A Printed, Dry Electrode Frank Configuration Vest for Ambulatory Vectorcardiographic Monitoring

Gordon Paul, Russel Torah, Steve Beeby and John Tudor*

Abstract— **This paper describes the design and fabrication of a screen printed network of bio-potential measurement electrodes on a garment, in this case a vest. The electrodes are placed according to the Frank configuration, which allows monitoring of the electrical behavior of the heart in three spatial orientations. The vest is designed to provide stable contact pressure on the electrodes. The electrodes are fabricated from stencil printed carbon loaded rubber and are connected by screen printed silver polymer conductive tracks to an array of vias, which form an electrical connection to the other side of the textile. The vest is tested and compared to Frank configuration recordings that were obtained using standard self-adhesive ECG electrodes. The vest was successfully used to obtain Frank configuration recordings with minimal baseline drift. The vest is fabricated using only technologies found in standard textile production lines and can be used with a reduced setup effort compared to clinical 12-lead examinations.**

Index Terms—**Electrocardiogram, wearable, screen printing, smart fabrics**

I. INTRODUCTION

THE electrocardiogram (ECG) is a vital tool in the diagnosis of heart conditions. Some symptoms can be recognized with a single lead, which provides a view of the heart in only one dimension. This is achieved by comparing two points on the skin surface using skin contact electrodes. An examination with greater detail can be achieved by measuring the skin surface voltage from several directions, providing a three-dimensional view of the heart's behavior [1].

Examinations of this type are usually carried out in a hospital setting using self-adhesive silver/silver chloride (Ag/AgCl) electrodes. The 12-lead system is typically used. This is obtained using an electrode on each arm and leg and six across the front of the chest. However, this requires significant training and setup time for correct placement of the electrodes and the electrodes usually cannot be re-used [2]. A Frank configuration electrocardiogram, using only 8 electrodes, provides the same information as a 12 lead examination. Research has been carried out on extrapolating the 12-lead data, with which physicians are trained, from the Frank configuration ECG [3]. It has been shown that transformations from such reduced lead systems are clinically accurate when the signal to noise ratio is

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sufficiently high [4]. Multiple lead electrocardiographic systems have advantages over single lead systems for ambulatory monitoring in some situations. For example, they have an improved sensitivity in detecting events such as myocardial ischemia [5].

Electrodes for biopotential monitoring are defined as passive or active, depending on whether they contain active components such as op-amps which require a power supply. Previously researchers have implemented passive electrodes for heart monitoring on textiles with knitted [6] and embroidered [7] conductive yarns. More recently, researchers have fabricated passive electrodes using screen printing on to woven [8] and nonwoven [9] textiles. The fabrication techniques described here have also been used in previous work to create screen printed conductive tracks on textiles that can reliably endure 10 machine washes without failure [10,11].

This work aims to reduce the material cost and setup time of multiple electrode examinations by creating a reusable, textile garment for ambulatory vectorcardiographic monitoring. This will also allow such examinations to be taken on a longer term basis, outside of a hospital setting. These are currently restricted to single-lead examinations, partially because the placement of the electrodes is not considered reliable when they are placed by the patient and not by a physician. An ambulatory vectorcardiogram vest, to be worn by an ambulatory patient for a fixed period of, for example, one week, facilitates a more detailed and accurate diagnosis of cardiac events. Some such events occur infrequently and are therefore unlikely to occur when a patient is in a clinical setting undergoing a multiple lead examination.

A Frank configuration monitoring vest is fabricated here using screen and stencil printing to create an insulated, conductive network on a vest that connects dry, passive, conductive rubber electrodes to a centralized set of conductive vias. The Frank configuration electrode position system is used because this system gives a full three-dimensional view of the heart with only seven differential electrodes and a reference electrode. The resulting system is examined with table-top analogue amplifiers and data acquisition systems. Portable electronics and data transmission are outside of the scope of this paper.

II. VEST DESIGN

In Frank's original design [12] there was an electrode placed on the neck and on the foot. For an easily wearable monitoring garment these electrode positions must be moved on to the torso, so that all electrodes can be placed on single garment, in this case, a vest. The revised electrode positions, as defined by the BRAVEHEALTH project [13] from which

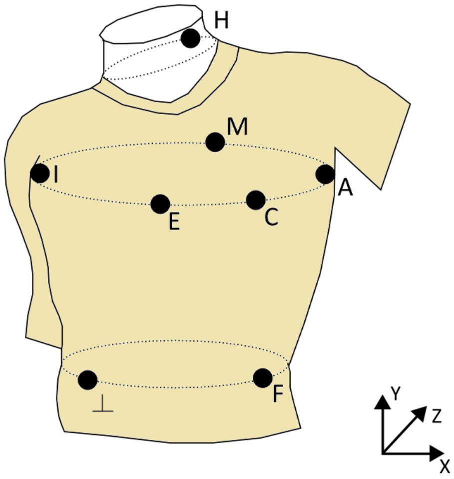

Fig. 1. The Frank configuration vest concept design from the BRAVEHEALTH project.

this research originated, are shown in Fig. 1. Electrode F is moved up from the foot and electrode H is moved down from the neck.

A conductive network was designed to connect electrodes in the Frank configuration positions to vias at a centralized point on the vest. From this centralized point the electrodes can be connected to an external instrumentation amplifier with a single set of cables. In future, amplification and wireless communication electronics can be integrated into this central point so that cables are not required.

Screen printing is used to fabricate a network that is composed of electrode pads, centralized via contact pads and the conductive tracks that connect between the electrodes and the vias. Dry passive electrodes are used here to simplify fabrication, however this technology is compatible with dry active electrodes described previously [14,15]. Because the maximum printable area is limited for the equipment used, the printed network is fabricated with two separate designs that are printed individually, as shown by the two highlighted areas in Fig. 2. The printed textiles are sewn to a vest textile with silicone foam inserted between the printed and vest textiles, as recommended by Ottenbacher et al [16], to improve contact pressure stability. The vest textile then has elastic strips sewn to the opposite side to improve form fitting, ensuring the electrodes make stable skin contact. A diagram of the layer structure at an electrode site is shown in Fig. 3. The electrical connection to the electrode is not shown.

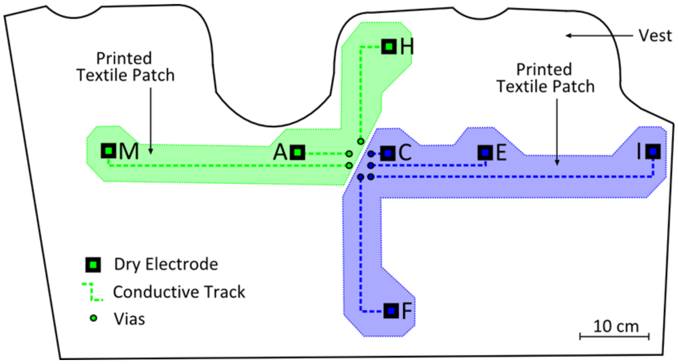

Fig. 2. A concept diagram showing the positions of electrodes, conductive tracks and vias on the textile vest from the inside.

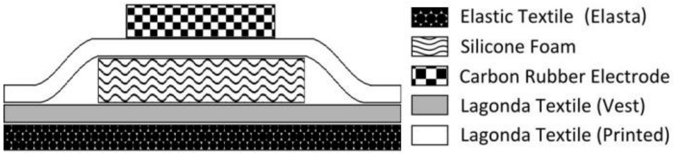

Fig. 3. The layer structure at the site of an electrode. The electrical connection to the electrode is not shown.

III. FABRICATION METHODS

Since the conductive network is screen printed on to a woven textile, an interface paste is used to reduce the surface roughness of the textile. This interface is screen printed directly on to the textile and is polyurethane based. Using this interface, a low-resistance network of conductive tracks can be fabricated on the textile using a thinner layer of silver polymer paste than would be possible without the interface. This conductive network is then insulated with the same polyurethane paste as used for the textile interface. This methodology was first described by Yang et al [17].

The network is screen printed on to a large square (50 x 50 cm) of a woven textile, Lagonda, supplied by Klopman International S.R.L. This textile was selected because it is commonly used by the supplier in medical clothing and provides a good compromise between comfort and suitability for printing. The yarns of this textile are composed of cotton, polyester and Lycra and the textile thickness is 290 µm. The screens used have a mesh density of 250/inch and a mesh angle of 45^0, with the emulsion thickness varying depending on the required layer thickness. First, FabInks-UV-1004 [18] interface paste is printed and cured several times using a screen with emulsion thickness 30 µm. This creates a smooth interface layer on the textile, with a thickness around 100 µm above the textile surface. Then, Fabinks TC-C4001 silver conductor is printed using a screen with emulsion thickness 5 µm, resulting in a layer 5-10 µm thick. This is cured in an oven at 120 ^{0}C for 10 minutes. Finally, the conductive tracks are encapsulated with a further two print-cure cycles using FabInks-UV-1004 and a screen emulsion thickness of 30 µm, providing an encapsulation layer of thickness 60 µm. The textile patches are then cut out from the larger square of textile. The screen designs are shown in Fig. 4 and the printed textile patches are shown in Fig. 5. The resistance of each silver track was measured with a Tenma 72-7735 digital multi-meter and the measured resistances are marked on Fig. 5. The resistance of each conductive track is measured from the central point of the via pad to the central point of the electrode pad.

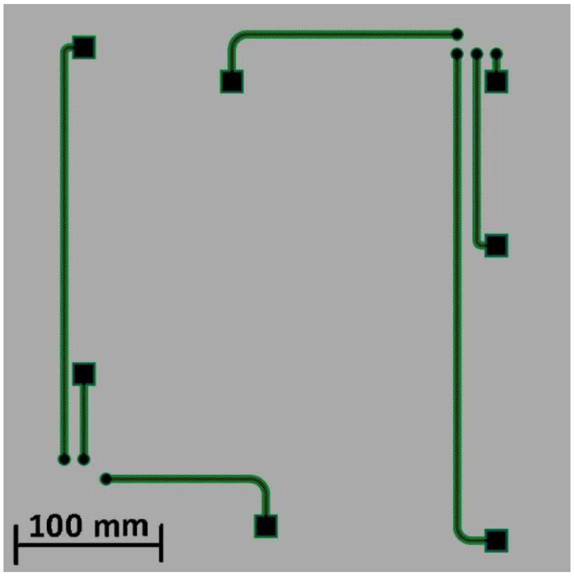

Fig. 4. The screen design for the Frank configuration monitoring vest.

The electrode pads are then stencil printed with carbon black loaded silicone rubber. This material is selected because it provides a high level of flexibility for a conductive material, while being water resistant and having a low surface energy, which prevents hair and dirt gathering on the electrode and facilitates cleaning. It can also be molded into different shapes and consequently an uneven skin contacting surface can be created, which allows the electrode to make contact more easily when the skin is hairy. An aluminium

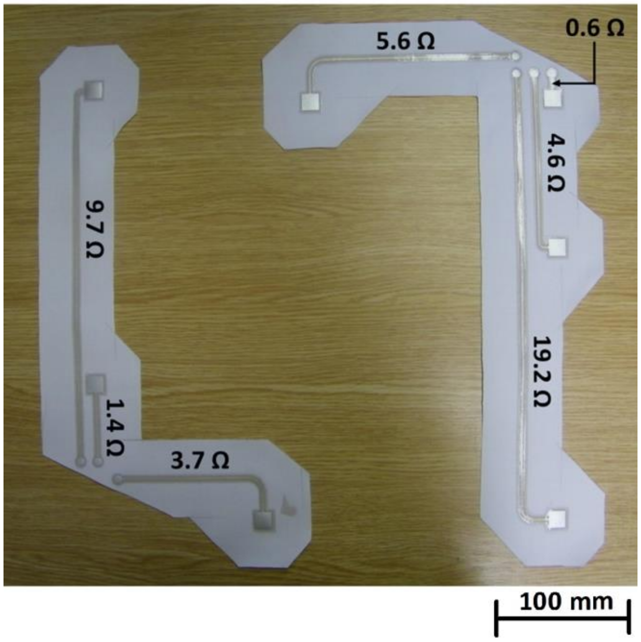

Fig. 5. Screen printed textile patches used in the Frank configuration monitoring vest and associated track resistance values.

stencil with a thickness of 3 mm is used. The stencil printed carbon loaded rubber, forming the skin contact area of each electrode, has a thickness of 3 mm and a length and width of 26 and 22 mm respectively. The screen and stencil printed textile patches are shown in Fig. 6.

The printed textile patches are then sewn to a vest-shaped textile. Silicone foam with thickness 6.3 mm is placed between the two Lagonda textiles. Elastic strips of width 50 mm and thickness 1.05 mm are then attached to improve the contact stability of the electrodes when the vest is worn. Every electrode has an elastic strip over it. These elastic strips have hook and loop textile attached at the ends of the strips so that the vest can be secured around the torso. The complete vest is shown in Fig. 7.

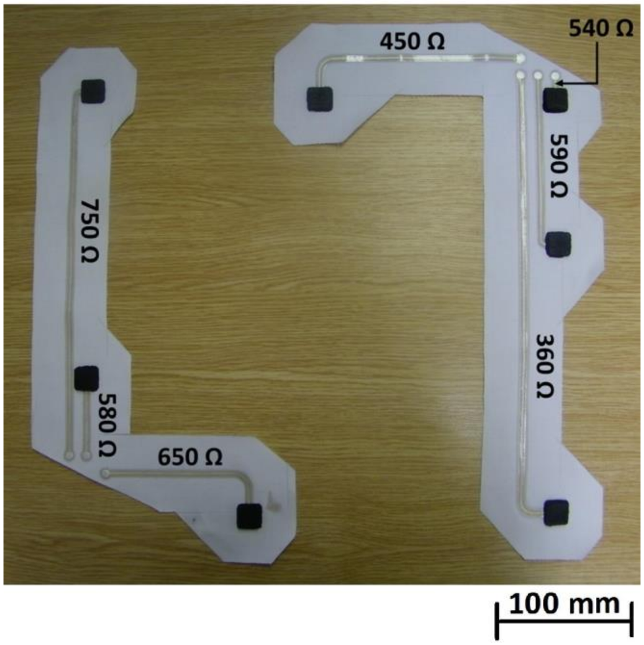

Fig. 6. The screen printed textile patches with stencil printed carbon black loaded silicone rubber electrodes and associated track resistance values after stencil printing.

Fig. 7. The Frank configuration vest with the screen and stencil printed patches and elastic strips attached.

Fig. 8. Left - Frank configuration vest worn inside-out viewed from 45^0 . Right - Frank configuration vest worn inside-out viewed from 225^0.

Fig. 8 shows the vest worn inside-out so that the electrode positions can be observed. The final step of the fabrication process involves clamping a steel button, of the type found commonly in garments, through each of the screen printed via pads in the centralized array. This allows electrical connection through the textile so that electronics can be added on the outer, non-printed side of the vest without discomfort when the vest is worn. These steel buttons have short wires attached that connect to the amplifier via a resistive network. The fabrication process for similar stencil printed electrodes and textile vias has been described previously in greater detail [19].

IV. TESTING METHODS

The impedance spectrum of the electrodes in this work was examined using a Wayne Kerr 6500B precision impedance analyzer. An impedance-frequency sweep with 400 points from 20 Hz to 10 MHz was performed using two of the textile electrodes placed face to face with a contact pressure of ~25 kPa. The skin-electrode impedance is not tested here. The impedance and phase angle are shown in Fig. 9. The DC impedance is around 1 kΩ and remains relatively stable from 20 to 1000 Hz, changing less than 20%. The phase angle is near 0° at these frequencies.

The Frank configuration vest is tested using the resistive network proposed by Frank. This network is designed to use combinations of signals from groups of electrodes to provide three leads which represent the electrical activity of the heart in the X, Y and Z axes as defined in Fig. 1. The resistive network used in this work is unshielded and connects between the vest and the amplifier cables. The value of R, the resistance multiplier in Fig. 10, was chosen as 50 kΩ in this work to ensure the network resistance is significantly larger than the electrode resistance, as recommended in Frank's original paper [12]. It has been reported that the skin-electrode impedance can exceed even this high value, and rubbing or wetting might be required in some circumstances with this prototype.

The amplifier circuit used in this work is the instrumentation amplifier circuit described by Spinelli et al which has a gain of 1000 [20]. This amplifier circuit was chosen because it has a high common mode rejection ratio (123 dB at 50 Hz) and contains an AC-coupling element that rejects DC drift at the electrodes. AC coupling is useful when using dry electrodes that do not have a stable electrochemical potential at the electrode-skin interface, because it rejects some DC drift prior to amplification. A set of these amplifiers in a shielded box were used for this work. All cables other than those printed on to the textile are shielded. The output signals from the amplifiers are digitized using a National Instruments USB-6008 data acquisition device and the signals are recorded and viewed in National Instruments SignalExpress 3.0. The full experimental setup is shown in Fig. 10.

The presence of sweat during the recordings improved the performance of the Frank configuration vest due to reduced skin-electrode impedance, while the conventional gel electrodes were more prone to slipping off in sweaty

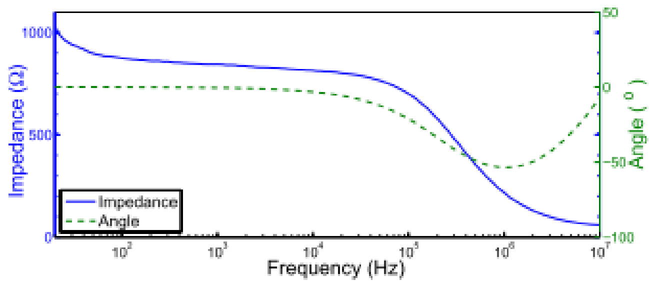

Fig. 9. An impedance/frequency sweep with two textile printed electrodes face to face. No conductive paste is used. Contact pressure is ≈25 kPa.

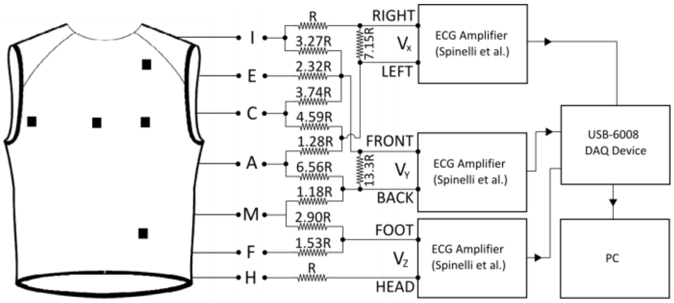

Fig. 10. Full experimental setup for recording signals from the Frank configuration vest.

conditions. To prevent this affecting the results, the skin was wiped dry before each recording.

V. RESULTS

First, measurements are taken using standard Ag/AgCl self-adhesive electrodes. To examine the effect of changing the position of the head (H) and foot (F) electrodes, one measurement is taken with the electrode positions originally proposed by Frank and another is taken with the electrodes on the torso, with the head and foot electrodes in the modified positions. Recordings are taken using 3M RedDot self-adhesive electrodes [21] which are taped to the body and connected to the amplifier with shielded cables. The amplified signals from recordings with the original and modified Frank positions are shown in Fig. 11 and Fig. 12 respectively.

The main difference between these recordings is observed on the Y signal. In the recordings with the modified positions the amplitude of the peaks on the Y signal recordings is significantly larger. This is because the Y signal electrodes (H and F) have been moved on to the torso.

A recording was then taken with the Frank configuration vest. The setup time is under 10 seconds, significantly faster than individually applying electrodes which can take several minutes. No conductive gel was used. The driven right leg (DRL) electrode was not printed in combination with the other electrodes so that different DRL positions could be examined. It was found that the placement and material of the DRL electrode had minimal effect as long as it had stable skin contact, although signal quality appeared to improve with the DRL on the limbs compared to the torso. The DRL

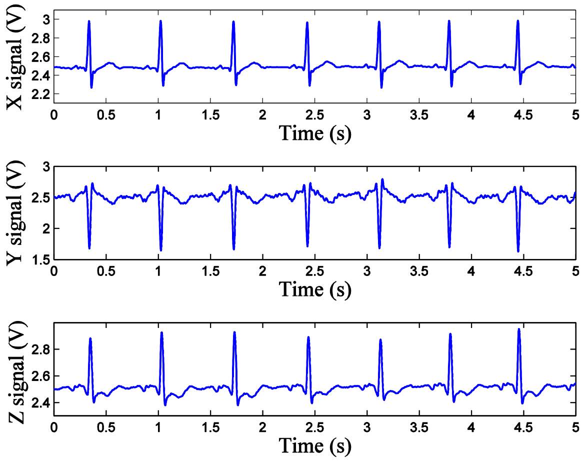

Fig. 11. Amplified signals from Frank configuration recording with the original electrode positions using 3M RedDot Ag/AgCl self-adhesive electrodes.

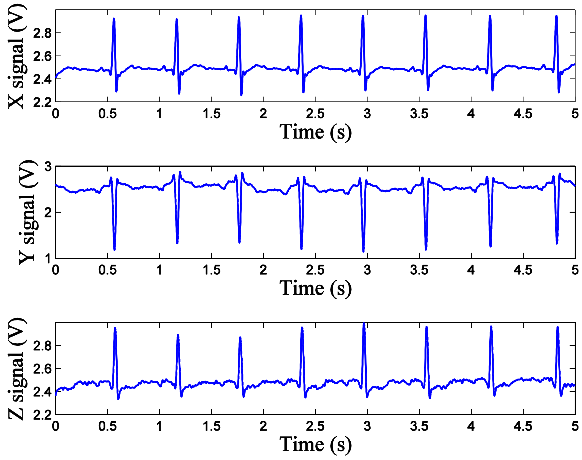

Fig. 12. Amplified signals from Frank configuration recording with the modified electrode positions using 3M RedDot Ag/AgCl self-adhesive electrodes.

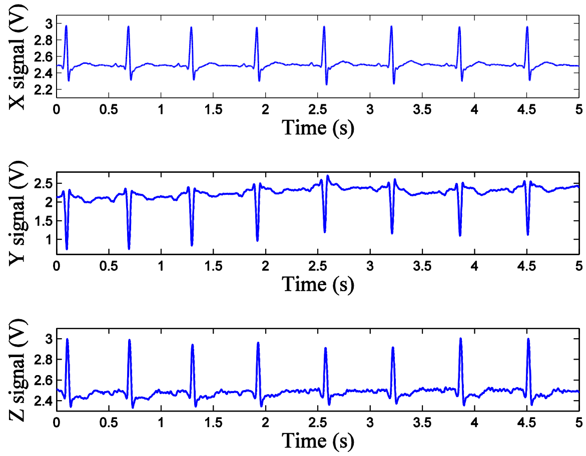

Fig. 13. Amplified signals from Frank configuration recording taken with the screen and stencil printed vest.

electrode used in the recordings shown here was a 3M RedDot solid gel electrode connected to the torso as described in Fig. 1. The amplified signals from a recording with the vest is shown in Fig. 13.

These electrodes match well with the previously recorded modified Frank configuration. There is some 50 Hz noise on the recordings, notable on the example recording here on the V_Z lead. Baseline drift is also more significant, observable here on the V_Y lead. There was a settling time of less than five minutes, during which large amounts of baseline drift occurred during motion artefacts. Despite these limitations, these results demonstrate a clear proof of concept, showing that an accurate vectorcardiogram can be recorded from an ambulatory patient using a printed woven textile garment.

VI. CONCLUSIONS

This paper has demonstrated the use of screen and stencil printing to fabricate a prototype Frank configuration monitoring garment. The garment allows the electrical potential from the heart to be monitored in three different axes with a setup time of around 10 seconds and no discomfort.

In a final application several different sizes of the vest would be required to fit various body types because the textile is not stretchable. Increasing the stretchability of the conductive tracks would allow one garment to fit various body sizes and allow for greater skin contact pressure. The fabrication approach outlined here could be used to implement alternative reduced lead configurations, such as the EASI configuration [22], which might be less affected by motion artefacts.

The testing method used here is limited, in that there is no numerical analysis of the results or testing on multiple subjects. However, the experiments described here provide a proof-of-concept for this monitoring device and fit within the scope of this paper. With the printed vest there was a settling time of less than 5 minutes due to impedance mismatch while the impedance of the electrodes stabilized. During this settling time motion artefacts and baseline drift were significant and prevented an accurate ECG from being recorded. Even after this settling time some minor motion artefacts were present; although the author could walk without obviously affecting results, the motion artefacts were clear when, for example, an arm was lifted above the head. In practice, this would not prevent diagnostically useful information from being recorded, but would reduce the amount of data available. It would also prevent information from being recorded in any cardiac event that was accompanied by a spasm or a fall. The settling time and the motion artefacts present with passive electrodes can be prevented by using dry active electrodes on woven textile, which have been demonstrated previously by the authors to have no settling time and motion artefact levels as low as clinical Ag/AgCl electrodes [14].

The vest reported here can be used to monitor a Frank configuration vectorcardiogram with high quality. After a short settling time the signal noise is low enough that all the ECG deflections, their timing and their relative magnitudes can be observed. The vest is simple to use and has potential to be used in telemedicine and home health care as it could conceivably be used without specialist training. It also has the potential to save time in hospitals with significantly faster setup procedures.

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