often occur, make the use of conventional ECG devices impractical. As a result, ECG monitoring is rarely implemented in the field.

Smartphone-based ECG devices offer a potential solution to these logistical challenges. They are compact, affordable, and user-friendly, and therefore more practical for use in remote locations compared to more conventional ECG equipment. These devices have demonstrated reliability in domestic species, such as dogs and horses (Alberti *et al.*, 2020; Welsch-Huston *et al.*, 2020; Romito *et al.*, 2023; Spitale *et al.*, 2024;), but their performance in white rhinoceroses is currently unknown.

This study sought to evaluate the use of smartphone-based ECG devices KardiaMobile (AliveCor, USA) in white rhinos by comparing it to the more conventional veterinary ECG device Televet 100 (Televet, Germany) for the following cardiac parameters: heart rate, wave lenght (P wave and QRS complex) and interval (PR, QT and RR) durations, as well as amplitudes (P wave, QRS complex and T wave). It was hypothesised that the measurements of these cardiac parameters would not be statistically different compared to the measurements

obtained with Televet 100. Demonstrating their utility in field conditions could lead to an increase of implementation of ECGs in rhino immobilisation procedures, ultimately reducing risks during immobilisation and contributing to the conservation of this emblematic species.

2. Material and Methods

2.1. Study Design

A comparative field study was performed, evaluating the performance of the smartphone-based ECG device (KardiaMobile) against a more conventional ECG device (Televet 100) during the immobilisation of white rhinoceros. Data collection was conducted during a routine dehorning operation; no animals were immobilised solely for the purpose of this research. Data collection was therefore opportunistically.

2.2. Study population and location

Data was collected from 21 white rhinoceroses. Table 1 show the sexes, age categories (based on Emslie *et al*., 1995) of the rhinoceroses included in this study. The rhinoceroses were selected based on accessibility during the dehorning procedure. The study was conducted at a private game reserve bordering the Kruger National Park, Mpumalanga, South Africa.

Table 1. Sex and age class of the white rhinoceroces (Ceratotherium simum) that were sampled for this study.

Sex	Age Class	Number
Male	C	1
Male	D	1
Male	F	9
Female	C	6
Female	D	1
Female	F	3

Age class for white rhinoceroces (Emslie *et al*., 1995): A = 0–3 months, B = 3 months–1 year, C = 1–2 year, D = 2–3½ year, E = 3½–7 year, F = 7+ years

2.3. Equipment

The following equipment was used for the purpose of this study:

- Modified (according to Vera *et al.,* 2019) KardiaMobile (AliveCor, USA) was used as the smartphone-based ECG device.
- Televet 100 (Televet, Germany) served as the conventional ECG device.

The KardiaMobile is a single-lead ECG device that transmits the electrical signal it records to a smartphone via ultrasonic sound waves. The signal is processed by the Kardia application (AliveCor, USA) on the smartphone, which converts it into an ECG tracing. Each recording lasts 30 seconds, after which the application automatically analyses the tracing for arrhythmias and displays the calculated heart rate. Prior to this study, the KardiaMobile device was tested both on awake rhinoceroses in a zoo and on immobilized rhinoceroses in the field. In these initial trials, signal quality was insufficient for reliable use. The device was therefore modified (based on a study by Vera *et al*., 2019): two ECG stickers (Medi-Trace® Adult, Cardinal Health, Dublin, Ohio, USA) were placed on both electrodes, to which wires were attached and subsequently connected to stickers placed on the rhinoceros. This modification allowed for acquisition of interpretable ECG tracings.

The Televet 100 is a portable ECG device designed for veterinary use. It streams tracings in real time via Bluetooth® to a phone or computer and it also saves them to an SD card so they can be reviewed in detail later with the Televet 100 software (ECG Software Version 7.0.2 Build: 004 Copyright © 2006-2019, Germany). The Televet 100 device had previously been validated in field studies, demonstrating reliable ECG recordings (unpublished data, Eberhardt and Gazendam, 2025). Figure 1 shows both ECG devices in the research setting. The upper device is the modified KardiaMobile, and the lower device the Televet 100.

Figure 1. *Modified KardiaMobile (upper device) and Televet 100 (lower device) are shown in research setting.* Photo by author.

2.4. Immobilisation protocol

The immobilisation and monitoring of the white rhinoceroses followed standard field immobilisation protocols. After locating the rhinoceros from a fixed-wing aircraft, they were darted from a helicopter. The immobilising drug combination consisted of etorphine (Captivon®, etorphine hydrochloride 9.8 mg/ml, Wildlife Pharmaceuticals (Pty) Ltd, RSA),

azaperone (Azaperone 100 mg/ml, V-Tech, RSA), and hyaluronidase (Hyaluronidase, 5000 IU, Kyron Laboratories, RSA) and was administered IM using a dart. The dose of the potent opioid drug was determined based on the age class of the rhinoceroses (Emslie *et al*., 1995). Butorphanol (Butorphanol, 50 mg/ml, Kyron Laboratories, RSA) was given as a partial reversal IV. Complete reversal was achieved with naltrexone hydrochloride (Trexonil®, naltrexone hydrochloride 50 mg/ml, Wildlife Pharmaceuticals (Pty) Ltd, RSA), administered at 20 times the etorphine dose IV. Table 2 gives an overview of the drugs and doses used during the dehorning operation.

Table 2. *Overview of drug doses used for immobilisation of white rhinoceroses (Ceratotherium simum) during the dehorning operation for each different age category.*

Sex	Age Class	Etorphine(mg)	Azaperone(mg)	Hyalase(IU)	Butorphanol(mg)	Naltrexone(mg)
Male	C	3	30	5000	30	60
Female	C	3	30	5000	30	60
Male	D	4	40	5000	40	80
Female	D	3	30	5000	30	60
Male	E/F	5	50	5000	20	100
Female	E/F	4	40	5000	40	80

Age class for white rhinoceroces (Emslie *et al*., 1995): A = 0–3 months, B = 3 months–1 year, C = 1–2 year, D = 2–3½ year, E = 3½–7 year, F = 7+ years

2.5. ECG measurement protocol

As soon as the rhinoceros was accessible, ECG electrodes for both the modified KardiaMobile (mKM) and the Televet 100 (TV) were applied. Only one rhinoceros was processed at the time. For the mKM, two stickers were positioned on the left side of the thorax, behind the forelimb, approximately 20 cm apart vertically. The white wire, attached to the right electrode of the mKM, was connected to the lower sticker, while the black wire, attached to the left electrode, was connected to the upper sticker. This ensured that recordings were collected in a consistent manner.

For TV, four stickers were placed. Three were positioned on the left thorax: two adjacent to the mKM stickers and one approximately 30 cm higher, on average 30 centimetres from the withers. The fourth sticker was placed on the right thorax, about 30 cm ventral to the spine. The leads were connected as follows: green to the lower left sticker, yellow to the middle left sticker, black to the upper left sticker, and red to sticker on the right side of the rhino. Figure 2 and figure 3 show the electrode placement for both devices as performed during this study.

While the TV records a continuous ECG, mKM produces 30-second tracings that are automatically processed. To enable later synchronisation of both recordings for statistical analysis, the TV signal was deliberately interrupted by briefly shaking one of the leads. The disturbance was stopped at the exact moment the mKM was restarted. Using this method, the 30-second mKM segments became clearly identifiable within the continuous TV tracing.

Figure 2. *Electrode placement on left side of the thorax of a white rhinoceros (Ceratotherium simum).* The modified KardiaMobile is shown left on top of the box. A white cable connects to the lower electrode on the rhinoceros and a black cable to the upper electrode. Right on top of the box the Televet 100 is shown inside its protective case. Green, yellow, and black connections attach to the lower, middle, and upper electrodes respectively. Photo by author.

Figure 3. *Electrode placement on right side of the thorax of a white rhinoceros (Ceratotherium simum*). The red cable connection of the Televet 100 device attaches to the electrode on this side of thorax. Photo by author.

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2.6. ECG analysis

Of the 21 rhinoceroses sampled, 13 were included in the ECG analysis. The tracings sampled from these rhinoceroses were selected based on their ability to be synchronised between devices
225 and the presence of minimal artifacts. The tracings of 8 rhinoceroses were excluded from the analysis due to the impossibility to synchronise these tracings for both devices, major artifacts disrupting the ECG tracings and/or a weak signal from either one of the devices making analysis impossible.

After synchronising the ECG tracings from both devices, the duration of the P wave, QRS
230 complex, the PR interval, QT interval, RR interval and amplitudes of P wave, QRS complex and T wave of the first three complete complexes were manually measured, giving a total of 39 tracings (N=39) that were included in the analysis.

The TV tracings were analysed using the TV software, which allows measurement of vertical and horizontal distances on the tracing and automatically converts this into the correspondent
235 time values. Figure 4 and figure 5 show the measurements of the different parameters of a TV ECG tracing. For mKM tracings no such tool was available, so measurements were made manually with a ruler, and the time values were subsequently calculated using Microsoft Excel (Microsoft Corporation, Excel for Microsoft 365, Redmond, WA, USA).

Figure 6 and figure 7 show the measurements of duration-based and amplitude parameters
240 respectively for mKM. The heart rate of mKM was counted by hand from the number of complexes in the tracings in 30 seconds. For TV the specific heart rate for each tracing was calculated using TV software by measuring the RR interval. In the attachments ECG tracings as shown on both devices can be found.

Figure 4. *An example of electrocardiogram tracing measurements for the duration-based parameters on a Televet 100 tracing.*

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Figure 5. *An example of electrocardiogram tracing measurements for amplitudes on a Televet 100 tracing*

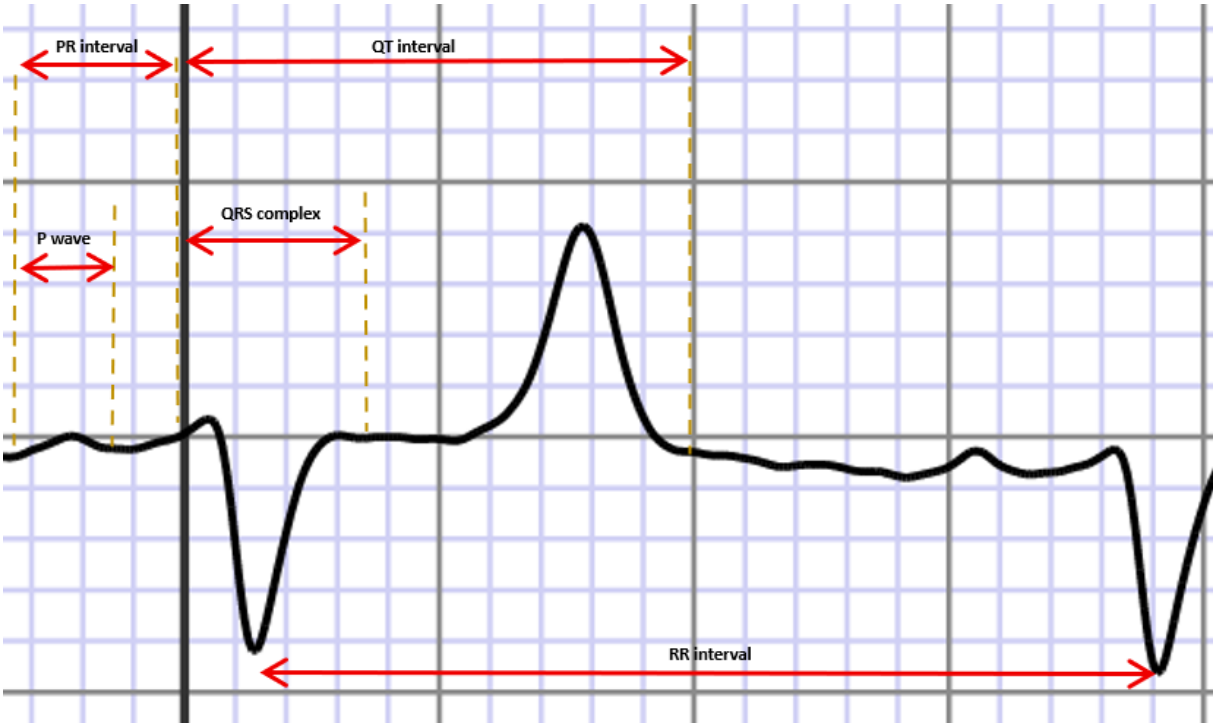

Figure 6. *An example of electrocardiogram tracing measurements for the duration-based parameters on a modified KardiaMobile tracing.*

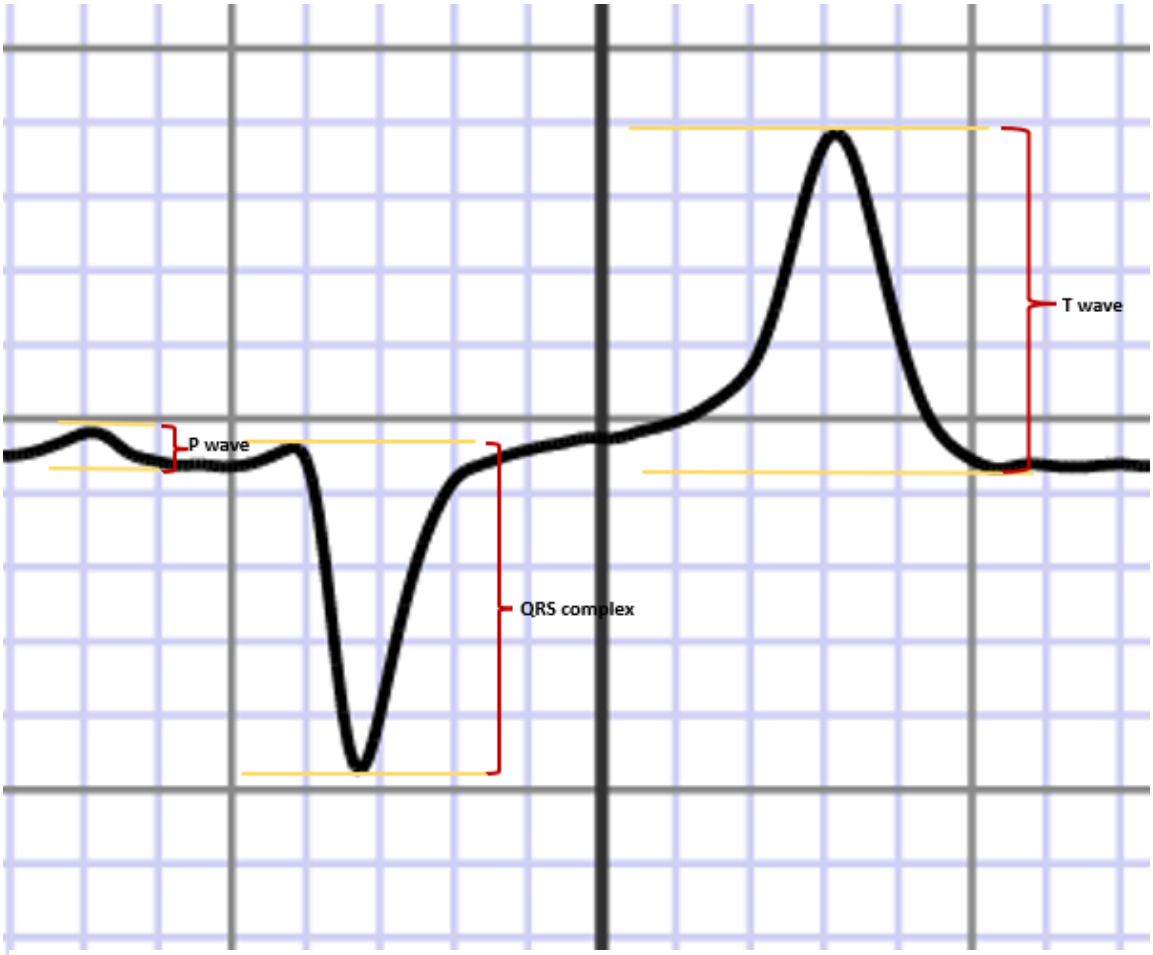

Figure 7. *An example of electrocardiogram tracing measurements for amplitudes on a modified KardiaMobile tracing.*

2.7. Statistical analysis

To determine the agreement between the duration of heart rate, P wave, QRS complex and the PR, QT and RR intervals and the amplitudes of P wave, QRS complex and T wave of the ECG tracings obtained from both devices, a Bland–Altman plot was used. This method assesses the presence of systematic differences between paired measurements (Giavarina, 2015). A t-test was performed to analyse the significance of the differences between the measurements for the various parameters.

All data was recorded in Excel and subsequently imported into IBM SPSS Statistics (Version 30.0; IBM Corp., Armonk, NY, USA) for analysis. To generate the Bland–Altman plots, the mean and difference of each paired measurement for each cardiac parameter were first calculated. Subsequently, the overall mean difference and standard deviation were determined using a one-sample t-test. The mean difference corresponds with the bias between both methods for the Bland-Altman plot. Normal distribution of the differences was verified by interpreting the histograms and performing the Shapiro-Wilk test. The mean difference and standard deviation values were then used to calculate the confidence intervals for the Bland–Altman plot, which serve as the limits of agreement (LOA) for the plot. The plot itself was created as a scatter plot, with the mean of each pair of measurements on the X-axis and their difference on the Y-axis. The mean and corresponding limits of agreement were added as horizontal reference lines. Significance was set at $p \leq 0.05$ with 95% confidence intervals when applicable.

2.8. Ethical considerations

An approval was obtained from the Animal Ethical Commission (AEC) to conduct the immobilisation for dehorning, AEC approval number: WLVAEC-2025-003. The form can be found in the attachments. No animals were immobilised specifically for this study. Data was collected opportunistically during a dehorning operation.

3. Results

3.1. Durations (seconds)

3.1.1. P wave

In the P wave measurement data one outlier was identified, and as a consequence the data was not normally distributed. This outlier was likely caused by human error during measurement of the ECG complexes. After removal of this outlier the differences were normally distributed (figure 8, Shapiro–Wilk, $p = 0.037$). No significant difference was detected ($p = 0.465$), with a mean difference of –0.00184 seconds (95% CI: –0.0069 to 0.0032), SD 0.01538, and SE 0.00250. The Bland–Altman analysis indicated a bias of –0.00184 seconds and the limits of agreement (LOA) of –0.03198 to 0.01177 seconds. The plot displayed a scattered pattern, indicating random variation without systematic bias (see figure 15).

3.1.2. QRS complex

The differences of the QRS complex were normally distributed (figure 9, Shapiro–Wilk, $p = 0.740$). No significant difference was found between devices ($p = 0.765$), with a mean difference of –0.00103 seconds (95% CI: –0.0079 to 0.0059), SD 0.02131, and SE 0.00341. The bias was –0.001 seconds, with LOA ranging from –0.04277 to 0.04077 seconds. The Bland–Altman plot demonstrated a scattered distribution, suggesting random variation between the two measurement methods (see figure 16).

3.1.3. PR interval

Differences in PR interval were normally distributed (figure 10, Shapiro–Wilk, $p = 0.089$). The t-test showed no significant difference ($p = 0.137$), with a mean difference of 0.00572 seconds (95% CI: –0.0019 to 0.0133), SD 0.02351, and SE 0.00377. The bias was 0.00572 seconds, with LOA of –0.04048 to 0.05168 seconds. The Bland–Altman plot again showed a scattered pattern, indicating random measurement differences without systematic bias (see figure 17).

3.1.4. QT interval

Differences in QT interval were normally distributed (figure 11, Shapiro–Wilk, $p = 0.587$). A significant difference was found between devices ($p < 0.001$), with a mean difference of –

0.01492 seconds (95% CI: –0.0224 to –0.0074), SD 0.02317, and SE 0.00371. The bias was –0.0149 seconds, and LOA ranged from –0.06031 to 0.03051 seconds. The Bland–Altman plot revealed a cluster of points around a mean of 0.37 seconds (see figure 18).

3.1.5. RR interval

The differences of the RR interval were normally distributed (figure 12, Shapiro–Wilk: p = 0.062). A significant difference was observed (p = 0.001), with a mean difference of 0.01451 seconds (95% CI: 0.0062 to 0.0228), SD 0.02559, and SE 0.00410. The bias was 0.01451 seconds, with LOA between –0.03566 and 0.06466 seconds. The Bland–Altman plot showed lower mean values corresponded to higher difference values, while higher mean values showed lower differences, suggesting a possible proportional bias (see figure 19).

These results indicate that the two devices produced comparable measurements for P wave, QRS complex, and PR interval durations. The differences between devices were not statistically significant, and the Bland–Altman plots showed a scattered distribution, suggesting a reasonable level of agreement without systematic bias. In contrast, QT and RR interval durations showed statistically significant differences, with the QT plot displaying a clustered pattern and the RR plot suggesting a trend in which lower mean values corresponded to higher differences.

3.2. Amplitudes (mV)

3.2.1. P wave

The P wave amplitude data were normally distributed (figure 13, Shapiro–Wilk, p = 0.347). A significant difference was found between devices (p < 0.001), with a mean difference of 0.13256 mV (95% CI: 0.1142 to 0.1510), SD 0.05674, and SE 0.00909. The bias was 0.13256, with LOA between 0.02135 and 0.24377 seconds. The Bland–Altman plot shows most dots above the bias line, indicating that the measurements from TV are systematically higher than the measurements from mKM (see figure 20).

3.2.2. QRS complex

The QRS amplitude data were not normally distributed (Shapiro–Wilk, $p < 0.001$). A significant difference was found between devices ($p < 0.001$), with a mean difference of 0.3985 mV (95% CI: 0.3008 to 0.4961), SD 0.30115, and SE 0.04822.

3.2.3. T wave

The T wave amplitude data were also not normally distributed (Shapiro–Wilk, $p < 0.001$). The t-test revealed a significant difference ($p < 0.001$), with a mean difference of 0.1677 mV (95% CI: 0.0854 to 0.2500), SD 0.25399, and SE 0.04067.

No Bland-Altman plots could be performed for the amplitudes of the QRS complex and T wave, since the data were not normally distributed (Giavarina, 2015).

Regarding the amplitude measurements, only the P wave amplitude data were normally distributed, while QRS and T wave amplitudes were not. For all three amplitude parameters, the differences between the devices were statistically significant, suggesting that amplitude readings from the mKM systematically differed from those of TV. This was further confirmed by the Bland-Altman plot for P wave, indicating the measurement of systemically higher amplitude values by TV compared to mKM.

3.3 Heart rate (beats/min)

Heart rate data were normally distributed (figure 14, Shapiro–Wilk, $p = 0.166$). No significant difference was found between the devices ($p = 0.938$), with a mean difference of 0.0256 bpm (95% CI: –0.6415 to 0.6928), SD 2.0582, and SE 0.32957. The Bland–Altman plot showed a bias of 0.0256 bpm and LOA between –4.008 and 2.108 bpm, with a scattered pattern indicating random differences (see figure 21).

Heart rate measurements were normally distributed, and no significant differences were found between the two devices. The Bland–Altman plot showed an evenly scattered distribution, and the limits of agreement were within a clinically acceptable range, suggesting that both devices can reliably assess heart rate under field conditions.

Table 3 shows the mean, median and range of the measurements of both devices for each cardiac parameter measured for this study. Table 4 gives an overview of the results of the statistical analysis comparing the measurements of both devices.

Table 3. *Mean, median, and range of data for each cardiac parameter measured in this study listed for the Televet100 and modified KardiaMobile devices.* The duration-based parameters are in seconds, the amplitudes in millivolt, and heart rate in beats per minute. For the parameters with an asterix (*) the mean values between both devices differed significantly.

Parameter	Device	Mean	Median	Range
P wave (sec)	TV	0.07742	0.078	0.028
	mKM	0.07908	0.076	0.06
QRS (sec)	TV	0.14062	0.138	0.072
	mKM	0.14164	0.144	0.1
PR (sec)	TV	0.13495	0.136	0.073
	mKM	0.12923	0.124	0.052
QT (sec)*	TV	0.37779	0.37	0.198
	mKM	0.39272	0.376	0.156
RR (sec)*	TV	0.70026	0.714	0.34
	mKM	0.68574	0.68	0.4
AmpP (mV)*	TV	0.17359	0.17	0.21
	mKM	0.04103	0.04	0.1
AmpQRS (mV)*	TV	0.79103	0.68	1.47
	mKM	0.39256	0.36	0.37
AmpT (mV)*	TV	0.5	0.4	1.54
	mKM	0.33231	0.3	0.56
HR (beats/min)	TV	87.72	84	44
	mKM	87.69	84	44

Table 4. *Overview of the results of the statistical analysis*. The duration-based parameters are in seconds, the amplitudes in millivolt, and heart rate in beats per minute.

Test		Pwave (sec)	QRS (sec)	PR (sec)	QT (sec)	RR (sec)	AmpP (mV)	AmpQRS (mV)	AmpT (mV)	HR (beats/min)
Shapiro-Wilk	Significance	0.037	0.74	0.089	0.587	0.062	0.347	<0.001	<0.001	0.166
T-Test	Significance	0.465	0.765	0.137	<0.001	0.001	<0.001	<0.001	<0.001	0.938
	Mean difference	-0.00184	-0.001	0.0056	-0.0149	0.0145	0.13256	0.3985	0.1677	0.0256
	Standard deviation	0.01538	0.02131	0.02351	0.02317	0.02559	0.05674	0.30115	0.25399	2.0582
	Standard error	0.0025	0.00341	0.00377	0.00371	0.0041	0.00909	0.04822	0.04067	0.32957
Bland-Altman	Bias	-0.00184	-0.001	0.0056	-0.0149	0.0145	0.13256			0.0256
	LOA+	0.0117736	0.0407676	0.0516796	0.0305132	0.0646564	0.2437704			2.108376
	LOA -	-0.0319848	-0.0427676	-0.04048	-0.0603132	-0.0356564	0.0213496			-4.008472

3.4 Histograms

In the following figures (figure 8 – 14) the histograms, drawn to visualize normal distribution of the differences in measurement data for the cardiac parameters, are shown. They were only drawn when the Shapiro-Wilk test showed no statistical difference between the measurements of both devices, indicating a normal distribution of the data. The Y-axis indicates the frequency, and the X-axis shows the difference between the measurements from TV and mKM devices.

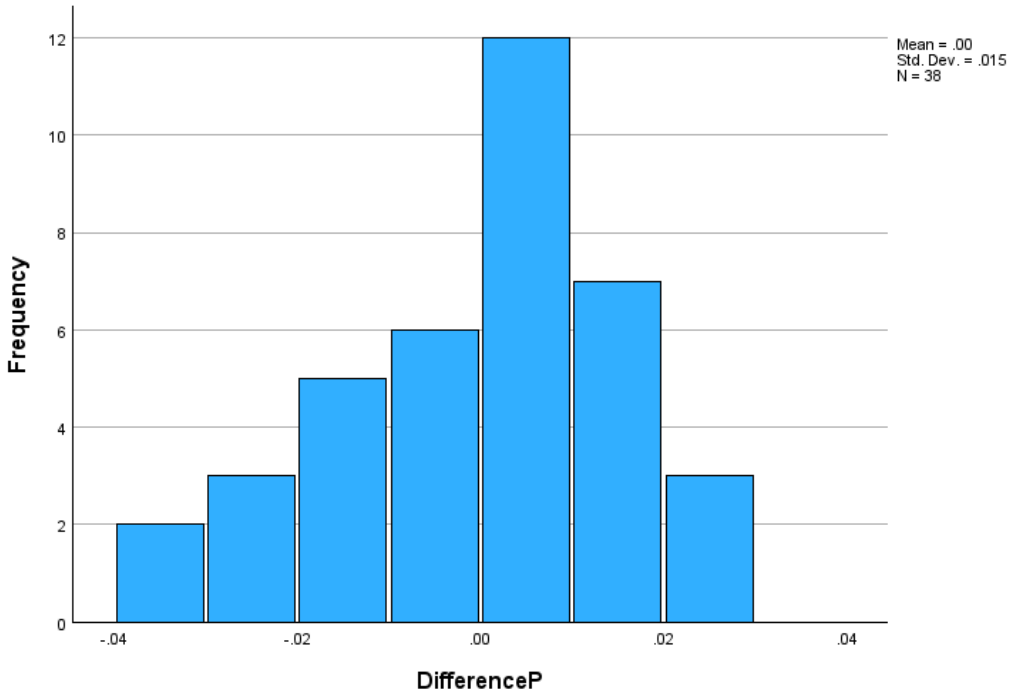

Figure 8. *Histogram of differences for P wave.* It shows a normal distribution of the data. The differences are given in seconds. One outlier was removed from this data set, so 38 instead of 39 ECG complexes from each device were used to draw this histogram.

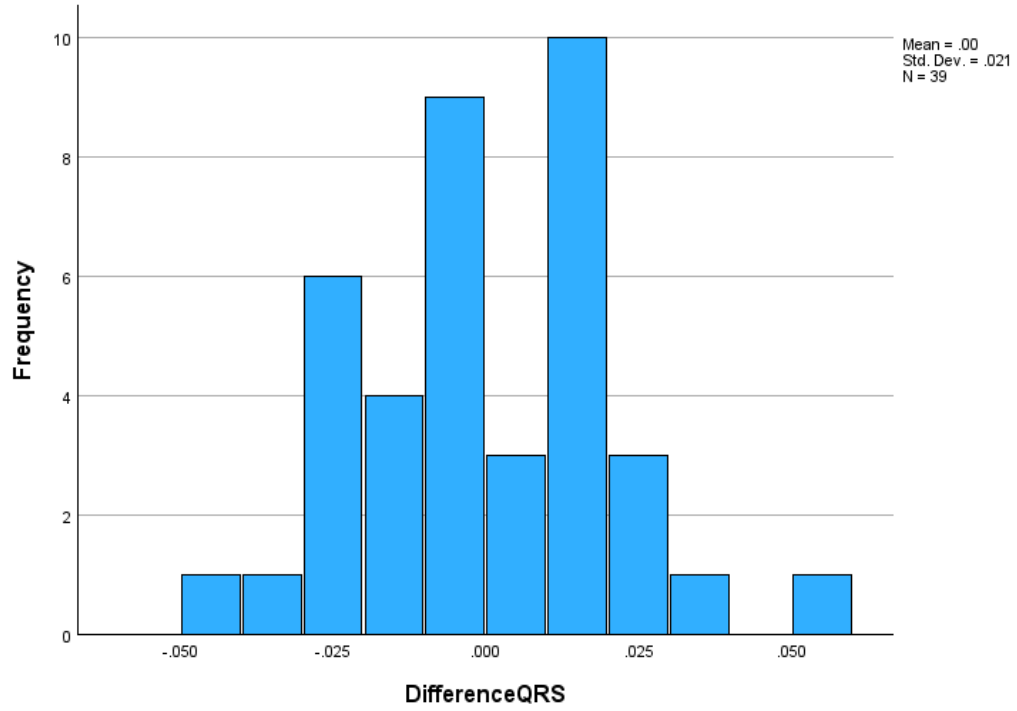

Figure 9. *Histogram of differences for QRS complex.* It shows a normal distribution of the data. The differences are given in seconds..

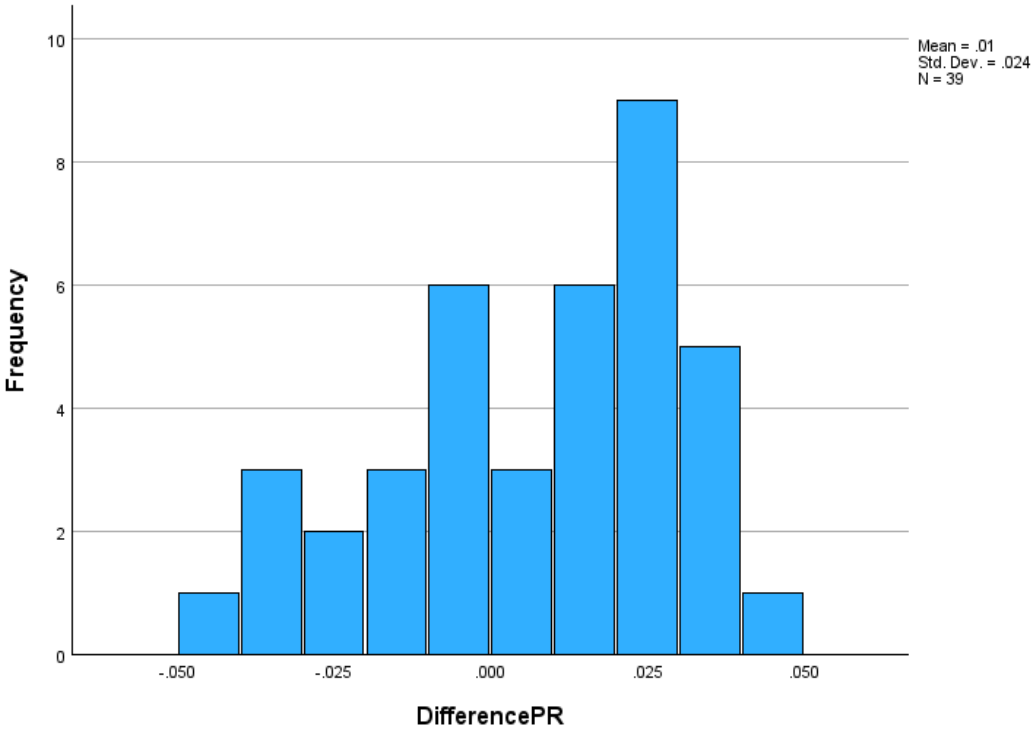

Figure 10. *Histogram of differences for PR interval.* It shows a normal distribution of the data.. The differences are given in seconds.

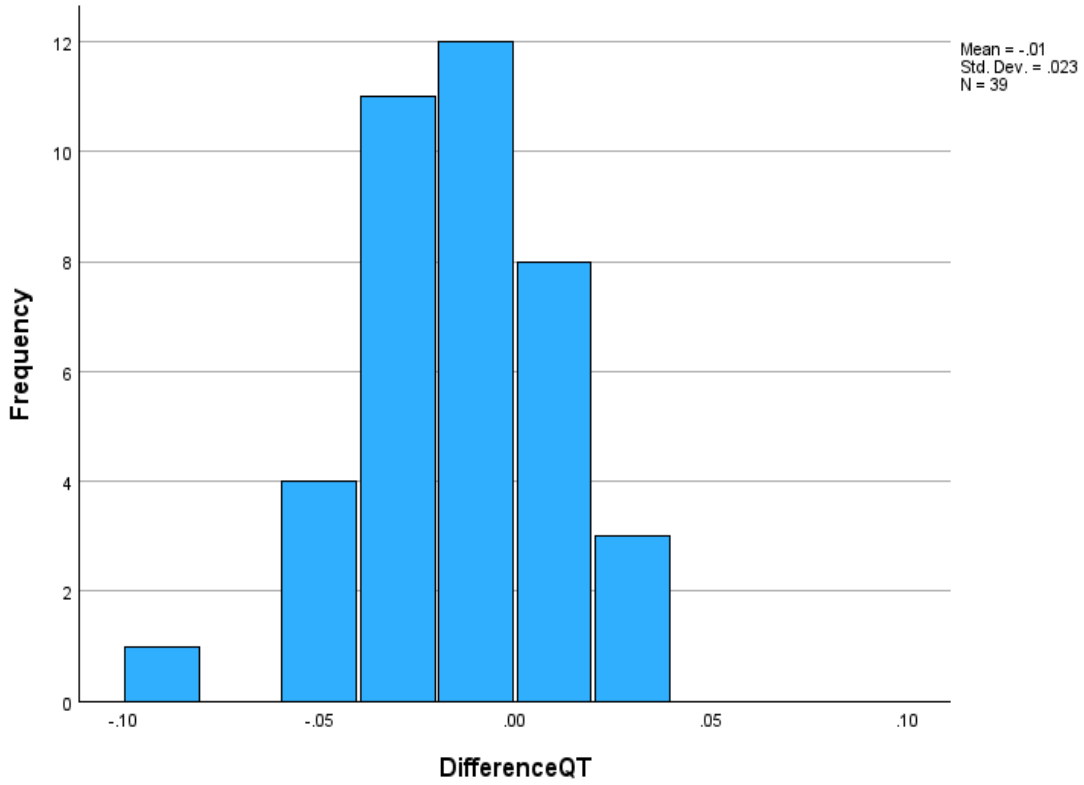

Figure 11. *Histogram of differences for QT interval.* It shows a normal distribution of the data. The differences are given in seconds.

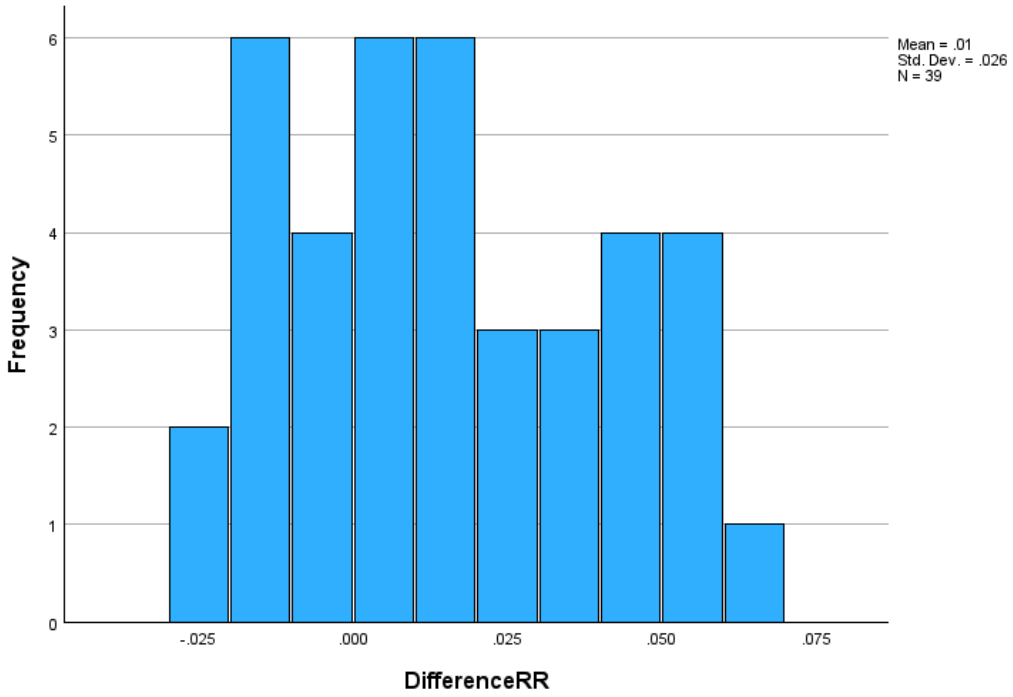

Figure 12. *Histogram of differences for RR interval.* It shows a normal distribution of the data. The differences are given in seconds.

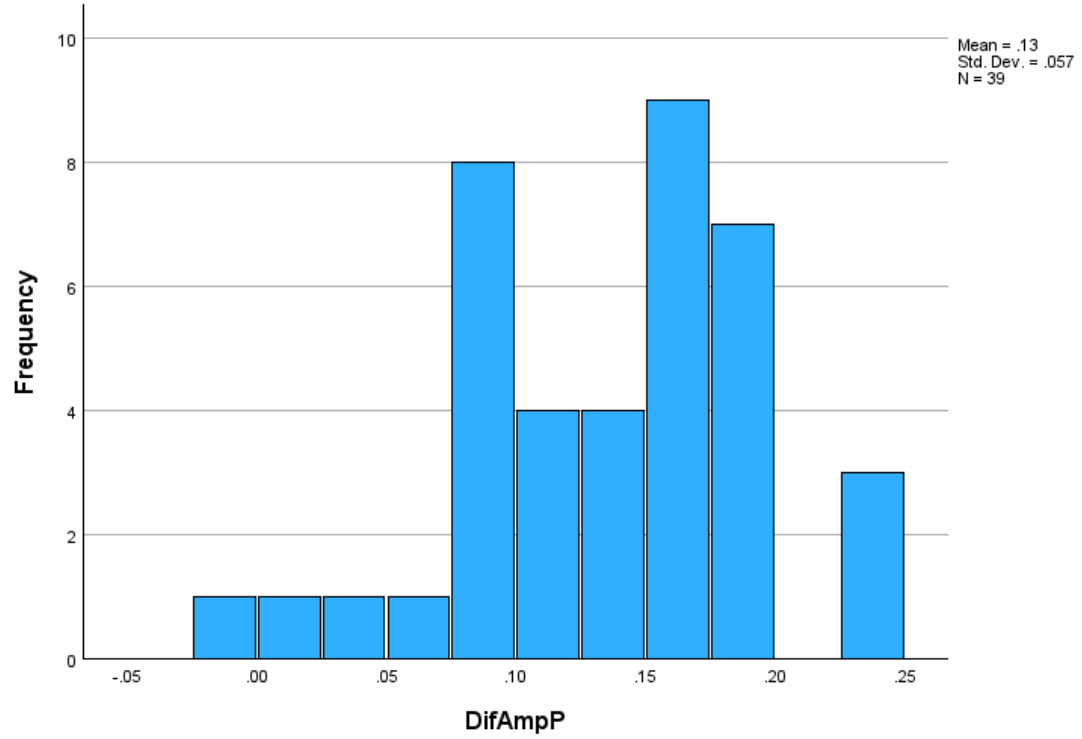

Figure 13. *Histogram of differences for P wave amplitude*. It shows a normal distribution of the data. The differences are given in millivolt.

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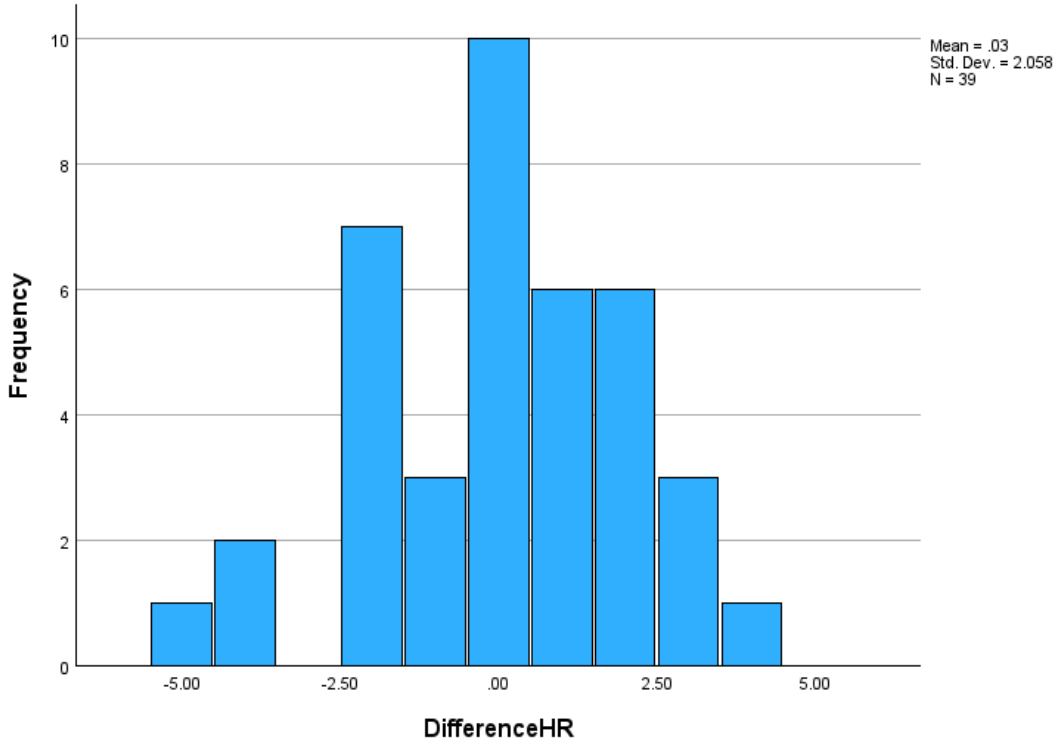

Figure 14. *Histogram of differences for heart rate measurements.* It shows a normal distribution of the data. The differences are given in beats per minute.

3.5 Bland-Altman plots

In the following figures (figure 15 – figure 21) the Bland-Altman plots are shown. The differences between the measurements of TV and mKM devices (Y-axis) are plotted against the mean of the measurements of TV and mKM devices (X-axis). The horizontal red line is the bias line, which corresponds with the mean difference. The closer this line is to 0 on the Y-axis, the better the agreement between the two devices. The horizontal green lines are the limits of agreement and were calculated as the mean difference between the two measurements ± 1.96 times the standard deviation of these differences. This range represents the interval within which approximately 95% of the differences between both measurement methods are expected to lie. A smaller range indicates a higher level of agreement between the two methods. A scattered pattern of the dots on the plot also indicate good agreement, whilst clustering or a trend may indicate proportional bias between both methods (Giavarini, 2015).

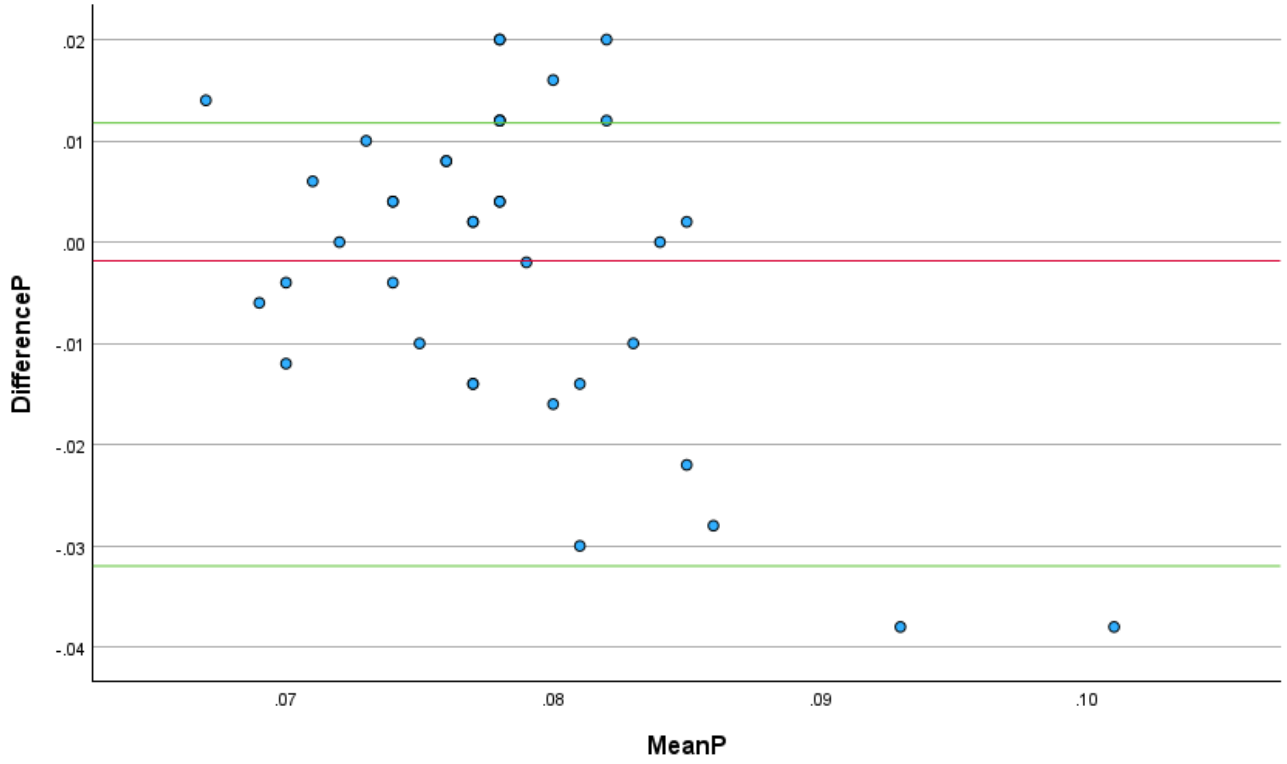

Figure 15. *Bland-Altman plot of P wave duration* . A scattered pattern can be observed, limits of agreement in close range to the bias line and close proximity of the majority of the dots to the bias line. Data on both the X- and Y- axes are given in seconds.

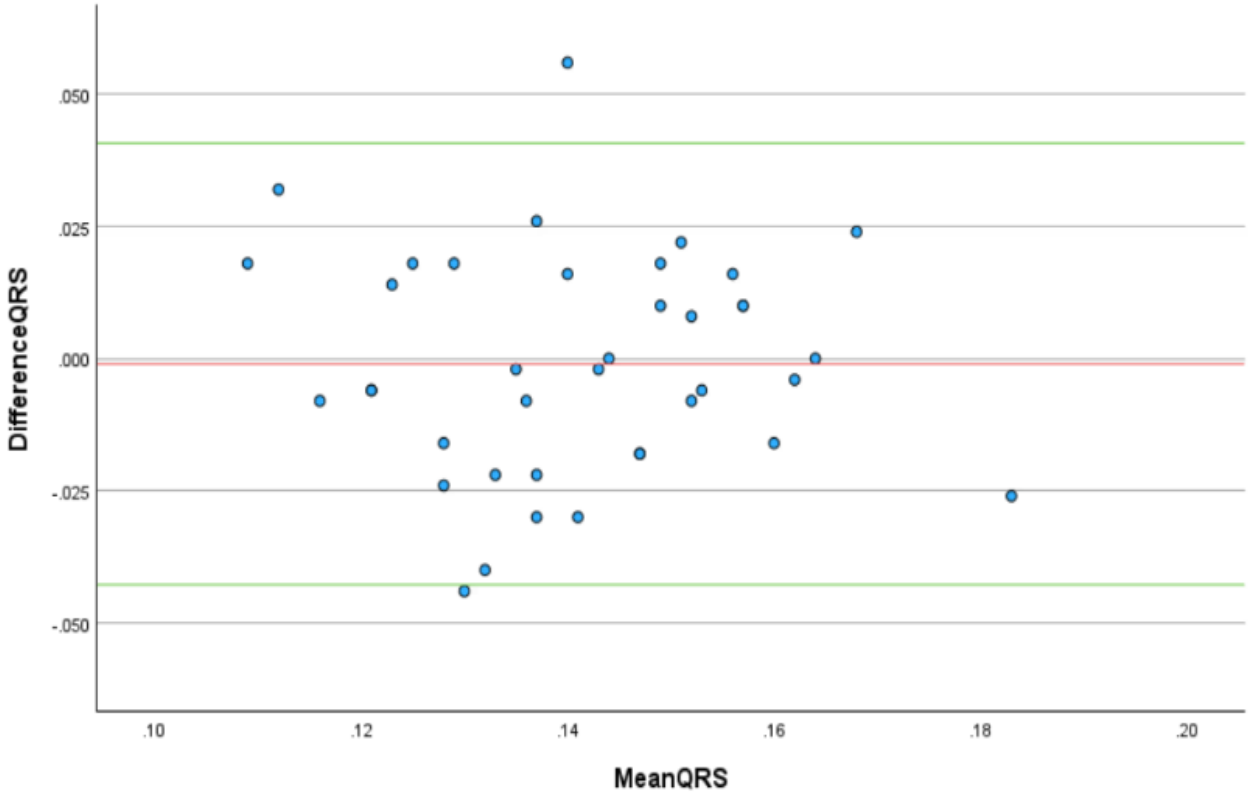

Figure 16. *Bland-Altman plot of QRS complex duration*. A scattered pattern can be observed, limits of agreement in close range to the bias line and close proximity of the majority of the dots to the bias line. Data on X- and Y-axes are given in seconds.

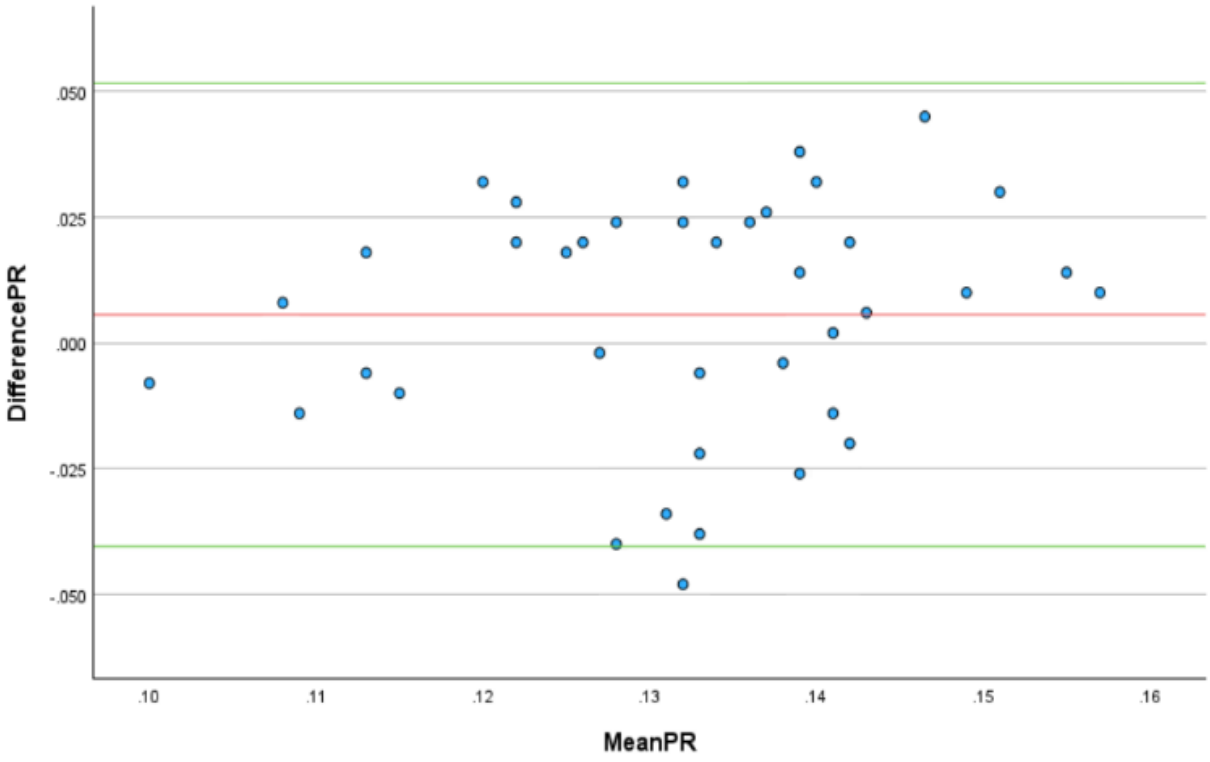

Figure 17. *Bland-Altman plot of PR interval duration.* A scattered pattern can be observed, limits of agreement in close range to the bias line and close proximity of the majority of the dots to the bias line. Data on X- and Y-axes are given in seconds.

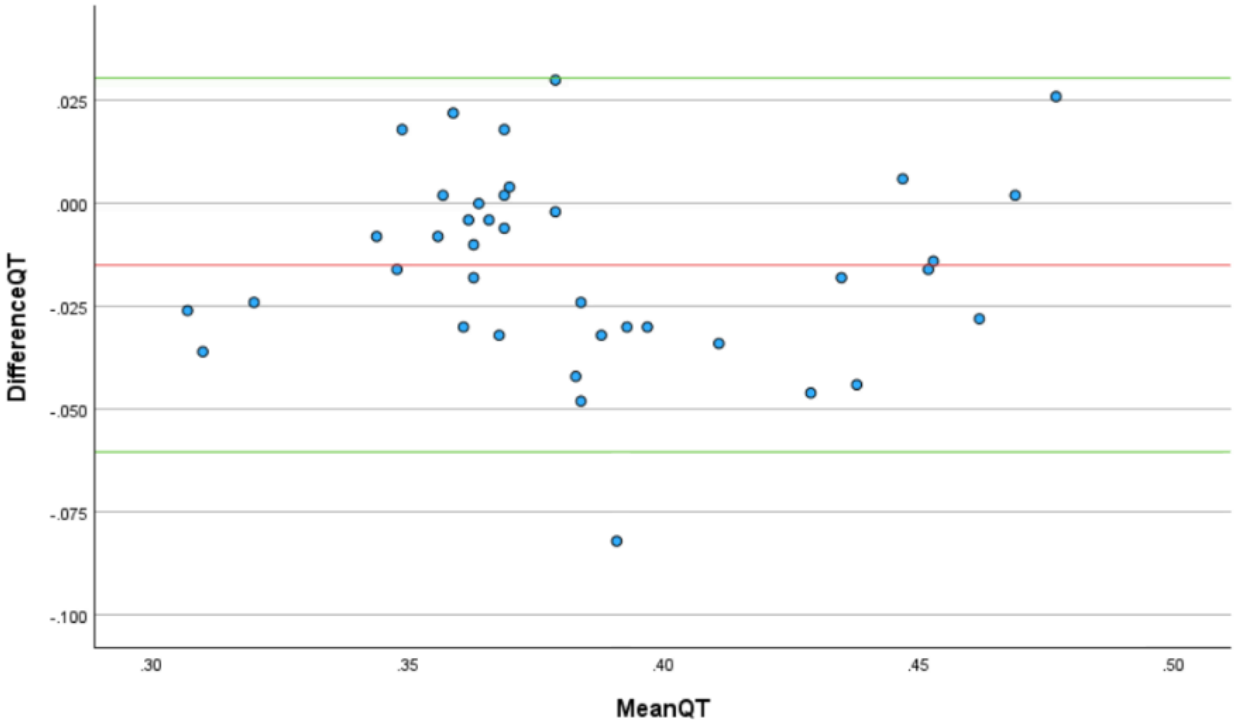

Figure 18. *Bland-Altman plot of QT interval duration.* A clustering of dots around (0.37;0.00) can be observed . The majority of the dots is in close proximity to the bias line. Data on X- and Y-axes are given in seconds.

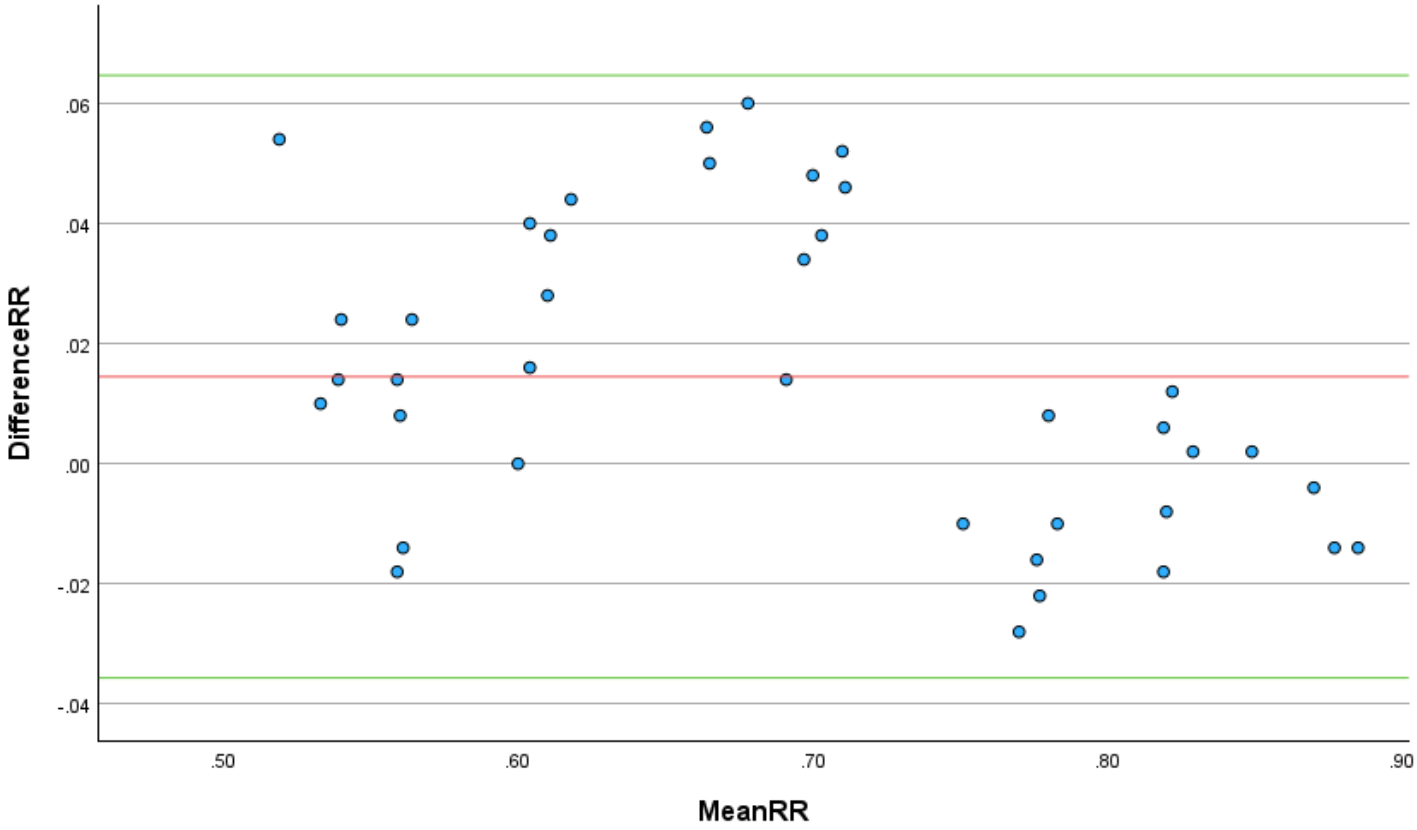

Figure 19. *Bland-Altman plot of RR interval.* Lower mean values corresponding to higher differences and higher mean values to lower differences can be observed, suggesting a possible proportional bias for this cardiac parameter. Data on X- and Y-axes are given in seconds.

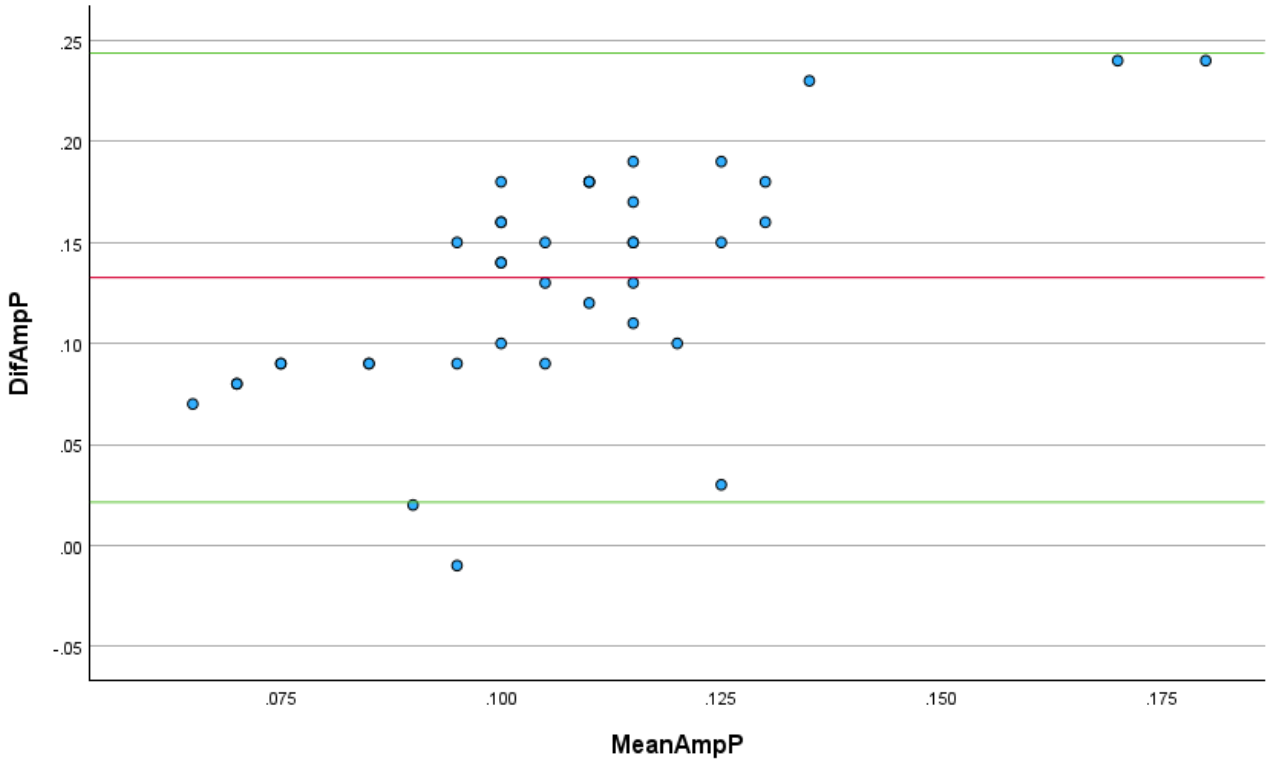

Figure 20. *Bland-Altman plot of P wave amplitude.* The bias line is well above Y=0, indicating poor agreement between both devices for this parameter. Data on X- and Y axes are given in millivolts.

425

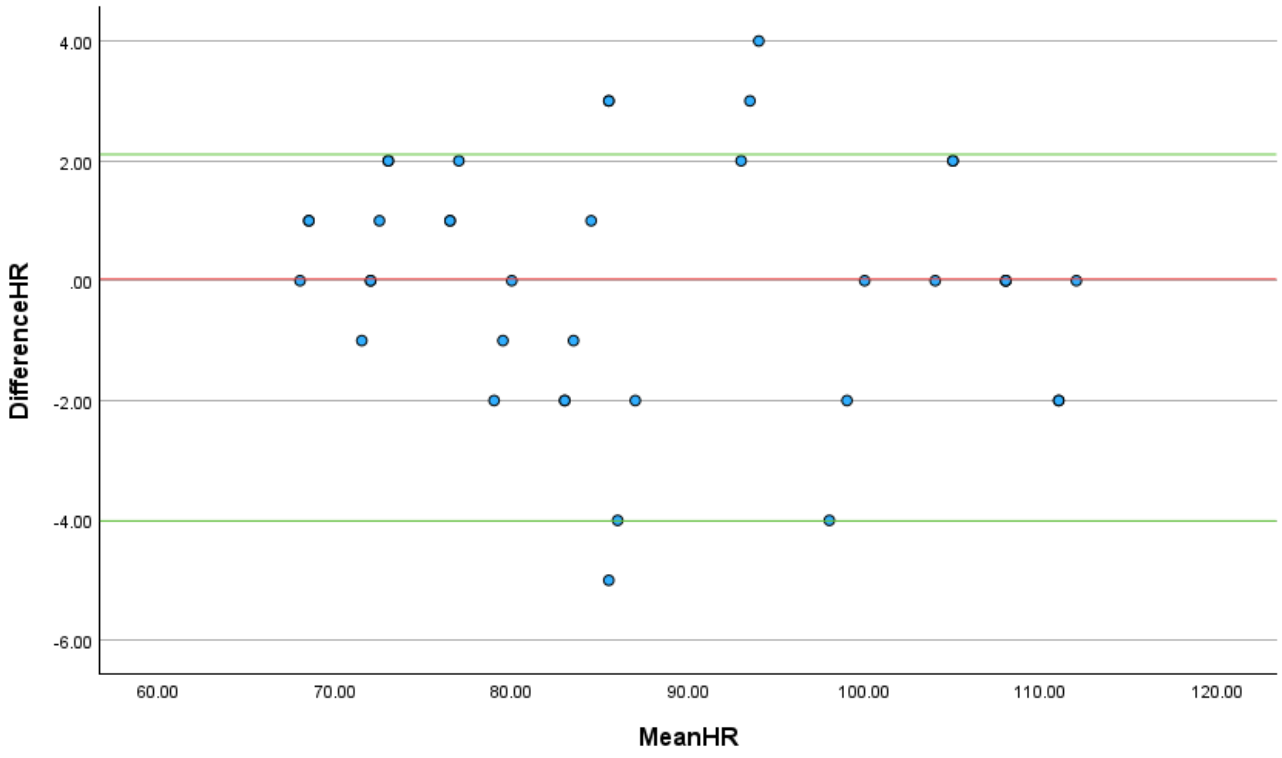

Figure 21. *Bland-Altman plot of heart rate measurements.* A scattered pattern can be observed, limits of agreement in close range to the bias line and close proximity of the majority of the dots to the bias line. Data on X- and Y- axes are given in beats per minute.

4.Discussion

This study compared ECG tracings obtained from the Televet 100 and the modified KardiaMobile device in 13 white rhinoceroses under field conditions. The aim was to assess the level of comparability and agreement between both systems in measuring ECG parameters. Heart rate and most parameters based on duration (P wave, QRS complex, and PR interval) were comparable between the two devices, with no statistically significant differences and no systematic bias visible in the Bland–Altman plots. However, significant differences were observed for the QT and RR intervals, and amplitude measurements consistently differed between devices.

The findings of this study generally align with previous research on smartphone-based ECG devices in other animal species. Earlier studies in horses, cattle, sheep, dogs, and camels have demonstrated that smartphone ECG devices can provide clinically acceptable results for heart rate, and wave- and interval duration measurements (Alberti *et al*., 2020; Bindi *et al*., 2024; Bonelli *et al*., 2019; King *et al*., 2023; Romito *et al*., 2023; Vitale *et al*., 2021). These observations correspond with the results of this study. The statistical difference in QT interval duration was also found in Vitale *et al.*, 2021, although a different smartphone-based device was used. More surprising was the statistical difference found in this study for RR interval duration: no other studies showed similar results. The RR interval on ECG devices can be different between two devices while the average heart rate is the same due to variations in R peak detection and device sensitivity, leading to different calculated RR intervals for the same underlying heart rhythm.

The significant amplitude differences observed in this study are likely the result of differences in electrode placement and inherent differences in signal processing between both devices, as has been described in comparable veterinary ECG validation studies (Bonelli *et al*., 2019; Kraus *et al*., 2019; Romito *et al*., 2023; Vitale *et al*., 2021).

A notable strength of this study is that all data were collected under field conditions, providing a realistic assessment of device performance under these conditions. The simultaneous recordings from both devices allowed for direct comparison between the two devices, thereby

minimising biological variation. However, prior to and during the study, several practical limitations regarding the use of mKM were identified.

A pilot trial was conducted on trained, *ex situ* kept black rhinoceroses (*Diceros bicornis*). During this trial, the device was placed against the left thorax, just caudal to the forelimb, similar to the positioning of the KardiaMobile on horses described by Welch-Huston *et al.* (2020) and Alberti *et al*. (2020). The signal obtained was too weak for interpretation, most likely due to the rhinoceros's thick skin and the close proximity of the two integrated electrodes. To address this issue, the device was modified as described earlier in this study. This modification considerably improved signal strength and quality, thereby making ECG recording in rhinoceroses feasible. However, it also reduced the device's ease of use, which is one of the main practical advantages of the mKM compared to TV.

During field trials with the mKM on white rhinoceroses, another limitation of the device became apparent. Background noise from chainsaws and helicopters caused significant interference with the ultrasonic transmission between the mKM and the smartphone, resulting in artifacts that made the ECG recordings unusable. As a result, data collection could only take place before and after the horn-cutting procedure, which limited the available recording time for this study. This issue, inherent to the device's method of signal transmission, restricts the feasibility of continuous cardiac monitoring with the mKM during dehorning operations. TV, however, does not make use of ultrasonic sound waves but directly tranfers the ECG signal from the electrodes to the device via the cables. Therefore, these issues did not occur while recording ECGs with TV during dehorning.

To enable a direct comparison between the ECG recordings of both devices, it was essential to synchronise the tracings for parameter measurement. The mKM performs 30-second recordings, after which the sample is processed, the heart rate is calculated, and the tracing is checked for arrhythmias. TV records a continuous ECG. To identify the exact 30-second TV segment corresponding to the mKM recording, one of the TV electrodes was briefly and manually disturbed at the moment the mKM recording started, and again when it ended. This created two short movement artifacts in the continuous TV tracing, between which the 30-second mKM sample could later be located. Although effective, this synchronisation method is susceptible to human error and can be challenging to perform accurately under field conditions. In fact, insufficient synchronisation was the main reason why ECG data from 8 of the 21

sampled rhinoceroses had to be excluded from the analysis. For future studies, a more precise and automated synchronisation method should be implemented to minimise human error and improve data reliability.

Despite these limitations, the results indicate that mKM can serve as a practical and reliable tool for basic ECG monitoring in white rhinoceroses for the assessment of heart rate and wave durations. Its portability, affordability, and ease of use make it highly suitable for application in field conditions. However, given the observed differences in amplitude and specific intervals, mKM should mainly be regarded as a monitoring instrument rather than a full alternative to conventional ECG systems such as TV.

Future studies should aim to include larger populations and take into account differences in age, sex, and physical condition. The use of automated measurement software, automated synchronisation and more standardised electrode positioning could help reduce human error and improve measurement consistency. Additionally, further research could focus on calibration and correction factors for the use of smartphone-based ECG devices in white rhinoceroses, which may improve agreement between smartphone-based and standard ECG systems.

5.Conclusion

This study demonstrated that the TV and the mKM produce largely comparable results for most ECG duration parameters and heart rate measurements in white rhinoceroses. However, significant differences were found for certain interval durations (QT and RR) and for amplitude measurements (P wave, QRS complex, and T wave), indicating that the two devices are not fully interchangeable. The mKM shows strong potential as a practical alternative for ECG recording under field conditions, particularly for assessing heart rate and wave durations. Its compactness, low price, and user-friendliness make it a valuable addition to more conventional ECG systems such as the TV. Nevertheless, the required modification to obtain a sufficiently strong signal slightly reduces the ease of use, and caution is necessary when interpreting amplitude values and specific interval measurements.

Another significant limitation for the use of mKM is the interference of loud noises with the ultrasonic sound waves used by the device to transmit its signal to the smartphone, impeding heart monitoring while using chainsaws for dehorning. Therefore, TV might be the preferred device for cardiac monitoring during dehorning operations.

Further research with larger sample sizes and more standardised methods is recommended to validate these findings and improve knowledge about the application of smartphone-based ECG devices in white rhinoceroses.

6.Literature

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7. Attachments

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7.1. AEC ethical approval form

LOWVELD WILDLIFE CONSULTING SERVICES T/A
WILDLIFEVETS.COM
SAVC Practice Number: FR 15/13330
Company Reg Number: 2001/042285/23
VAT NO 4470196009
P O Box 2673, White River, 1240, South Africa

APPROVAL TO USE SAMPLES FROM DEAD ANIMALS (THAT DIED NATURALLY OR WERE KILLED FOR ANOTHER PURPOSE) OR SAMPLES FROM ANIMALS IMMOBILIZED FOR ANOTHER PURPOSE

APPLICANT: Dr Bart Gazendam

UNIVERSITY / DEPARTMENT: Wildscapes Veterinary and Conservation Services and University of Pretoria, Onderstepoort Veterinary Campus

PROJECT TITLE: Evaluation of the performance of smartphone-based ECG devices in white rhinoceroses (*Ceratotherium simum*)

PROJECT / AEC APPROVAL NUMBER: WLVAEC-2025-003

APPLIED FOR APPROVAL BY WILDLIFE VETS.COM ANIMAL ETHICS COMMITTEE FOR THE PERIOD: 12 March 2025 **to** 1 April 2026

INVOLVING: The opportunistic collection of biological samples from animals either deceased (due to natural causes or for reasons other than the collection of said samples) or immobilized for routine management practices.

SPECIES	NUMBER OF ANIMALS	TYPE OF SAMPLE	NUMBER OF SAMPLES
White rhinoceros *Ceratotherium simum*	40	ECG traces using KardiaMobile and Televet 100	40

The AEC *has not* specified additional conditions of approval

Refer also to the accompanying letter setting out requirements applying to approval of this project.

Date: 19th March 2025

Chairperson: Liesel Laubscher

Wildlifevets.com

Dear Dr Bart Gazendam

Ref: ANIMAL ETHICS COMMITTEE PROJECT NO: WLVAEC-2025-003

PROJECT TITLE: Evaluation of the performance of smartphone-based ECG devices in white rhinoceroses (*Ceratotherium simum*)

I write to confirm that the Animal Ethics Committee has ***approved*** the above project for the period from **12th March 2025 to 1st April 2026**.

Your attention is drawn to the following requirements of the approval:

1. *Any adverse or unexpected effects that impact on animal wellbeing which occur during the period of the approved project must be reported promptly to the AEC.*
2. *You must ensure that records of the collection of samples in this project are maintained. Records should include the origin and fate of the animals from which samples were collected, any unexpected negative impact on animal wellbeing and notation of procedures.*
3. *You must provide an annual report to the AEC - the continuation of all projects is subject to receipt of written annual reports that should follow the given format. You must inform the Committee when an approved project is completed or discontinued.*
4. *It is necessary to apply to the AEC for approval if the project is to continue for a longer period of time, if additional samples are required or if any change to procedure is proposed. The format for such an application will be provided.*

Yours sincerely,

Chairperson

7.2. KardiaMobile ECG Tracing

Kardia

EKG Recording

Louk Boucher

DOB: **08/18/1999 (25 years)**
Sex: **Male**

EKG Recording Overview

Kardia Determination

Unclassified

Recorded:	Monday, May 26, 2025, 1:01:24 PM
Heart Rate:	89 BPM
Duration:	30s

Additional Information

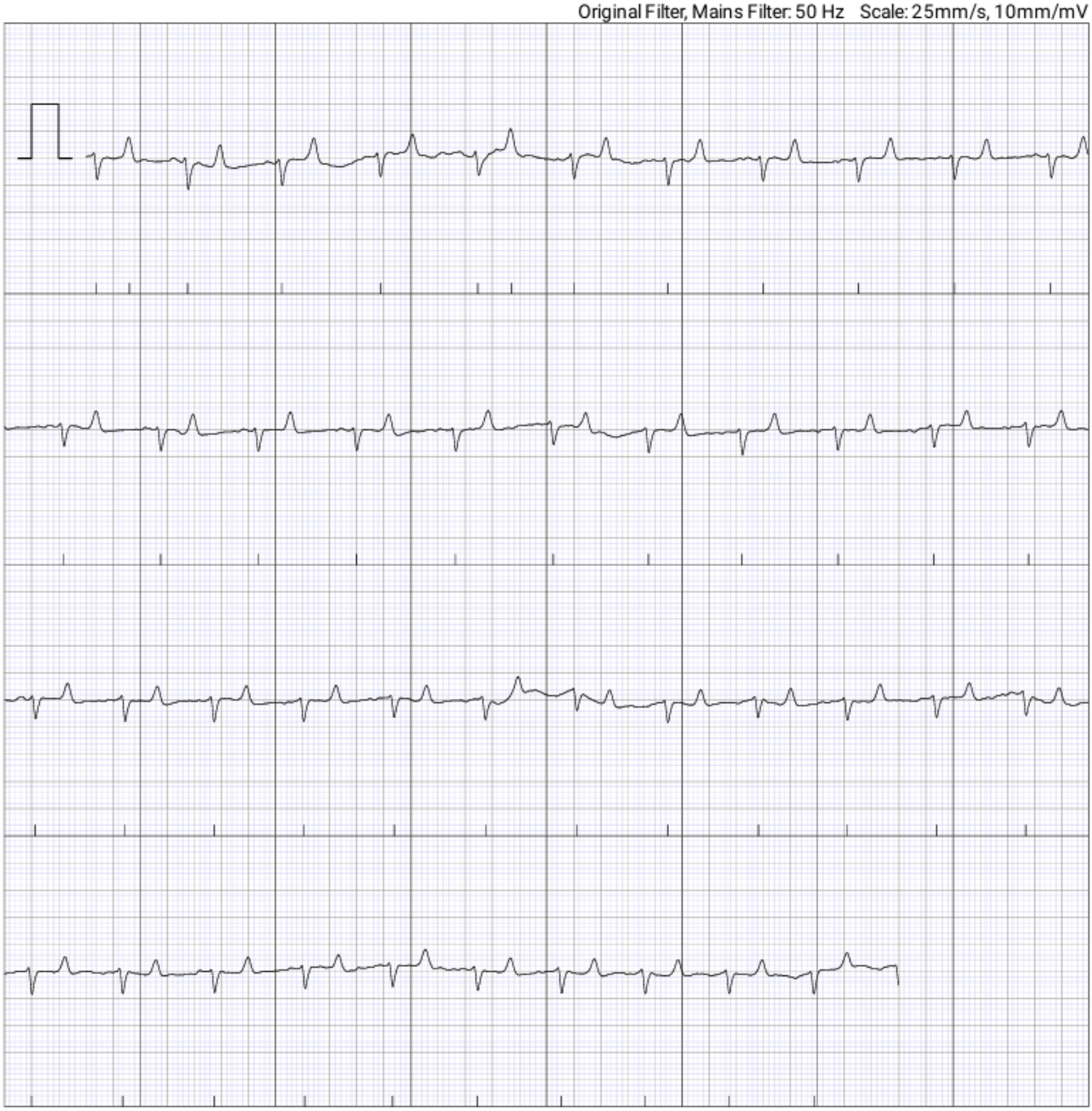
No additional information to display

Kardia

Patient: Louk Boucher
Recorded: 05/26/2025, 1:01 PM
Heart Rate: 89 bpm
Duration: 30s

Kardia Determination Unclassified

Original Filter, Mains Filter: 50 Hz Scale: 25mm/s, 10mm/mV



7.3. Televet 100 ECG Tracing

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