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Performance Evaluation of Cardiac Signal Recording Framework (CARDIF)-A Quantitative Assessment for Long Term Monitoring Applications

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Personal health monitoring with wearable electronics has gained momentum in the recent years due to its usage in flexible textile-based sensors/electrodes for recording of physiological vital parameters. Such system provides scope for long term ambulatory ECG measurement and motion tracking applications. The selection /design of textile sensors play a vital role as it has to overcome skin irritations, improve the skin-electrode impedance required for conductivity. The composition of textile materials, shape and size of the textile electrodes contributes significantly towards the conductivity. Objective: To assess the proposed Cardif system for its suitability to introduce in the clinical routine Method: The proposed textile electrodes were designed using knit jersey conductive material. The skin –contact impedance of the proposed textile material, was measured using two electrode impedance method and measurement was done for different age groups by varying the frequency. Results: The measurement results showed that the impedance was decreasing with increasing frequency and was found to be below 1.5Mohm/cm^2 in the frequency range of 20Hz to 1KHz for three different age groups. The performance of the CARDIF was assessed using heart rate, RR interval, SNR as well as qualitative assessment through visual inspection and were compared with gel based disposable Ag/AgCl electrodes. Qualitative and quantitative analysis was performed and the various results confirm the proposed textile electrodes for continuous patient monitoring applications.

Keywords: Cardiac monitoring; Continuous Monitoring; ECG; Fidelity Measures; Textile Electrodes.

The impact of wearable physiological monitoring system towards personalized healthcare and quality of lifestyle on daily basis can be well understood through current wearable devices available in the global market. Though this technology has created revolution in developed countries, it is to yet to reach the underdeveloped countries especially for resource-constrained settings. Due to the device development cost and reliability, there is a huge demand to cater to the needs of mid and low-income countries. Attempts have been made to develop wearable systems, but mostly it gets stopped at the academic laboratories. Translation from prototype to product, commercialization and market potential requires huge investments and due to this, the accessibility of such devices is still a dream for low-income countries. In the recent years wearable technology growth has created huge impact on the healthcare sector especially towards homocentric applications by lowering the cost factor without sacrificing the required clinical diagnostic requirements. This has shown the path for under developing countries towards design and development of wearable physiological monitoring devices.

Long term electrocardiogram (ECG) recordings assessment is very important for recognition of various cardiac episodes including syncope, palpitations etc.,[1]. Such automated computer aided quantitative assessment provides alerts to the patients and real-time qualitative annotation can be performed by the cardiologist remotely to understand the severity level. Hence there is a greater demand for developing external cardiac loop recorders, which can store the cardiac episodes for longer duration and the real time assessment of the cardiac activity by the cardiologist[2].

Most of the electrodes used for ECG data acquisition are gel-based Ag/AgCl surface electrodes. These surface electrodes have to be used with conductive gel to establish proper conductive path to acquire the bio-potentials. But, if it is used for longer duration, drying up of gel causes rise in skin-electrode contact impedance and also causes skin-irritation or rashes . These gel-based electrodes cannot be used repeatedly as they are not reusable. To avoid all these problems and to acquire ECG signal for long duration, textile electrodes are widely researched and proven to be beneficial in acquiring bio-potentials. Hence, textile electrodes seemed to be promising alternatives for continuous and long-term cardiac monitoring compared to gel-based electrodes[3-11].

Due to its inherent conductive properties, textile based dry electrodes are being designed as ECG sensors for continuous monitoring applications and such electrodes are less susceptible to artifacts. It is well-known fact that choosing textile materials for such applications merely depends on the material's durability, reusability and launderability.[9-12]. The objective of this study is to make use of conductive textile material as a biopotential sensor for long term ECG monitoring Applications at an affordable cost to cater the need of resource constrained settings. Though several attempts have been made, the scope for new sensor design still emerge due to the need for low cost sensor design requirements.

This specific study highlights the performance evaluation of cardiac signal recording framework (CARDIF) that consists of dry ECG electrodes as sensor with an AFE unit and Xilinx real time processor. Knit jersey conductive material was considered to design the dry ECG electrode as the sensing unit. The skin –contact impedance of the proposed textile material, was measured using two electrode impedance method and measurement was done for different age groups by varying the frequency. The measurement results showed that the impedance was decreasing with increasing frequency and was found to be below 1.5Mohm/cm^2 in the frequency range of 20Hz to 1 KHz for three different age groups. The performance of the CARDIF was assessed using Heart rate, RR interval, SNR as well as qualitative assessment through visual inspection and were compared with gel based disposable Ag/AgCl electrodes.

Background for the Proposed Study

Related Work

A wrist based Electrocardiography's performance was designed and its performance was reported[3]. A CamNtech recorder was used where three pre-gelled surface electrodes were placed on the non-dominant hand and the fourth one on the chest. The heart rate was measured and the study showed that the motion artifacts were nullified. The study confirmed the suitability for designing low power wearable settings. A specific study was reported by[14] towards developing smart garment for cardiac mechanical performance. The main focus was to monitor the physiological changes during sleep and assess the mechanical variation of the heart. The smart wearable system comprised of sensorized vest, electronic module, external module for thoracic skin temperature and the battery unit. The study was conducted by Italian space Agency. A multiparameter wearable system was proposed by[15] to assess the cardiopulmonary functionalities. Gait analysis was integrated with the physiological parameters analysis and the study showed a potential way towards developing assistive tools.

Conductive yarns form the basis for the textile sensors where process such as knitting, weaving, printing of conductive polymers on nonconductive fabrics were introduced for the formation of conductive yarn[16]. Several textile based electrodes were reported for measurement of ECG[17-26]. A hybrid textile electrode has been proposed for ECG measurement[16] and motion tracking. A silver-plated weft knitted conductive fabric was used along with the flexible motion sensor circuit. It was shown that the proposed approach ensured a synchronized mechanism between the two modalities.

It is a well-known fact that the conventional (Ag/Ag Cl)rigid metal plate electrode provides good conductivity through usage of the gel on the skin surface.Such gel often causes skin irritation and allergy. For wearable home centric applications textile based sensors/electrodes provides more flexibility than the conventional electrodes. Textile electrodes are dry/gel less based, soft in nature and its efficiency relies on the selection of material and its composition. Furthermore, these electrodes can be integrated into textile garment for making smart wearable T shirts for long term monitoring. The electrodes can be washed, reused and the cost factors can be brought down by making use of locally available electronic assembly thereby making it suitable for resource constrained settings. Due to such factors, several attempts have been made in the past to introduce textile based sensors/electrodes. A specific study was made to recognize the best textile materials for the development of capacitive Biosensors[27]. Six common textile materials and their characteristics were studied. A capacitance driven biosensor was designed and evaluated onthe electromyography signals[28]

There are two variants of electrodes for developing biosensors, contact based wet electrodes and noncontact dry electrodes. The bio signal which gets generated depends on the electrode-skin interface where typical Ag/AgCl based conductive gel are applied to reduce the impedance between the skin electrode to improve the signal quality. Such procedure leads to skin irritation, allergy to patients. Hence such wet electrodes do not suit for wearable monitoring applications. On the other hand, attempts have been made to introduce gel less dry electrodes.[14,29-30]. In the recent years textile based dry electrodes as biosensors have been proposed by several researchers for bio signal measurements[31-37.]

While designing textile electrodes, one has to give much consideration to contact impedance, conductive capability of the material, SNR of the resultant ECG signal, resistance/capacitance, material conductive area and shape of the textile material. The composition of textile materials plays an important role towards conductivity (better impedance between the skin and the electrode). Thereby making the resultant ECG signal to be good enough to make required diagnosis by the clinical community. Cotton based fabrics are ideally preferred for use as textile electrodes that provide more comfort ability to the user, than the use of cotton blended yarn.

A 3 channel wearable ECG was demonstrated by[10]. A real-time ECG recording monitoring system was proposed[38]. A specific study on ECG signal acquisition using standard Ag-Agcl electrodes with a reconfigurable real-time embedded processor with a virtual instrumentation platform was done. The study showed that single channel ECG from Lead Iand configured recordings could be interpreted with vital values displayed directly.The system consisted of real-time Xlinix processor and Labview platform.

An IoT cloud based real-time heart rate monitoring system was reported[39]. A reconfigurable embedded processor with wireless capability and virtual instrumentation Labview platform was used and IBM Watson IoT platform was used to process the data in cloud. The pilot study showed the possibility of configuring multi parameter monitoring system for telemedicine and smart rural healthcare services .

An IoT based Wi-Fi connected sensor for ECG recordings and monitoring of vital parameters was reported recently[40]. A low powered micro controller was used with TI CC 3100 Wi-Fi booster package to establish wireless communication from IoT module to Cloud platform.

A wearable ECG monitoring system for resource constrained settings was proposed[41]. The study showed the usage of limb electrodes for recordings of ECG signals with NI Myrio processor. The preliminary reported results showed that the study needed to be validated with large datasets. Further no attempt was made to test the efficiency of the textile material used for recording the ECG signals.

A pilot study with Indian population was proposed by[42] towards the assessment of ECG signals. A smart textile electrode belt was proposed and the experimental study was carried out with 147 healthy volunteers. The variation with heart rate was studied and the pilot study revealed that the proposed textile based ECG electrodes yielded comparable fidelity measures same as that of the standard Ag-Ag Cl gel based ECG electrodes.

A specific study on woven conductive dry textile electrodes was reported for continuous ECG signal recordings[43]. Two woven conductive textile materials were used and wearable electronics assembly was configured to record the ECG signals. Lead I configuration was adopted and the performance of the recorded signal was evaluated qualitatively by visual inspection by the clinician and quantitatively by fidelity measures.

A specific study has been proposed for animal ECG recordings using a wearable approach[49] where needle based electrodes were used to acquire the signal. With the advent of AI processor, a wearable ECG classification was reported[50] where the authors have shown the efficiency of the efficient cardiac classification using the recordings obtained through wearable ECG system. In order to analyze the long-term ECG recordings from the wearable patch recorders[51], a specific signal processing framework was proposed which shows the effective usage of patch recorders for signal recording and qualitative assessments

Standard disposable electrode

Attempts have been made in the past to design biomedical electrodes based on its conductivity requirement. From materials conductive perspective, electrodes are referred as capacitive and resistive[44]. According to[44,45] from functional point of view, it can be categorized into recording and defibrillation electrodes. Further classification are also available including wet and dry[45], flexible and rigid. The most common gold standard electrodes used in clinical recordings is the resistive electrode, Ag/Agcl. The wet gel electrolyte is essential for such electrodes to improve the skin conductivity. For brevity and understanding metal plate disposable ECG electrodes is shown in Fig.1.

The Ag/AgCl electrode is reliable even in extreme situations due to hypoallergenic adhesive and quick-recovery gel. It has a defibrillation-

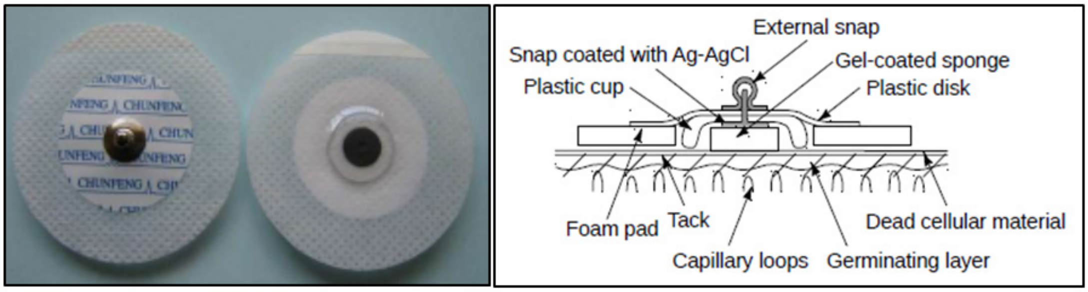


Fig. 1. Metal-plate ECG electrodes: top view (left), bottom and cross-section view[4,45]

Table 1. Properties and characteristics of the Textile material

Type of material	Composition	Electrode Surface Area A (mm^2)	Electrode Resistance (Ω)	Thicknessd (mm)	Skin-Electrode Impedance(Ω)	Physical Characteristic
Knit Jersey	63% cotton, 35% silver yarn 2% spandex	1000 mm^2	46Ω/foot (across rows) 460Ω/foot (across column)	1mm	2.2MΩ	absorbent, breathable, elasticity

resistant Ag/AgCl sensor which is subjected to a strict quality control during production.

MATERIALS AND METHODS

Design of textile electrode

The selection of the textile materials plays an important role towards the design of dry sensors. The material should have the capability of bending, stretching, twisting, rubbing etc., Further the preferred material for the electrodes should possess characteristics, such as, low AC impedance, non-polarizable , electrochemical stable, and mechanical robustness, etc. For better clarity, Table A1 as reported in Annexure A shows the commonly used electrode materials and its associated properties. For the current research, we have chosen the knot jersey as the conductive material which has the composition of spandex, cotton and silver yarn. Table 1 shows its characteristics.

The proposed textile electrodes comprise of two numbers of 50 mm x20 mm rectangle pieces that were stitched in such a manner that high impedance with better conductivity is assured in the inside portion. A medical grade snap button was stitched at the center portion of the textile electrode by ensuring that the button doesn't touches the skin. Then finally the wrist band was developed using the textile material stitched using a conductive thread and attached with a Velcro. Figure 2 shows the snap shot of the proposed textile material as a wrist band for this research study.

The electrode coupling model contains textile electrode on top of body and skin as shown in Figure 3a .The three element model of skin impedance, which represents capacitance and resistance is shown in Figure 3b. The skin

Fig. 2. Proposed Textile Material

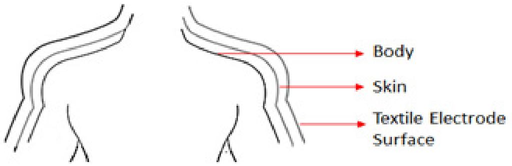


Fig. 3a. Electrode coupling model

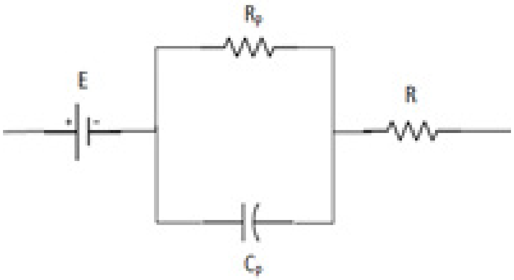


Fig. 3b. Three element model of skin impedance

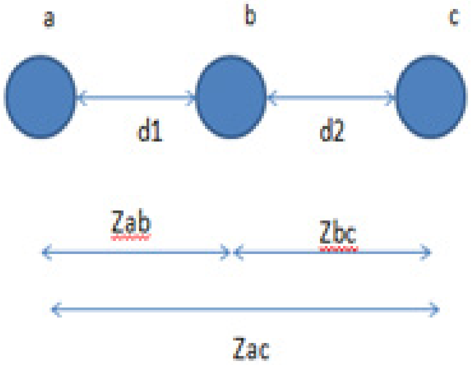


Fig. 4a. Skin-Textile Electrode Model

Fig. 4b. Impedance Measurement of Textile electrode

impedance is a combination of resistance and capacitance arranged parallel or serial. The three-element model is used to describe skin impedance at different frequencies. At high frequency, the impedance of the capacitance 1/(ùCd)is less than *Rd* , hence *Rd* is shortcircuit and the impedance is constant at *R* . At low frequency, the capacitance 1/(*ùCd)*is greater than *Rd* , and the impedance is constant at *R* + *Rd* .

Three wrist bands of same size were stitched and attached to right arm, right wrist and left arm The impedance of this material was determined first before performing the measurement of bio signal. The impedance was measured using an LCR meter, which had an isolation amplifier. The textile electrode was connected at the center and the standard Ag/AgCl electrodes were connected on both sides at about 5 cm away. The arrangement of textile electrode and disposable electrodes are shown in Figure 4a. The two reference Ag/AgCl electrodes were kept at 'a' and 'c'. The textile electrode was at the location 'b'. The skin - electrode contact impedance can be determined as per the model shown below. Let

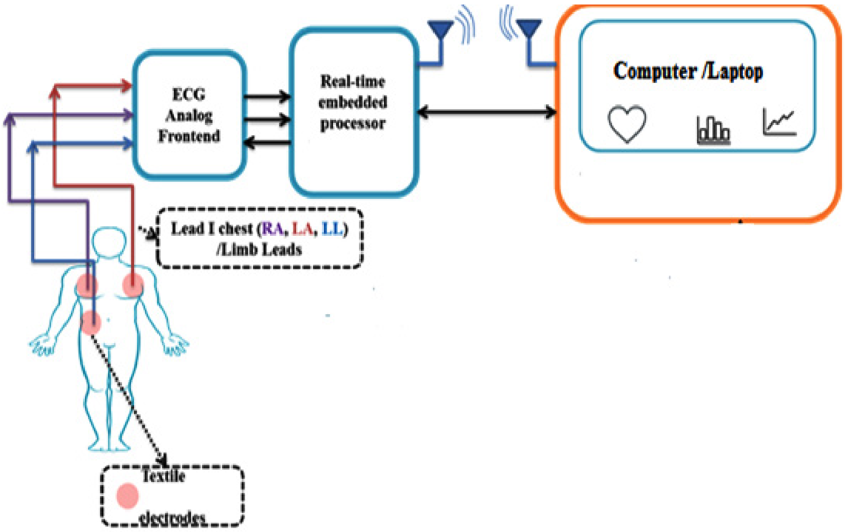


Fig. 5. Experiment Setup-CARDIF using Textile Electrode

Fig. 6. Experiment Setup with Textile Electrodes

Z_{ab} be the impedance between the center textile electrode and the Ag/AgCl electrode on one side and Z_{bc} be the similar impedance on the other side.

The unknown impedance Zx can be found out from the relation Zx = Zab-Zac/2, where Zac was the impedance between the two standard Ag/AgCl electrodes that were connected 10 cm away. The experiment set up for impedance measurement is shown in Figure 4b. The skin-electrode and contact impedance measurement were done for

Table 2. Baseline details of study group

No of Subjects		Age		Height in cm		Weight in Kg		BMI		Systolic/ Diastolic pressure	
Male	Female	Male	Female	Male	Female	Male	Female	Male	Female	Male	Female
122	148	26±6.3	29±4.8	161±4.4	154±2.3	65±7.2	58±4.3	26±1.3	25±1.4	124/83	121/81

different age groups. The age group of 18-24 was Group I, 25-40 was Group II and 45-60 was Group III. The impedance was measured for three different frequencies and they are listed in ANNEXURE B. Table B1 for Group I, Table for Group II and Table B3 for Group III.

The human skin conductivity when it gets dry, varies from 10^{-7} mhos for lower frequency and it will changes to 10^{-4} for higher frequencies. The conductivity of the human skin when it gets wet varies from 10^{-5} for lower frequency and it will go to10^{-4} for higher frequencies.

CARDIF Setup

In this proposed study, single ECG recording and analysis using CARDIF was implemented by textile electrodes with lead I configuration. An analog front end amplifier was configured with real time reconfigurable input output processor. The block diagram of the CARDIF setup is shown in Figure 5.

Study Design

In order to evaluate the proposed textile ECG electrode based CARDIF,a pilot study was conducted with healthy volunteers for a period of 20 months. An overall sample n=270(M=122,F=148)was considered. The volunteers were in the age group of 19-50 years and all of them belong to south India. Those who had symptoms of blood pressure and diabetics were excluded for this study. All procedure performed in the proposed work involving human participants were in accordance with the ethical standards of Ramaiah Medical College and hospital and also in accordance with the 1964 Helsinki declaration and its later amendments or comparable ethical standards. Subject consent form was obtained

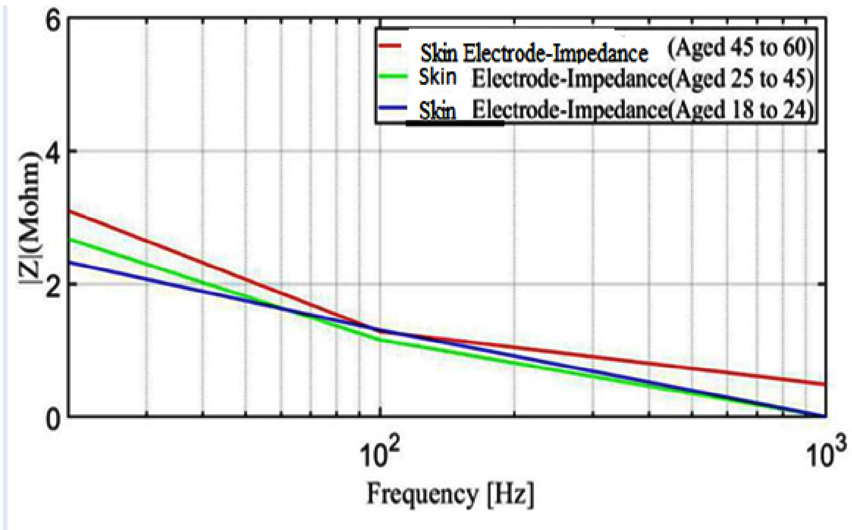


Fig. 7. Skin-electrode and Contact Impedance Characteristics

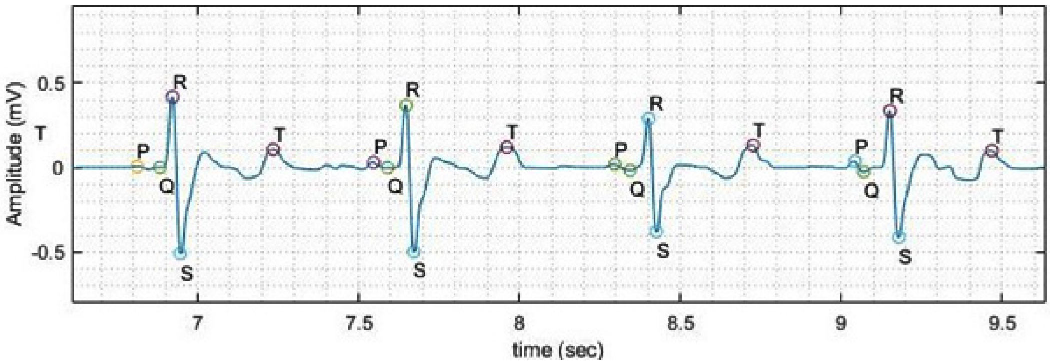


Fig. 8. ECG Output with Components

from every individual after briefing the importance of the proposed study. According to Einthoven lead configurations, single channel lead I was considered. Though precordial leads (v1,v2) was carried out for the study,due to non-cooperation from female participant, the proposed study reported only lead I configuration study.

As the main aim of the study is to test the

Table 3. Values of components of ECG from Standard American Heart Association clinical values, referenceAg/Agcland Textile Electrodes

Wave	Standard American Heart Association Clinical Values	Reference Electrode (Ag/AgCl)	Textile electrodes
P	<0.08s	0.05 s	0.06 s
QRS	0.08 to 0.10s	0.05 s	0.06 s
T	0.16s	0.15 s	0.14 s
PR	0.12s to 0.20s	0.10 s	0.11 s
QT	<0.44s	0.35 s	0.31 s
RR	1 s	0.84 s	0.88 s

Table 4. Results of Textile Electrodes and Disposable Electrodes

Parameters	Textile Electrodes Mean ±SD	Disposable Ag/AgCl Electrodes Mean ±SD
Heart rate(BPM)	83.44±3. 70	98.15±4.758
RR in sec	0.6857±0.115	0.6159±0.289
RMS in mv	0.9913±0.031	0.9935±0.106
MAX in mv	3.27±0.08	3.1±0.07
MIN in mv	1.20±0.06	1.1±0.08
Vpp in mv	3.18±0.821	3.02±0.60
AVGPSD	-5.05±0.271	-4. 5±0.74
SNR in dB	9.2±0.73	10.4±0.26
Range	0.58s	0.41s
Variance	0.013s	0.010s

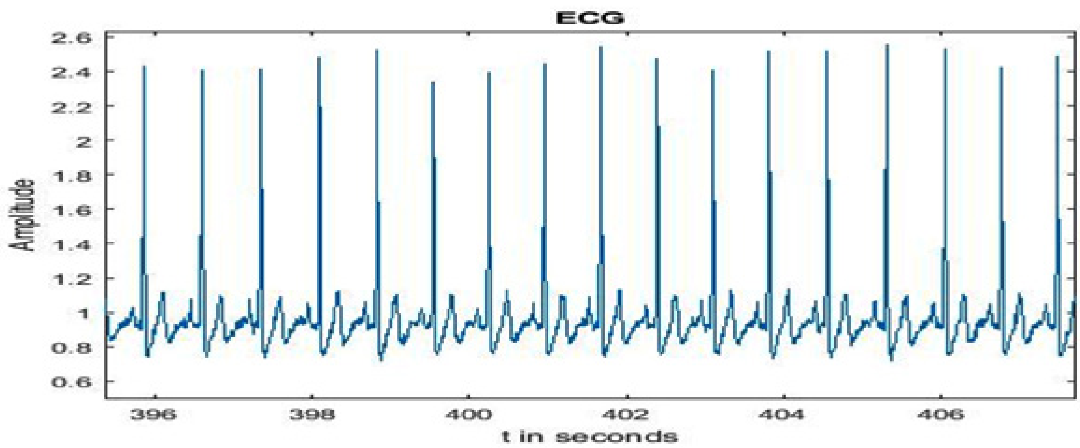


Fig. 9. ECG Output from Textile electrode

efficiencies of the suggested textile ECG electrodes, wo trials each with 180 minutes was considered. A gap of three weeks was given between the two trials. During the subjects recordings, there were no significant changes found between the trial 1 and trial 2 recordings. All the recordings were conducted in a sound proof room with subject kept in supine position. Figure 6 shows the experiment setup of the textile system using CARDIF.

Evaluation metrics

The performance of the proposed textile electrodes based CARDIF is evaluated in terms of fidelity parameters, visual inspection by clinicians, characteristics of ECG and statistical significance were also studied. The important parameters were calculated as follows,

RR interval is the duration in seconds between the adjacent R peaks in the ECG signal.

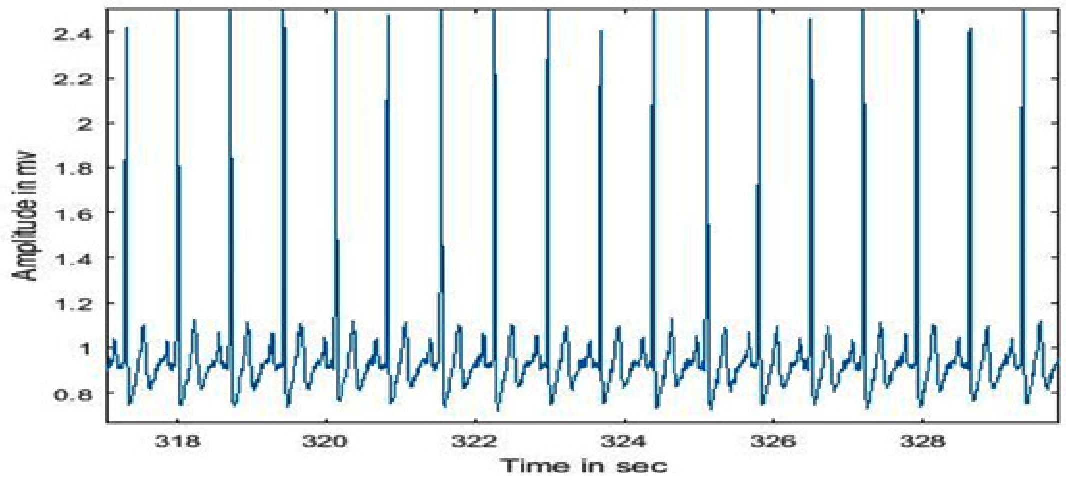


Fig. 10. ECG Output from disposable Ag/Agcl

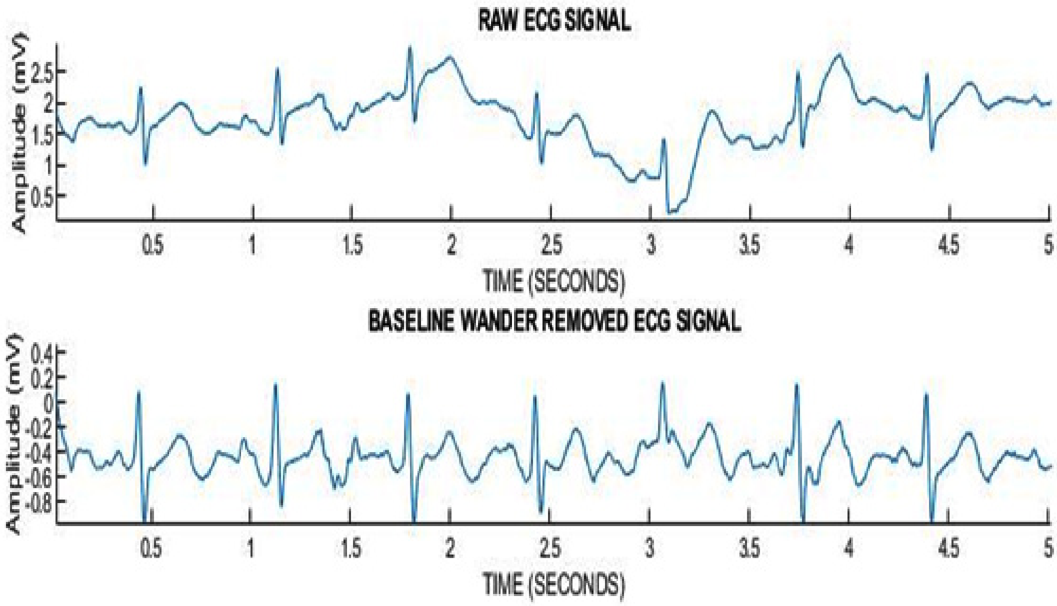


Fig. 11. Raw ECG and Output after Baseline Wandering Removal

It is the time interval between R_i and R_{i+1} wave of the ECG signal. Heart rate is the speed of the heartbeat measured by the number of contractions of the heart per minute. It is the ratio of the number of R peaks occurring in a minute. The duration of the RR interval is measured and Heart Rate is calculated using (1)

$$HR_{bpm} = 60/\text{Duration of the RR interval in sec} \quad ...(1)$$

For the QRS wave, the average value and the CV was also calculated. The coefficient of variation (CV) is a statistical measure of the dispersion of data points in a data series around the mean.

The QRS amplitude was defined as the difference between the value at the R peak and the minimum value in the Q and S peaks. The SNR and CV were derived with Equations (2) and (3), respectively[46].

$$SNR = 10 \log_{10} ((\text{Power of Signal})/(\text{Power of Noise})) \quad ...(2)$$

$$CV = ((\text{Standard deviation of QRS- Complex amplitude})/(\text{Average value of QRS-Complex amplitude})) \times 100 \quad ...(3)$$

$$Cross-correlation(R_{xy}(m)) = \sum_{n=0}^{N-m-1} x(n+m)y^{*}(n), m \geq 0 \quad ...(4)$$

$$Correlation\ Coefficient\ (\rho) = \frac{1}{N-1}\sum_{i=1}^{N}\left(\frac{A_i-\mu_A}{\sigma_A}\right)\left(\frac{B_i-\mu_B}{\sigma_B}\right) \quad ...(5)$$

where A and A are the mean and standard deviation of A, respectively, and B and B are the mean and standard deviation of B. N is the length of the sequence.

The baseline details of the study group were given in the Table 2 which includes gender, age, height, weight, BMI and Systolic/Diastolic pressure.

Performance evaluation

Skin-Impedance Characteristics

The skin electrode contact impedance was found out for three different age group for various frequencies. In each group twenty people were considered and it was measured using LCR meter. Lower age group had less impedance compared with the upper age group for all the frequencies. As the frequency increases, the skin electrode contact impedance decreases. All the contact impedance was less than 5 M&!, which is essential for the textile material to be used as an electrode. In addition, the skin electrode and contact impedance increased with age. Lower age group I had less impedance compared with the upper age group III for all the frequencies. So, the textile material could be used as an electrode on par with disposable electrode.Figure 7shows the variation of the impedance with respect to the frequency.

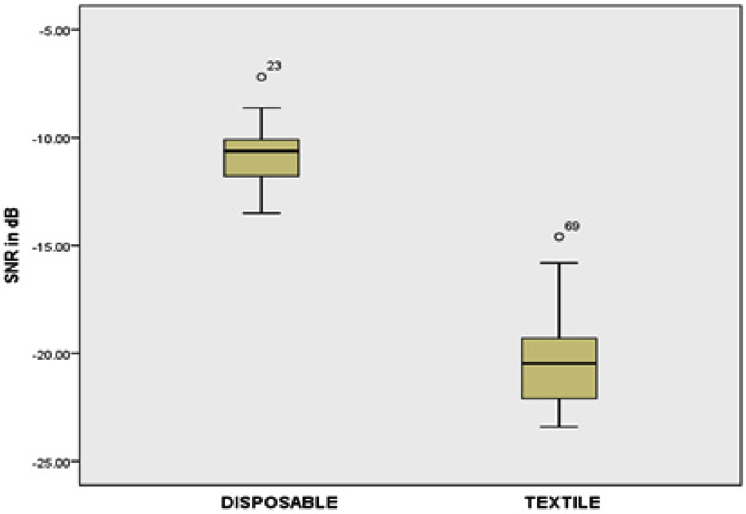


Fig. 12. SNR Box Plot of Disposable and Textile Electrode

It can be inferred from Fig.7 that the increase in frequency results in the decremental impedance which is very much essential for the skin conductivity. Further usage of dry ECG sensor ensure better skin conductivity which can be very used for long term wearable recordings. With different age group, the skin electrode impedance ensures better conductivity thus making the proposed dry ECG sensor as better candidate for ECG recordings

ECG Characteristics

A sample waveform obtained from the textile electrodes is shown in Figure 8 with differentECG components.

It can be inferred from the waveform shown in Figure 8 that the presence of all ECG fidelity confirms the typical ECG signal requirements for analysis and ensures the suitability of proposed dry ECG sensor for data recordings.

The values of the different components of ECG signal such as P wave, QRS complex, T wave and PR interval from reference and textile electrodes were shown in Table 3. The values obtained from the textile electrodes were found to be close to the values obtained from the reference electrodes as well as with the Standard American Heart Association clinical values.

It can be inferred from Table3 that the proposed designed ECG sensor/electrodes found to yield the necessary fidelity duration to confirm the normal functionality of the heart.

Fidelity Measures

The ECG Output from disposable Ag/AgCl electrode and the output obtained from Textile electrodes are shown in Figures 9 and 10 respectively.

The selected ECG parameters were obtained for all the subjects using textile electrode. The average and standard deviation of these parameters are shown in Table 4 along with the results obtained from disposable Ag/AgCl electrode.

It can be seen from Table 4 that the fidelity measure obtained using the wet and dry sensors were lying with in the range acceptable by the cardiology community. Further signal to noise ratio seems to be better for the dry sensors using the textile electrodes and makes it usable for long term monitoring applications. In the case of wet disposable electrodes, due to application of gel skin irritation as well as loss of conductivity occurs if used for longer duration

The raw ECG data was processed by low pass with F_l= 40Hz and high pass with F_h=0.5Hz. The base line wandering removal was done and R peak was extracted using Pan Tompkins algorithm. The raw ECG and output after baseline wandering removal is shown in Figure 12.

The result shows that the values obtained from textile electrodes are comparable with that taken from standard disposable electrode.Using Box plot, SNR and HR were determined.The SNR

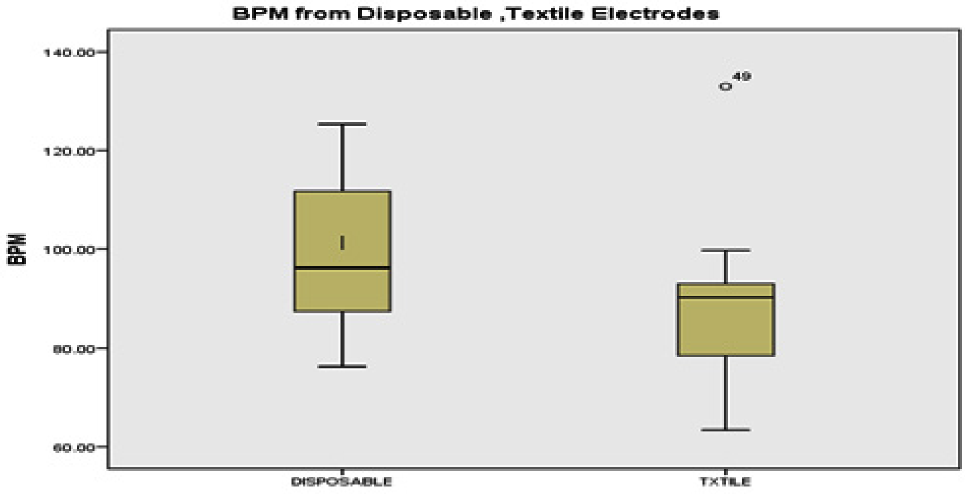


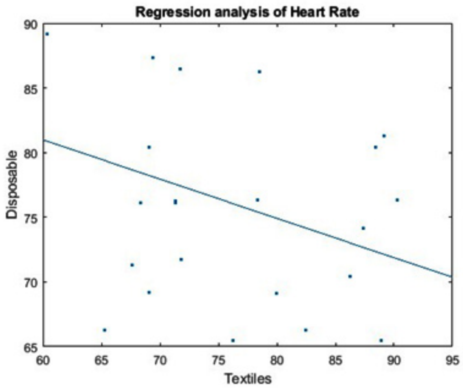
Fig. 13. Heart rate (BPM) Box Plot of Disposable and Textile Electrode

box plot was obtained with disposable and textile electrodes is shown in Figure 12 .

The results show that there is a considerable improvement in the signal to noise ratio of the textile electrodes compared with the disposable electrodes. The Box plot for Heart rate (BPM)is shown in Figure 13.

The heart rate (BPM)obtained from both the methods were almost same range within the limits of ideal values. So the textile electrodes were comparable with disposable electrodes. Figure 14 illustrates the Bland–Altman analysis of differences in HR between textile electrode signal and disposable electrode signal. The average of the differences is 0.76 units. The mean difference is not zero, which infers the textile electrode measures 0.76 beats/min more than that of the disposable electrode. It demonstrated insignificant bias because almost all differences remained in the 95% confidence interval (23 [–22 – 24] beats/min).

From Figure 14, it can be observed that the Confidence Interval (CI) of mean difference and limits of agreement describes less possible error estimates. It indicates that the difference between HR measured by textile electrodes and disposable electrodes is less significant. The coefficient of correlation between HR derived by the textile electrode signal and disposable electrode signal was significant ($p < 0.0001$). Figure 15 illustrates the Bland–Altman analysis of differences in RR between textile electrode signal and disposable electrode signal. The average of the differences is zero units. The mean difference is zero, which infers the textile electrode measures the same RR as that of the disposable electrode. It demonstrated insignificant bias because almost all differences



(Slope =-0.4288 ± 0.2078,Y-intercept = 108.1 ± 16.0,X-intercept = 252.0)

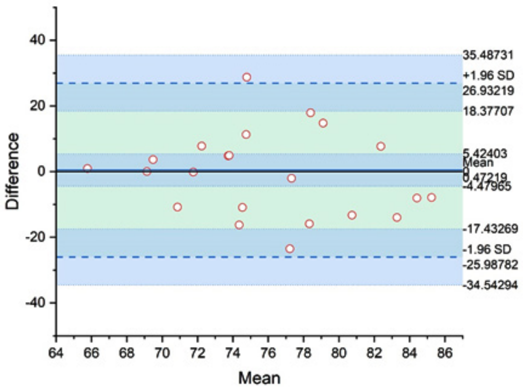
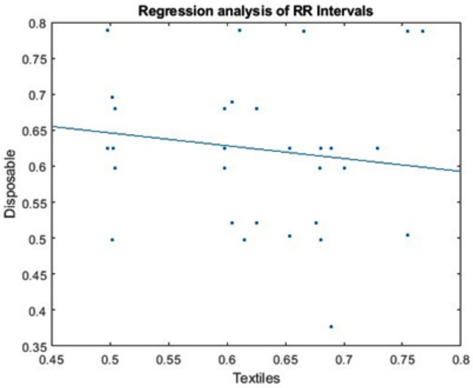


Fig. 14. (a)Regression Analysis and (b)Bland Altman Plot of HRV(BPM) interval from Disposable and Textile Electrode



(Slope = -0.1107 ± 0.1448,Y-intercept = 0.6905 ± 0.09177,X-intercept=6.237)

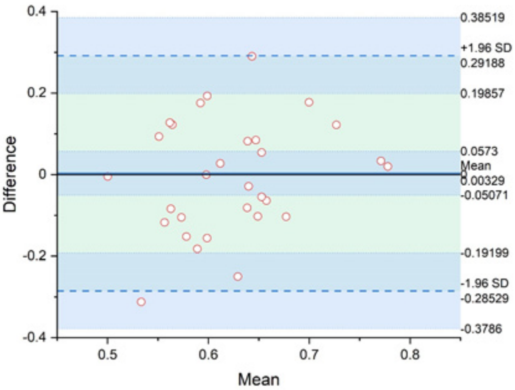


Fig. 15. (a) Regression Analysis and (b) Bland Altman Plot of RR interval from Disposable and Textile Electrode

remained in the 95% confidence interval (0.32 [–0.32 – 0.31] sec). It shows clearly that the parameters HR and RR interval obtained using textile electrodes were similar to the disposable electrodes.

DISCUSSION

Attempts have been made in the past towards developing textile electrodes for continuous ECG recordings[16,31,47,48]. The PEDOT:PSS based dry ECG electrodes were developed by making use of stringent procedure as reported by[47]. Ten healthy volunteers were involved for this study and fidelity measures confirms the suitability of PEDOT electrodes for continuous recording of ECG signals. It can be observed from the reported research study that the fabrics of the dry electrodes were doped with chemical solution for achieving better conductivity. The process found to be amber some and huge cost factor found to be involved.

Table 5. Specification of the proposed CARDIF

Parameter	Specification
Max current consumption	4 mA
Battery life cycle	5 hours
ADC Sampling Rate	Aggregate sample rate 500 Hz
Max communication range	Wireless
Weight	193 g(6.8 oz)
Dimension(LxBxH)of CARDIF	9cm x 6cm x 2cm
ECG signal resolution	12 bits
Non volatile memory	512MB

Table 6. Average QRS amplitude and coefficient of variance

Sub No	Gender	Disposable		Textile	
		Average QRS Amplitude (mV)	CV of QRS Amplitude	Average QRS Amplitude (mV)	CV of QRS Amplitude
Sub1	Male	2.0385 ±0.1682	0.0825	0.4532±0.0921	0.2033
Sub2	Male	1.3419 ± 0.0824	0.0614	0.1877±0.1877	0.0895
Sub3	Female	2.4194±0.1491	0.0616	0.4655±0.0631	0.1355
Sub4	Female	2.3992±.2786	0.1161	0.4380±0.0314	0.0716

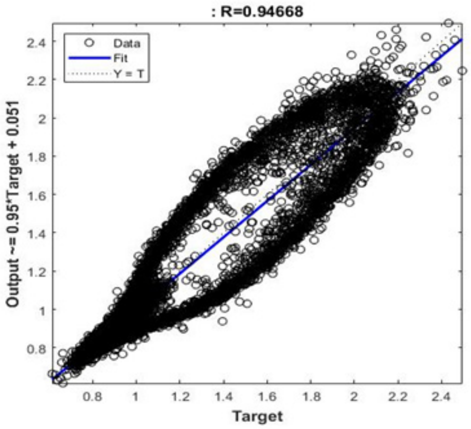


Fig. 16. Correlation between Ag/AgCl disposable wet and proposed Textile electrode signals

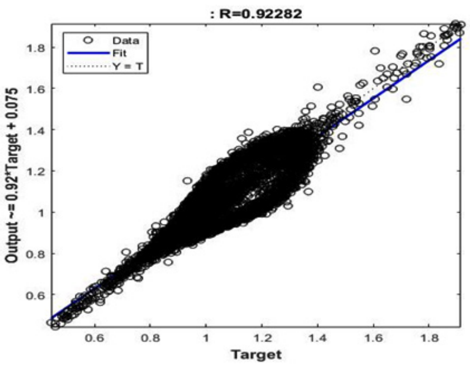


Fig. 17. Correlation between CARDIF (Textile electrode) and Active cardio (Ag/AgCl electrode)

A similar attempt has been made by[31] where silver coated nylon thread embroidered on polyster was used as conductive textile electrodes. The electronic circuity assembly information was not reported and ten volunteers were involved for the study. Though[9] suggested a hybrid textile electrode for ambulatory ECG measurement, the integration of circuit board and conductive fabric were found to be complex in nature. The number of test sample considered for the study was not reported. The quality of the resultant ECG signals suffers severely due to baseline drift and high frequency noises. A textile based inductive sensor for measurement of heart rate and respiration was proposed[18]. Lead II configuration was adopted and electromagnetic characterization of the proposed sensor was studied. The complexity of the proposed sensor in term of cost involved towards design, reusability was not reported.

The proposed textile electrode was evaluated for comfort and longevity. Unlike the traditional Ag/AgCl electrodes where factors such as gel dryness contributes significantly, the proposed electrode was evaluated for 8 hours with selective group (n=31) and the resultant ECG recordings were assessed qualitatively by a clinician. The fidelity measures confirm the suitability of the recordings for clinical diagnosis. A smart wearable garment is under development by considering the Lead I and Lead III configuration. Due to non-cooperation of female volunteers, the proposed study doesn't include the chest-based textile electrode recordings and the corresponding fidelity measurements.

With the proposed framework, all significant components of ECG, QRS complex, P wave, T wave, RR interval were able to be detected by the automated algorithm. The proposed framework suits well for low cost and resource-constrained settings for screening of cardiac episodes, early detection of arrhythmias etc. The textile electrode was washed 10 times and study was conducted to check the quality of the resultant ECG recordings. Through clinician's inspection, it was informed that the conductivity of the proposed textile sensors embedded in smart wearable garment could be explored for home-centric wearable monitoring applications. The overall specification of the proposed CARDIF is shown in Table 5.

The average QRS amplitude of the textile electrode and the disposable electrode was found out for two male and two female subjects.The coefficient of variance was also found out for each case.Table6 shows the results obtained from both variant electrodes. It can be noticed that the results were found to be comparable with the earlier reported work[46].

The quality of the ECG signals obtained using CARDIF with wet electrodes (Ag/Agcl disposal) and dry electrodes (proposed textile electrodes) were correlated and the resultant regression analysis is shown in Fig.16

The analysis result showed that the ECG signal from the textile-based electrodes were highly associated with the signals obtained through the Ag/AgCl gel based wet electrodes (R=0.94668). The value of R will vary from +1 to -1.The obtained R value which is positive with close to 1, shows that there exists a strong correlation between both the methods.

The ECG signals obtained from the CARDIF using textile electrodes were compared with the research grade Active Cardio ECG system using gel based Ag/AgCl disposable electrodes. It can be seen from Fig,17 that the proposed CARDIF is very well correlated with the research grade active cardio system with correlation coefficient of R= 0.92282,.

CONCLUSION

A cardiac signal recording framework (CARDIF) has been proposed by making use of dry textile knit jersey based conductive electrodes in this proposed study. The acquired electro cardiogram (ECG) signals were quantitively assessed in terms of impedance characteristics, fidelity measures and were compared with that of standard wet Ag-Agcl electrodes. The qualitative assessment by the clinician along with the fidelity result confirms the suitability of the proposed framework for continuous and long-term monitoring application. Further the physiological variation in terms of R-R interval, heart rate variability assessed during the experimental period (20 months) confirms the suitability of CARDIF for resource constrained settings due to its low cost design. Currently flexible electronics driven miniaturization work is undergoing to develop a compact module suitable for long term cardiac monitoring. As a future study, application of nanomaterial based sensor design will be carried out to enhance the efficacy of the proposed system.

Credit Author Statement

Sriraam and Uma Arun designed the proposed CARDIF system and performed the quantitative assessment and Prakash did the clinical validation of the proposed system. Sriraam prepared the conceptualization of the manuscripts and all authors have endorsed the content.

Conflict of Interest

There is no conflict of interest involved in this study.

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