

INVESTIGATING TEXTILE-BASED ELECTRODES FOR ECG MONITORING IN VETERINARY CLINICAL PRACTICE

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Abstract:

There is an increasing interest in long-term electrocardiography (ECG) monitoring in veterinary clinical practice. ECG is the most essential physiological signal in diagnosing and managing heart diseases both in humans and animals. Electrodes are the main components that affect the quality of the acquired signal. This study focuses on the development of silver-coated textile electrodes for veterinary ECG testing (particularly for dogs). Silver printed polyester, embroidered, and silver-plated conductive hook textile electrodes were used for ECG measurement in dogs. This is an important validation for the use of textile ECG sensors in combination with hairy skin. ECG signals were collected while the animal was in a static position and walking on a smooth surface. The ECG signals collected from the dog using the silver printed polyester and embroidered textile electrodes with slight skin preparation have identifiable P, QRS, and T waveforms and were comparable with signals from standard silver/silver chloride (Ag/AgCl) electrodes. Results revealed that these textile electrodes can be used for ECG monitoring in a dog to avoid associated problems with commercially used crocodile clamps and standard Ag/AgCl electrodes. The hook electrodes show promising results when placed on the hairy regions of a dog without any skin preparation.

Keywords:

ECG, ECG in veterinary, silver-coated electrodes, textile electrodes

1. Introduction

Electrocardiography (ECG) is the graphical representation of the electrical activity of the heart that contains essential information concerning the heart condition [1,2]. Heart disease is as common in animals as it is in humans [3], and ECG is the most versatile technique for the diagnosis of heart-related diseases. There is an increasing interest in long-term ECG monitoring in veterinary clinical practice. Long-term ECG monitoring with acceptable signal quality is very important for an accurate evaluation of heart diseases that cannot be detected with standard ECG monitoring both in humans and animals [4–8]. Studies have been reported [5–10] on continuous ECG monitoring (24–72 h) for animals. In veterinary clinical practice, Holter monitoring with silver/silver chloride (Ag/AgCl) electrodes has been used most frequently in dogs for long-term ECG monitoring for detecting episodic weakness, intermittent arrhythmias, and assessing response to antiarrhythmic drug therapy [5,9,11]. The quality of the ECG signal is essential for receiving accurate information and electrodes are the main components that affect the quality of the acquired signal [12]. Usually, crocodile clamp electrodes together with adhesive gel are used for ECG monitoring in veterinary clinical practice [11,13]. In such electrodes, the teeth of the clamps bite the skin of the animal, and this could distress the animal. Ag/AgCl gelled adhesive electrodes are another type of electrode commonly used, especially for Holter monitoring. The electrolyte gel employed in crocodile and Ag/AgCl electrodes becomes dehydrated over time affecting the quality of signal during prolonged time usage

and electrolyte gel as the skin in animals is covered with thick, long, and dense hair, the use of adhesive electrodes becomes limited [11,13]. Moreover, the adhesive electrodes require intensive skin preparation to improve the skin–electrode interfacial contact; it is also painful and increases skin infection and such electrodes are not likely to stick properly to the animal's skin [14]. All the above drawbacks of the crocodile and Ag/AgCl electrodes led to the search for alternative dry electrodes.

Virtanen et al. [15] demonstrated pin-type electrodes with 12-pin developed from polymer coated with Ag/AgCl and another 12-pin gold-plated metal electrode coated with poly (3,4-ethylenedioxythiophene) polystyrene sulfonate (PEDOT:PSS), which were embedded in the harness of a dog in order to fix the electrodes at the intended locations (around the chest) for dog heart rate measurement. It was reported that the electrodes give a promising result and can be a milestone for future research on animal ECG monitoring. In another work, the following three types of pin electrodes were reported: two electrodes constructed with spring-loaded test pins and a third molded polymer electrode with Ag/AgCl coating spring-loaded pin electrodes for canine heart rate monitoring [16]. Such pin electrodes are used without any skin preparation and also without using electrolyte gels; however, the pins cause discomfort for the animal during prolonged use. The use of a dry textile-based electrode for animal ECG monitoring could provide several advantages, especially for long-term monitoring. Animal skin, also dog's and certainly horse's, generates sweat, which affects the signal quality acquired with self-adhesive



electrodes. As such, textile electrodes could be a potential choice for long-term ECG monitoring in animals, just as they are in humans. Because of their air and water permeability, they can absorb sweat and this could improve the acquired signal quality; moreover, they are more comfortable. Limited studies have been reported on the use of textile electrodes for ECG monitoring in animals [17–19]. Textile-based electrodes are lightweight, flexible, and easy to apply, which makes them suitable for long-term ECG monitoring both in humans and animals. Such electrodes have a lot of advantages for application in animals because they provide good comfort and can be used without adhesive and with limited skin preparation [17].

Even though there are many works reported on textile-based ECG electrodes for human ECG monitoring [20,21], the use of such electrodes for animal ECG monitoring is limited. This study focuses on the development of textile electrodes, particularly silver-coated textiles for dog ECG testing. The electrodes investigated in this study are silver-coated textile electrodes, including screen-printed textile electrodes, embroidered electrodes developed through machine embroidery on cotton fabric with the same size and design as the printed electrodes, and a fully silver-plated electrically conductive hook fabric. Both the screen-printing and embroidering techniques were selected because they are easy to adopt, relatively cheap processes and they are compatible with the conventional roll-to-roll processing of textiles. Each type of electrode was evaluated for animal health monitoring in regard to ECG signal quality and the results were compared with signals collected using standard Ag/AgCl electrodes. Metallic silver will come in contact with the skin but does not have a negative effect as it is difficult to absorb silver through the skin. The acquired ECG signals collected from the dog using the silver printed polyester and embroidered textile electrodes have identifiable waveforms and were comparable with signals taken using Ag/AgCl electrodes.

2. Materials and methods

2.1. Materials and electrode development

Four types of electrodes (embroidered and silver printed textile polyester, hook electrodes, and standard gelled Ag/AgCl electrodes) were used to acquire ECG signals from a dog. The embroidered textile electrodes were designed using the Ink/Stitch software, an embroidery plugin for the vector drawing program Inkscape, and created using a computerized embroidery machine with a 1.5 mm stitch length. A gray cotton woven

fabric having a yarn density of 37 ends/cm and 17 picks/cm has been used as a base material to develop the embroidered textile electrodes. This gray woven fabric was selected as a base material for embroidery to minimize the shirking effect and damage to the fabric during machine embroidery. A fully silver-plated polyamide thread purchased from Madeira Inc. was used as an embroidery yarn. Silver ink (Metalon HPS-FG32) having a solid content of 75% and a particle size of 1.5 μm purchased from Novacentrix and 140 GSM knitted polyester fabric were used to develop the silver printed electrodes. The electrodes were prepared by printing the silver ink onto knitted polyester fabrics using a flat screen (with a mesh count of 90). The printed electrodes were then cured in an oven dryer at 120°C for 30 min as in our previous works [22,23]. The surface resistance of developed electrodes was measured via the two-point probe method using a multimeter. Three samples were developed for each type and five readings from each sample were taken to compute the mean and standard deviation of the surface resistance. Both electrodes were developed with (34 mm² × 24 mm²) dimensions. Figure 1a and b shows the actual screen printed and embroidered electrodes, respectively.

A fully silver-plated electrically conductive hook tape (2"-DuraGrip® brand) with a resistivity of 0.28 Ohms per square cm having 5.08 cm width was used to prepare the hook electrodes. The electrode was designed using Inkscape as a circle with a dimension of 18 mm diameter (active area), and the connection track was 10 mm × 11 mm. The electrodes were cut using a laser cut machine (Figure 2a). Two healthy dogs were included in this study. A metallic snap connector was attached to all the textile electrodes (Figures 1 and 2a) to connect to the wires of an ECG recording device.

2.2. ECG measurements and signal evaluation method

For embroidered and silver printed electrodes, ECG measurements were carried out by placing the electrodes around the chest behind the shoulder of the dog with a lead I configuration (Figure 3), where the signal depends on the voltage difference between the right shoulder (RA) and left shoulder (LA) and left front leg (LL) used as a reference electrode. The intended spots were shaved to shorten the hair length as much as possible without damaging the dog skin and the site was cleaned with a soft dry fabric to remove short haircuts and dirt. ECG signals were acquired using the textile and gelled Ag/AgCl electrodes for comparison, via asynchronous method, i.e., both types of electrodes were fixed at the same place, and ECG signals were

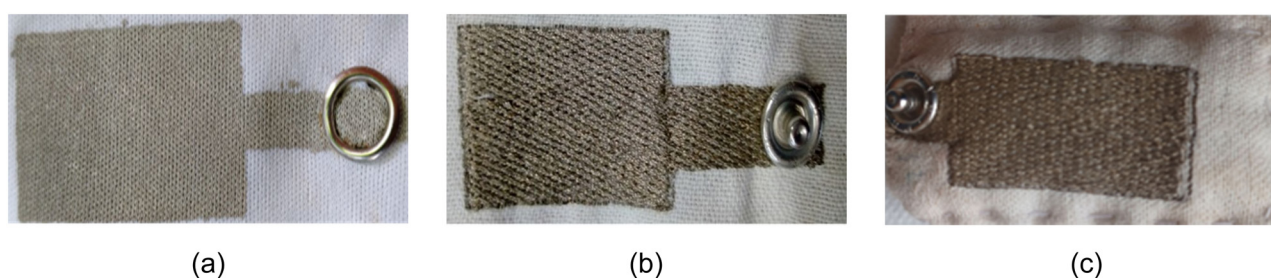


Figure 1. (a) Silver printed polyester textile electrode, (b) embroidered textile electrode, and (c) sandwiched structure.

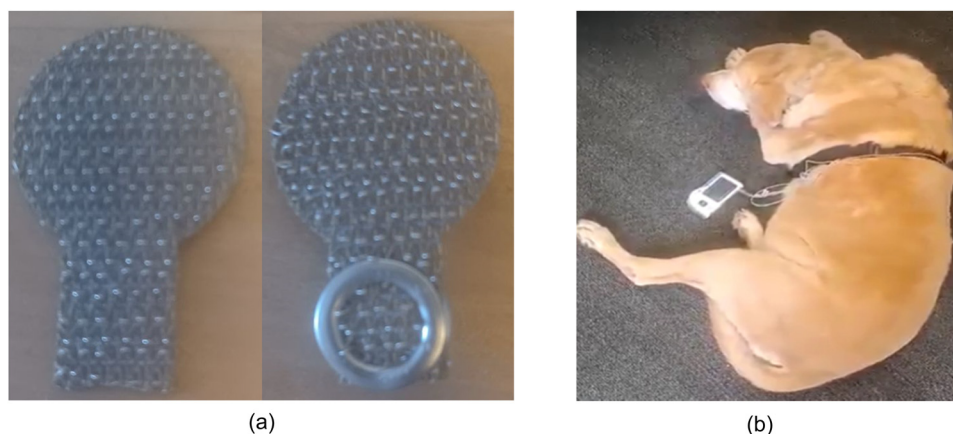


Figure 2. (a) The hook fabric electrode with a metallic snap button (left) and (b) ECG measurement while the dog was laying down.

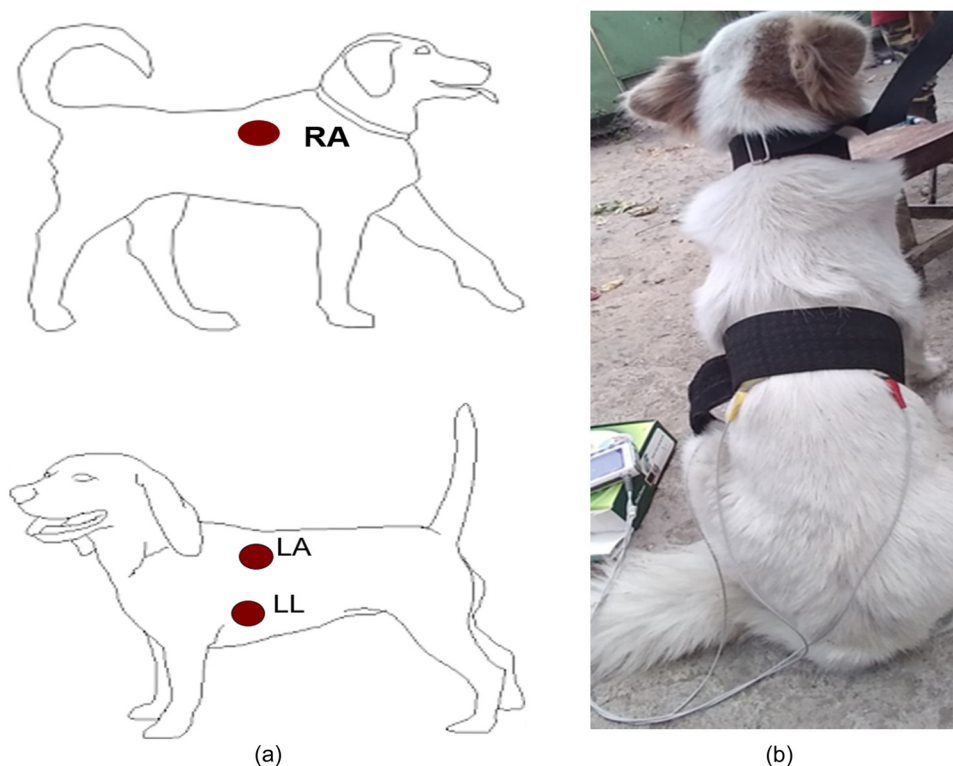


Figure 3. (a) Schematic block diagram of electrode placement and (b) actual setup for ECG measurement on a dog.

collected at different times. Measurements were carried out first using textile electrodes and then gelled Ag/AgCl electrodes and the skin was cleaned after testing to remove gel residuals from the wet electrodes on the skin. The textile electrodes were prepared in a sandwiched structure (Figure 1c) by sewing the conductive sensor fabric on a foam layer and an outer layer of non-conductive fabric to improve skin–electrode contact [18]. They were fastened on the dog using an elastic chest belt which has an adjustable length to securely fix the electrodes in the correct position on various chest sizes at different tightness levels prepared particularly for this purpose, as shown in Figure 3b. A pocket was sewn on the elastic chest belt to put the ECG device inside the pocket and close its zip for the safety of the device during ECG measurement under dynamic conditions. During long-term monitoring, the elastic strap and the

sandwich structure textile electrodes attached inside the elastic chest strap increase the amount of sweat and reduce the rate of evaporation. This extra saline moisture reduces the skin–electrode interface impedance and helps to have good electrical contact between electrode and skin, allowing for acquiring a high-quality signal [17]. The commercial wet Ag/AgCl electrodes on the other hand were attached to the skin with their self-adhesive pads. The electrode positioning methodology in a dog was derived from the previously reported research [24]. The effect of washing on ECG detection performance of the textile electrodes was studied by washing the electrodes using 4 g/L non-ionic detergents at 30°C for 30 min in a Launder-o-meter.

For the hook textile electrodes, the ECG detection performance of the electrodes was measured by wrapping the measuring

electrodes on the right and left armpits of the dog, and the reference electrode around the chest behind the back shoulder without shaving the hair. To investigate the effect of hair density on the performance of the electrodes, measurement was carried out by placing the measuring electrodes in the left and right armpits of lower hair density and around left- and right-side rib cages around the shoulder where the hair is long and dense relatively. The electrodes were held in place using an elastic band with Velcro® (standard hook and loop), which has an adjustable length to securely attach the electrodes to various chest sizes. ECG signals were obtained in a static position while the dog is laying down using a PC 80B ECG portable measuring device, which was also a similar device for the other electrodes. All measurements were recorded without any skin preparation except moisturizing the skin with tap water. In order to reduce the time required for creating conductive contact between the hook electrode and skin, the skin of the dog was moistened with tap water by cleaning the intended spot using a moistened sponge and ECG waveforms were recorded for 1.5–3 min after a 5 min waiting period. Two dogs participated to study the ECG performance of the hook fabric electrodes.

ECG signals were collected using a portable ECG device mentioned above while the dog was in a sitting position (Figure 3b) and walking on a smooth surface with each measurement lasting 3 min. One dog was selected for an ECG test using silver printed, embroidered, and standard electrodes, and the owner was informed to read the consent form and he agreed to participate his animal in the study. The dog takes a 5-min break after every measurement before going to the next test. Measurements were conducted based on a protocol approved by the Institutional Review Board of Wollo University, Ethiopia (reference number CMHS 1412/13).

The collected signals were uploaded to a computer for evaluation of their quality using the ECG viewer manager software. Every ECG cardiac cycle, both in humans and mammals, contains a P wave, QRS complex, and T wave major peak, where the P wave reflects upward deflection due to the atrium depolarization, and the QRS is a complex generated by the depolarization of the ventricles, whereas the T wave represents the repolarization, i.e., relaxation of the ventricles. An ECG waveform is acceptable if the major peaks are clearly visible, with no missing R-peaks or falsely detected R-peaks in the QRS complex [25]. The R-peak is the highest positive deflection in the QRS complex. The acquired signals were evaluated based on the visibility and amplitude of major waveforms (P, QRS complex, and T). Heart rate can be calculated from the RR interval, which is the time duration between two consecutive R peaks. Signal intervals such as RR intervals and heart rate were calculated from 22 consecutive cardiac cycles of each measurement.

3. Results and discussion

Electrical conductivity is one factor that affects the performance of electrodes to collect ECG signals [26]. The surface resistance of the electrodes was 0.7 ± 0.1 and $1.78 \pm 0.2 \Omega/\text{Sq}$ for embroidered and silver printed electrodes, respectively. The ECG detection performance of the electrodes on a human

was studied in our previous work and the textile electrodes provided a comparable ECG signal result with standard gelled Ag/AgCl electrodes [22,23]. When we compare the human and animal hearts, they show some differences in the ventricular activity process. Small animals have a similar ventricular activity to humans but horses and other large animals show a slight difference. The other basic difference in human and animal ECG monitoring is that the nature of animal skin is different from humans as their skin is covered with dense and long hair, which makes ECG measurement more challenging. Continuous and long-term ECG monitoring is very important for the early detection and treatment of heart arrhythmias both in humans and animals as described earlier. Both the crocodile and standard wet electrodes are not suitable for this long-term ECG monitoring. Textile-based electrodes can address these problems.

3.1. ECG signal acquired using textile electrodes

The ECG signals collected using the embroidered textile electrode, silver printed textile electrodes, and the standard gelled Ag/AgCl electrode are given in Figure 4a–c, respectively. The signals collected from both embroidered and silver printed textile electrodes have clearly visible P, QRS, and T waveforms; they provide comparable signal quality with the standard Ag/AgCl electrodes. There are no missing peaks in both signals collected from the textile and standard electrodes, except for 1 cycle among the 22 cardiac cycles, which shows a suspected fast beat. In some instances, it can be difficult to identify P waves unless the signal is zoomed in.

Table 1 shows the amplitude of major peaks in millivolt and duration of intervals in milliseconds of signals acquired using the three electrodes while the dog was at the sitting position during asynchronous measurement. The mean and standard deviation of each parameter was calculated from the values of 22 consecutive cardiac cycles. The mean amplitude of the P wave was 0.06 ± 0.01 , 0.07 ± 0.01 , and 0.08 ± 0.02 mV for signals collected using silver printed polyester, embroidered, and standard Ag/AgCl electrodes, respectively. Statistical tests revealed that there is a significant difference in P wave amplitude (p -value = 0.001 at α -value = 0.05) among signals collected using standard Ag/AgCl electrodes and silver printed polyester, but there is no significant difference using embroidered textile electrodes. Signals from Ag/AgCl showed a larger P wave amplitude value relatively, but still, they were clearly visible in signals from the textile electrodes. The P wave amplitude in a normal adult dog is expected to be <0.4 mV [6], which means all the values were in the range of normal values. The average amplitude of the T-wave was 0.38, 0.37, and 39 mV for signals acquired using silver printed polyester, embroidered, and Ag/AgCl electrodes, respectively. No significant difference was noted in the value of T wave amplitudes among signals from the three types of electrodes. There was a significant difference in R-peak amplitude ($p < 0.001$ at α -value = 0.01) among the signals acquired using the developed textile electrodes and the commercial Ag/AgCl electrodes, but still all the results were in the range of standard value, which is <2 mV for adult dogs even if it varies from breed to breed [6]. The embroidered textile electrodes show relatively better signal quality

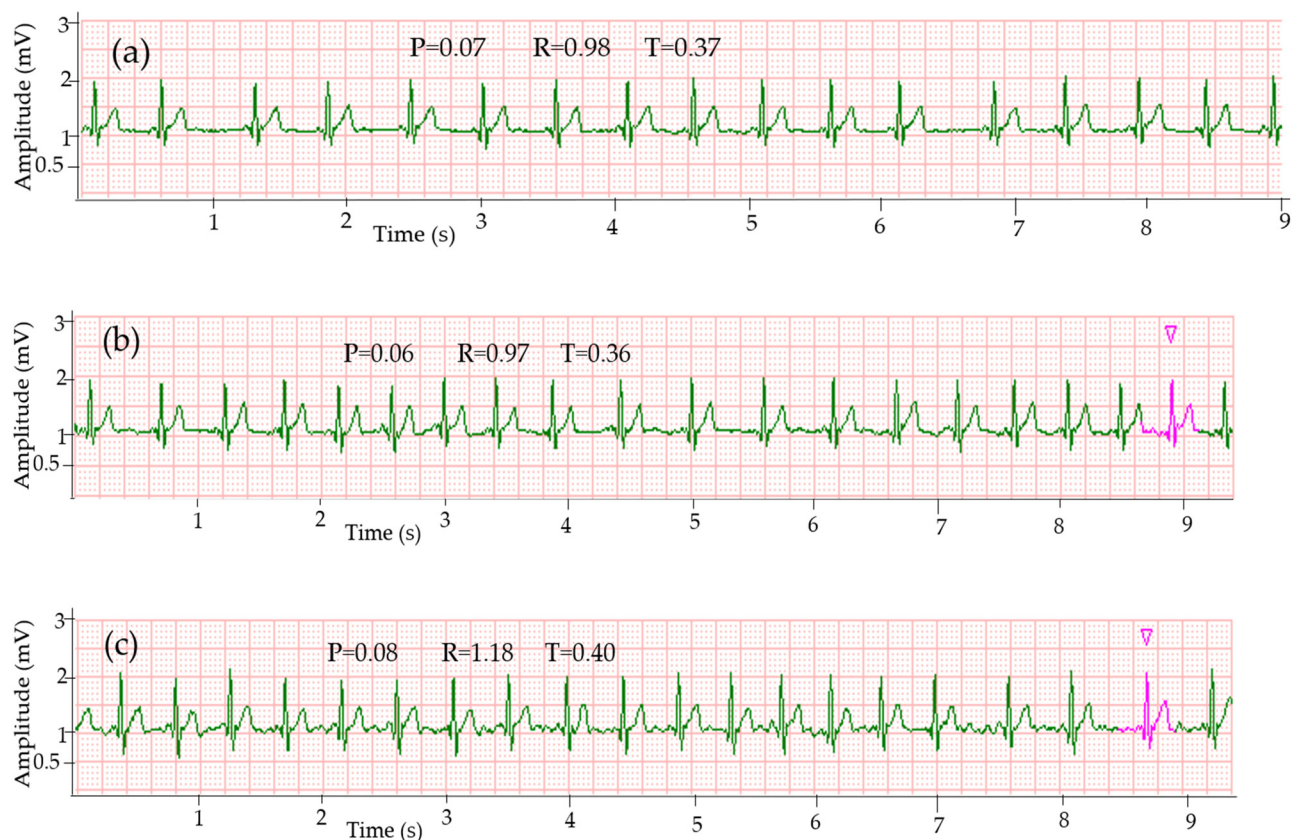


Figure 4. Signal waveforms and average peak amplitudes in millivolt collected while the dog was at rest position using: (a) embroidered electrode, (b) silver printed textile electrode, and (c) Ag/AgCl electrodes.

Table 1. Comparison of signals acquired using textile and gelled electrodes from a dog, mean and SD over 22 consecutive cycles

Waveforms and intervals	Electrode type		Ag/AgCl
	Silver printed polyester	Embroidered	
P (mV)	0.06 ± 0.01	0.07 ± 0.01	0.08 ± 0.02
R-peak amplitude (mV)	0.97 ± 0.05	0.98 ± 0.05	1.18 ± 0.05
T (mV)	0.38 ± 0.03	0.37 ± 0.03	0.39 ± 0.04
PR (ms)	57.76 ± 5.66	56.00 ± 4.24	55.53 ± 7.89
QRS (ms)	91.65 ± 2.74	90.75 ± 3.45	94.01 ± 2.17
QT (ms)	240.53 ± 7.34	246.81 ± 4.02	238.73 ± 23.32
RR interval (ms)	517.47 ± 72.81	567.67 ± 66.93	449.80 ± 44.90
HR (bpm)	127.06 ± 5.57	125.07 ± 4.86	127.20 ± 4.71

compared to silver printed electrodes, which could be due to their high electrical conductivity.

The mean duration of the PR interval was 57.76 ± 5.66 , 56.00 ± 4.24 , and 55.53 ± 7.89 ms for signals collected using silver printed, embroidered, and standard Ag/AgCl electrodes, respectively. There was no significant difference in PR interval values of the signals from the three types of electrodes. The difference between PR, QRS, and QT interval values acquired using the three electrodes was small and there is no significant

difference in all the values of the parameters among the three electrodes. The RR intervals for signals taken using silver printed textile electrodes showed higher standard error compared to the others. The heart rate result was 127 and 123 bpm for the embroidered and printed electrodes, respectively, and 127 bpm for the standard electrodes. No significant difference was found in the heart rate of the signals collected using different electrodes. The standard value of HR for an adult dog is expected to be in the range of 70–160 bpm [6], and all the results were in this range.

3.1.1. Effect of washing on electrode performance

Figure 5 shows ECG signals collected after washing the embroidered textile electrodes. The washed electrodes still contain clearly visible P, QRS, and T waves with a signal amplitude of 0.07, 0.97, and 0.40 mV, respectively, which are approximately the same as signals acquired before washing. No significant difference was found in the R peak amplitude of the signals collected before washing using the same electrode.

3.1.2. Effect of body motion on ECG signal quality

Figure 6 shows the ECG signal collected during the dynamic condition while the dog was walking on a smooth surface. Signals collected during slow walking showed a small deterioration in quality as shown in Figure 6a and as walking speed increased the signal quality became lower and lower as shown in Figure 6b with a significant difference ($p < 0.001$ at $\alpha = 0.01$) in R-peak amplitude compared to signals collected while the dog was sitting. This would be due to unstable skin–electrode contact, but still, the signals are good enough to obtain a qualitative view of the heart condition.

3.2. Hook electrodes for acquiring ECG signal from dog

A problem with the previous research is the need to shave and prepare the skin of the dog. A possible solution is using

materials that can penetrate the hair and still make contact with the skin underneath. Therefore, silver-plated conductive hook electrodes were used to collect ECG signals from the dog. The focus of this study was to find out whether these electrodes could be used effectively for ECG monitoring from the animal without any skin preparation and also without using electrolyte gels. Earlier research showed that electrodes with microscale spikes (pins) can function well on hairy skin since the hair can be positioned in the space between the pins and hence results in skin–electrode contact without shaving the hair [27]. The hook part of a hook and loop textile might provide the same functionality as microscale spike electrodes, provided it is conductive. Hook and loop fabric is more commonly called Velcro® by people, though this is a brand name, and should not be used to denote the fabric. So, in this study, the hook electrode was studied for ECG monitoring from a dog, as the hair could be positioned between the hook spaces. Such an electrode might show promising results when placed on the hairy regions of a dog.

3.2.1. Signal acquired from a dog using hook fabric electrodes

The ECG signals collected using the hook fabric electrodes are given in Figure 7. Two healthy dogs were (Figure 2b for one of the dogs) included in this study. The signals collected from the skin of the dog with relatively lower hair density, where the measuring electrodes were placed around the armpit of the

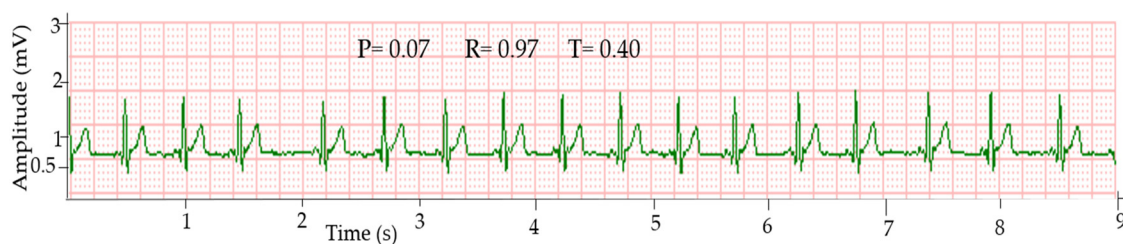


Figure 5. Waveforms and average peak amplitudes in millivolt collected for embroidered electrodes after washing.

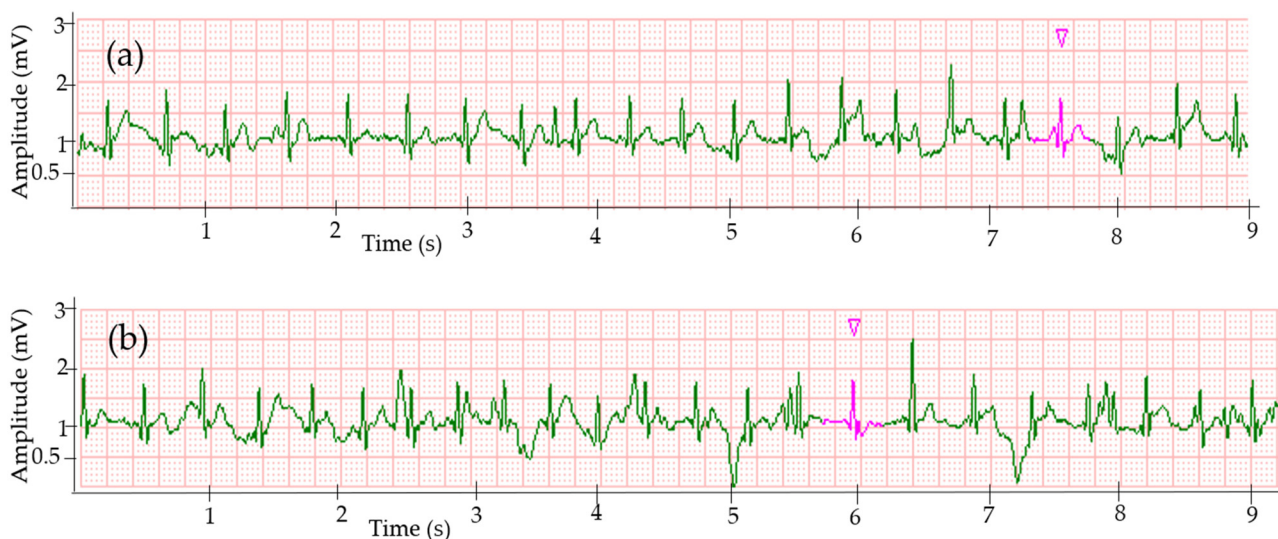


Figure 6. Signals collected using an embroidered electrode: (a) while the dog was slowly walking and (b) while the dog was walking rapidly in a garden.

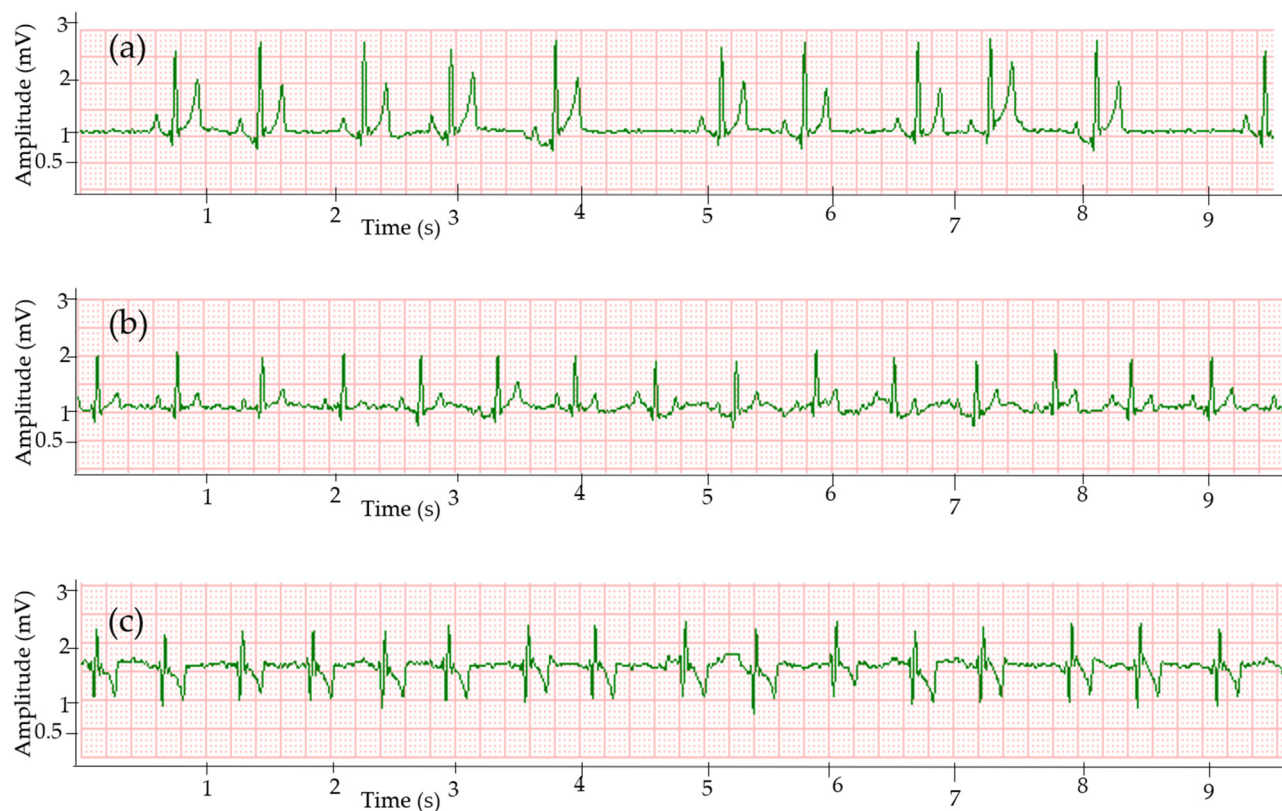


Figure 7. Signals collected using hook fabric electrodes: (a) from around the armpit, (b) from around the shoulder from dog 1 (2× zoomed), and (c) from around the armpit/shoulder of the second dog (2× zoomed).

dog, have clearly visible P, QRS, and T waveforms as shown in Figure 7a. However, the RR intervals are inconsistent and this could be due to the position of the electrodes. To create better contact between the hook and the skin, we slightly slide and push the electrodes on the skin in order to bring the hair in between the hooks. ECG signals from around the shoulder (electrodes placed around the right and left side of the rib cage near the belly) with relatively higher hair density show lowered amplitude of the major waves, as presented in Figure 7b and c, where the figure was zoomed 2× on the ECG viewer manager software to simplify identifying the waveforms. The ECG signals in Figure 7b and c contain all the major peaks. There are no missing major peaks in both signals collected using the developed electrodes.

Results in Table 2 show a comparison of the ECG signals taken using hook fabric electrodes from different positions of the measuring electrodes (armpit and around the shoulder). Signals collected around the armpit have better signal amplitude than signals collected from around the shoulder, this could be due to the variation in surface potential differences in different body positions and high hair density around the shoulder of the dog, which hinders contact of the hooks to the skin. Increasing the length and thickness of the hooks might improve the contact of the electrodes with the skin and hence improve the signal detection performance of the electrodes even from positions with higher hair density. ECG signals taken around the shoulder have approximately the same P, R, and T wave amplitudes with a small standard deviation while more affected by noise. In the signal collected around the armpit, the P, QRS, and T waves have large amplitude values

Table 2. Comparison of signals acquired using hook fabric electrodes from the first dog, mean and SD over 22 consecutive cardiac cycles

Waveforms and intervals	Electrode position	
	Armpit	Around shoulder
P (mV)	0.23 ± 0.02	0.09 ± 0.02
R-peak amplitude (mV)	1.76 ± 0.32	0.53 ± 0.02
T (mV)	0.79 ± 0.10	0.11 ± 0.19
PR (ms)	149.00 ± 10.50	132.33 ± 6.97
QRS (ms)	86.50 ± 3.66	92.17 ± 7.23
QT (ms)	240.08 ± 7.57	246.81 ± 4.02
RR (ms)	847.56 ± 268.11	601.94 ± 144.89
HR (bpm)	75.00 ± 3.89	93.00 ± 1.83

with signal amplitude of 0.23, 1.76, and 0.79 mV, respectively; however, their R-peak amplitude shows severe fluctuation with a standard deviation of 0.32. The heartbeat result was 75 and 93 bpm for signals taken around the armpit and around the shoulder, respectively, which is within the range for an adult dog [6].

4. Conclusions

ECG is the most versatile technique for the diagnosis of heart-related diseases that are common both in humans and animals.

Textile-based ECG electrodes were used for ECG monitoring. The ECG signals acquired using embroidered and silver printed textile electrodes from a dog under static conditions have clearly visible P, QRS, and T waveforms without any missing peak and were comparable with signals from standard Ag/AgCl electrodes. The developed textile electrodes were successfully used for ECG monitoring under static conditions even after washing. However, under dynamic conditions, the quality of collected signal showed some deterioration as walking speed increased for all the electrodes, but still, they were good enough to determine the heart rate of the dog and the magnitude of the R-peak amplitude, signal intervals, and segments. Further investigation would be required to improve the signal quality under dynamic conditions. Silver-plated Velcro hook electrodes were also studied for ECG monitoring from a dog. To investigate the effect of hair density on the performance of the electrodes, measurement was carried out by placing the electrodes in the left and right armpits of lower hair density and around left- and right-side rib cages around the shoulder without any skin preparation. Promising results were found, especially in the areas with lower hair density, showing that this approach has merit. As the literature on the use of textile-based electrodes for animal ECG monitoring is scarce, this study on the use of textile electrodes for ECG monitoring on dogs forms an important contribution and can guide further studies.

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References

- [1] Dupre, A., Vincent, S., Iazzo, P. A. (2005). *Basic ECG theory, recordings, and interpretation. Handbook Of cardiac anatomy, physiology, and devices* (1st ed.). Humana Press (Totowa, N.J).
- [2] Lanata, A., Guidi, A., Baragli, P., Valenza, G., Scilingo, E. P. (2015). A novel algorithm for movement artifact removal in ECG signals acquired from wearable systems applied to horses. *PLoS One*, 10(10), e0140783. doi: 10.1371/journal.pone.0140783.
- [3] Hoque, M., Saxena, A. C., Gugjoo, R.-M. B., Bodh, D. (2019). Cardiac diseases in dogs. *Indian Journal of Animal Health*, 58(1), 1–20. doi: 10.36062/ijah.58.1.2019.01-20.
- [4] Webster, J. G. (2010). *Medical instrumentation - application and design* (4th ed.). John Wiley & Sons (New York, USA).
- [5] Ware, W. A. (1999). Twenty-four-hour ambulatory electrocardiography in normal Cats. *Journal of Veterinary Internal Medicine*, 13, 175–180.
- [6] Martin, M. (2002). ECG interpretation in small animals: 3. practical guidelines. In *Practice*, 24(5), 250–261. doi: 10.1136/inpract.24.5.250.
- [7] Kaese, S., Frommeyer, G., Verheule, S., van Loon, G., Gehrmann, J., Breithardt, G., et al. (2013). The ECG in cardiovascular-relevant animal models of electrophysiology. *Herzschr Elektrophys*, 24(2), 84–91. doi: 10.1007/s00399-013-0260-z.
- [8] Nigusse, A. B., Mengistie, D. A., Malengier, B., Tseghai, G. B., Langenhove, L. V. (2021). Wearable smart textiles for long-term electrocardiography monitoring—a review. *Sensors*, 21(12), 4174. doi: 10.3390/s21124174.
- [9] Meurs, K. M., Spier, A. W., Wright, N. A., Hamlin, R. L. (2001). Use of ambulatory electrocardiography for detection of ventricular premature complexes in healthy dogs. *Journal of the American Veterinary Medical Association*, 218(8), 1291–1292. doi: 10.2460/javma.2001.218.1291.
- [10] Guccione, J., Piantadosi, D., Di Loria, A., Veneziano, V., Ciaramella, P. (2014). Long-term electrocardiography recording with holter monitoring in 15 donkeys. *Journal of Equine Veterinary Science*, 34(2), 302–306. doi: 10.1016/j.jevs.2013.07.001.
- [11] Verheyen, T., Decloedt, A., Clercq, D. D., Deprez, P., Sys, S. U., van Loon, G. (2010). Electrocardiography in horses – part 1: how to make a good recording. *Vlaams Diergeneeskundig Tijdschrift*, 79(5), 331–336.
- [12] John, G. W. (2010). *Medical instrumentation application and design*. John Wiley & Sons (New York, USA).
- [13] Pace, C. (2018). How ECG monitoring contributes to patient care. *The Veterinary Nurse*, 9(4), 216–223. doi: 10.12968/vetn.2018.9.4.216.
- [14] Yu, L. M., Tay, F. E. H., Guo, D. G., Xu, L., Yap, K. L. (2009). A microfabricated electrode with hollow microneedles for ECG measurement. *Sensors and Actuators A: Physical*, 151(1), 17–22.
- [15] Virtanen, J., Leivo, J., Vehkaoja, A., Somppi, S., Törnqvist, H., Fiedler, P., et al. (2018). Dry contact electrodes performance in canine ECG. *Proceedings of the Fifth International Conference on Animal-Computer Interaction, Atlanta, Georgia, USA*. pp. 1–5. doi: 10.1145/3295598.3295609.
- [16] Virtanen, J., Somppi, S., Törnqvist, H., Jeyhani, V., Fiedler, P., Gizatdinova, Y., et al. (2018). Evaluation of dry electrodes in canine heart rate monitoring. *Sensors*, 18(6), 1757. doi: 10.3390/s18061757.
- [17] Guidi, A., Lanata, A., Valenza, G., Scilingo, E. P., Baragli, P. (2017). Validation of smart textile electrodes for electrocardiogram monitoring in free-moving horses. *Journal of Veterinary Behavior*, 17, 19–23. doi: 10.1016/j.jveb.2016.10.001.
- [18] Felici, M., Nardelli, M., Lanatà, A., Sgorbini, M., Pasquale Scilingo, E., Baragli, P. (2021). Smart textiles biotechnology for electrocardiogram monitoring in horses during exercise on treadmill: validation tests. *Equine Veterinary Journal*, 53(2), 373–378. doi: 10.1111/evj.13296.
- [19] Guidi, A., Lanata, A., Baragli, P., Valenza, G., Scilingo, E. (2016). A wearable system for the evaluation of the human-horse interaction: a preliminary study. *Electronics*, 5(4), 63. doi: 10.3390/electronics5040063.
- [20] Ferri, J., Llinares, R., Segarra, I., Cebrián, A., Garcia-Breijo, E., Millet, J. (2022). A new method for

- manufacturing dry electrodes on textiles. Validation for wearable ECG monitoring. Electrochemistry Communications*, 136, 107244. doi: 10.1016/j.elecom.2022.107244.
- [21] An, X., Stylios, G. K. (2018). A hybrid textile electrode for electrocardiogram (ECG) measurement and motion tracking. *Materials*, 11(10), 1–18.
- [22] Nigusse, A. B., Malengier, B., Mengistie, D. A., Tseghai, G. B., Van Langenhove, L. (2020) Development of washable silver printed textile electrodes for long-term ECG monitoring. *Sensors*, 20(21), 6233. doi: 10.3390/s20216233.
- [23] Nigusse, A. B., Malengier, B., Mengistie, D. A., Van Langenhove, L. (2021). Evaluation of silver-coated textile electrodes for ECG recording. 2021 IEEE International Conference on Flexible and Printable Sensors and Systems (FLEPS), Manchester, United Kingdom. pp. 1–4. doi: 10.1109/FLEPS51544.2021.9469834.
- [24] Brloznik, M., Avbelj, V. (2015). Wireless electrocardiographic monitoring in veterinary medicine. 2015 38th International Convention on Information and Communication Technology, Electronics and Microelectronics (MIPRO), Opatija, Croatia. pp. 356–359. doi: 10.1109/MIPRO.2015.7160294.
- [25] Taji, B., Shirmohammadi, S., Groza, V., Bolic, M. (2013). An ECG monitoring system using conductive fabric. 2013 IEEE International Symposium on Medical Measurements and Applications (MeMeA), Gatineau, QC. pp. 309–314. doi: 10.1109/MeMeA.2013.6549758.
- [26] Das, P. S., Kim, J. W., Park, J. Y. (2019). Fashionable wrist band using highly conductive fabric for electrocardiogram signal monitoring. *Journal of Industrial Textiles*, 49(2), 243–261. doi: 10.1177/1528083718779427.
- [27] Chen, Y. H., Op de Beeck, M., Vanderheyden, L., Carrette, E., Mihajlović, V., Vanstreels, K., et al. (2014). Soft, comfortable polymer dry electrodes for high quality ECG and EEG recording. *Sensors (Switzerland)*, 14(12), 23758–23780. doi: 10.3390/s141223758.