Comparison of PS25015A Dry Electrodes and Two Different Ag/AgCl Wet Electrodes for ECG Applications

Nika Zolfaghari, Mohsen Shafeie, Shahini Sirikantharajah, and Kristiina M. Valter McConville
Electrical and Computer Engineering
Ryerson University
Toronto, Canada
kmcconvi@ee.ryerson.ca

Abstract— **The electrocardiogram (ECG) is one of the most important signals acquired from the body, as it serves as the immediate source of information relating to heart performance. Hence, a lot of research has gone into various types of ECG acquisition methods and systems. With the numerous methods and systems available at hand, it is important to compare, contrast, and evaluate the existing techniques. Not only does this help distinguish between the different techniques, it also helps build on the existing methods to create successful acquisition systems that can surpass the effect of unwanted factors, such as movement and other noise artifacts. This paper compares two different ECG acquisition systems, one of which uses PS25015A dry electrodes and the other, which uses two different silver/silver chloride (Ag/AgCl) wet electrodes. ECG signals were acquired from three healthy individuals, in the sitting position, using both systems simultaneously. Signals were first filtered to diminish noise then the R-wave peaks were detected. The voltage values of these peaks were compared between the devices and electrodes via statistical analysis. The signal-to-noise ratio (SNR) values of the signals were obtained as well and finally, the correlation coefficient of the signals were obtained. Overall, the dry electrodes may have a better SNR. However, the dry electrodes provided a lower wave amplitude, compared to the wet electrodes.**

Keywords-Electrocardiogram (ECG), wet electrode, dry electrode, cross correlation, peak detection

I. INTRODUCTION

The electrocardiogram (ECG) has arguably become one of the most recognized and used biomedical signals. ECG is the electrical interpretation of the activity of the heart, and can easily be recorded with the use of surface electrodes either on the chest or limbs [1]. As the heart is one of the most important organs in the body, its contraction activity and performance is vital to monitoring health. The most important attribute of the ECG is that its shape is altered by abnormalities and cardiovascular diseases, such as arrhythmia, myocardial ischemia, premature ventricular contraction (PVC), infarction, and many more [1].

In terms of its signal acquisition, there are various methods of electrode placement. ECG is traditionally recorded using 12-channels for clinical use. In this 12 lead configuration, electrodes are placed on the right leg, and both wrists. The three augmented leads are (aVR, aVL, aVF) and six leads are placed on the chest [1]. Additionally, the left and right arm, and the left leg are used for leads I, II, and III, which together form Wilson’s central terminal (reference for chest leads) [1]. However, ECG can also be recorded using 6, 5, or 3 leads [1]. Recently, the advancement in technology has made it possible to record ECG from only 1 lead, either on the chest or on a limb. Furthermore, various reputable sources, such as the American Heart Association (AHA), recommend that a minimum sampling rate of 500 Hz be used for ECG data acquisition, but that a sampling rate twice that of the theoretical minimum would be ideal, i.e., 1000 Hz [1][2][3].

ECG is traditionally used in clinical settings, such as in the operating room, to monitor the heart rate of the patient, or to analyze a patient for various cardiovascular diseases or abnormalities. However, as technology progresses and as we become more and more aware of our health and the proper functioning of our body, this important biomedical signal is being slowly introduced in our daily life as a way of continuously monitoring one of our most important organs. New electronics and hardware, with their high efficiency and small size, have created an opportunity for the design of wearable and wireless ECG recording devices and real-time monitoring systems.

Like other biomedical signals, raw ECG signals contain various sources of interference. These noise interferences are comprised of high and low frequencies from the power line, muscle movement, breathing, and other near-by electromagnetic sources and/or cables [4]. Since in many cases real-time monitoring of ECG is important, the ECG needs to be filtered and processed in such a way that there is nearly no delay between the acquisition and representation of the signal. Different processing techniques and algorithms have been suggested by researchers and used by manufacturers, however, when we look into implementing such processing techniques in a wearable wireless ECG device, extra caution needs to be employed with the algorithm design due to processing times and data transfer speeds.

Another way in which ECG data acquisition differs is in the choice of electrode. The two most common categories of surface electrodes are wet and dry electrodes. Wet electrodes, specifically Ag/AgCl, are among the most commonly used electrodes for bioelectric applications. They certainly have their advantages, such as their simplicity, ease of use, low weight, and that they are disposable [5]. However, they are not without their disadvantages. Electrolytic gel should be applied between the skin and the electrode in order to improve conductivity. This gel could cause allergic reactions or skin irritation [5]. These electrodes also have a limited shelf life due to dehydration, which affects impedance, generating noise [6]. The dehydration issues make these electrodes unsuitable for long-term continuous measurement [7]. Finally, the spacing between electrodes may be so small that the gel may smear and lead to short circuiting [8]. On the contrary, dry electrodes, generally metal plates, do not encounter any of these problems, and are easier to set up, however, they have their own drawbacks as well. Since there is no secure adhesion between the electrode and the skin, they can shift during motion [6]. Furthermore, these electrodes have relatively large contact impedance with the skin [6][9].

For the purpose of this pilot study, two wet Ag/AgCl electrodes (3MTM Red DotTM Monitoring Electrodes, and Bio-Protech Telectrodes) and a PS25015A dry electrode will be used to simultaneously record ECG signals from the chest using one lead for 60 seconds while the subjects are seated. The resulting signals will then be analyzed and compared in order to draw conclusions based on their performance.

This paper will proceed by looking at previous studies which have been done in relation to the comparison of dry and wet electrodes, in section II. Section III will move on to outlining the proposed procedure. The results will be presented in section IV, and finally section V will wrap up with the concluding remarks.

II. PREVIOUS STUDIES

A paper by Chi M.Y., et al. [10] compared dry electrodes by analyzing the data acquired, as well as their performance limits. As mentioned in this paper, the circuit designs of electrodes seem to be described well in literature; however a detailed comparison between electrodes are yet to be found. A standard testing procedure that compares noise and errors between the electrodes does not exist.

Furthermore, Gandhi N., et al. [11] compared Ag/AgCl wet electrodes to dry and non-contact electrodes. The comparisons were made by analyzing noise processes, as well as the physiological measurements. The non-contact electrodes had a higher resistance compared to the conductive electrodes. ECG data acquired from various materials were all compared to data acquired Ag/AgCl electrodes. Simple comparisons were made between the graphs, by analyzed different amplitudes, noise artifacts and frequency drifts. Results showed that the best dry electrodes that can potentially replace wet electrode are ones with a PCB finish. Many dry non-contact electrodes were found to have low frequency noise, which restricts their use for clinical purposes.

Additionally, another study performed by Chi M. Y. et al. [12] compared wet and dry electrodes for EEG purposes. The electrodes were compared using EEG data acquired from 10 subjects as they gazed at a target simulus, and amplitude sizes and steady state visual evoked potential (SSVEP) were used to compare the signals. The signals were compared using PSD values, signal-to-noise ratios, and cross correlation. The correlation between the wet and dry electrodes was nearly perfect. However, the correlation between the wet and non-contact were lower. However, a lot of the comparisons made between electrodes seem to be based on just the graphs or a few parameters, such as amplitude, SNR, and correlation. Table I compares the existing techniques used to compare electrodes, and shows how this paper further builds on these techniques to compare wet and dry electrodes.

TABLE I. Comparison of Existing Techniques

Comparison of Existing Techniques	
Chi M.Y., et al.	✓ Circuit designs ✓ Performance limits
Gandhi N., et al.	✓ Amplitudes ✓ Noise artifacts ✓ Frequency drifts
Chi M. Y. et al.	✓ Amplitudes ✓ SNR
Currently Presented Method	In-depth Statistical Analysis: ✓ Amplitudes ✓ Noise artifacts ✓ SNR ✓ Cross correlation ✓ DC off-set ✓ Mean ✓ Variance ✓ Std deviation ✓ Std error

Moreover, the previous studies have been limited in the parameters used for comparison. This paper proposes an in-depth statistical analysis method with numerous parameters to compare wet and dry electrode systems.

III. METHODS

A. Subjects

This comparison method was tested on data acquired from the first three authors of this paper, which included one 32 year old male, and two females, 23 and 22 years old. The subjects were healthy and had no history of heart conditions.

B. Experimental Setup

Testing was performed on two ECG acquisition systems. The systems as well as different electrode types were compared by acquiring ECG signals from the chest at 1000 Hz. The Plessey ECG system was used to acquire dry electrode data, while the wet electrode system used was the CleveMed BioCapture. The skin was cleaned with alcohol wipes before positioning the wet electrodes.

The dry and wet electrodes can be seen in Figure 1 and 2 respectively. As prescribed in the user manuals of the systems, the PS25015A dry electrodes, 3M Red Dot Ag/AgCl electrodes, and the Bio-Protech Ag/AgCl Telectrodes were placed near the subclavius muscles (3cm beneath the left and right clavicles), as seen in Figure 3 [13].

 ISBN: 978-1-61208-375-9

Figure 1: PS25015A Dry Electrodes

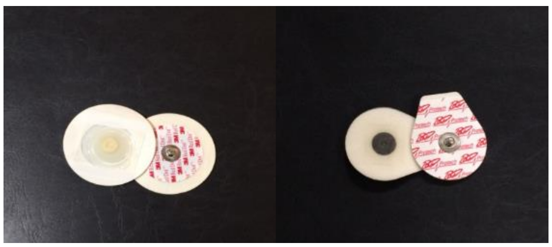

Figure 2: Wet Ag/AgCl Electrodes: 3M™ Red Dot™ Monitoring Electrodes (left) and Bio-Protech Telectrodes (right)

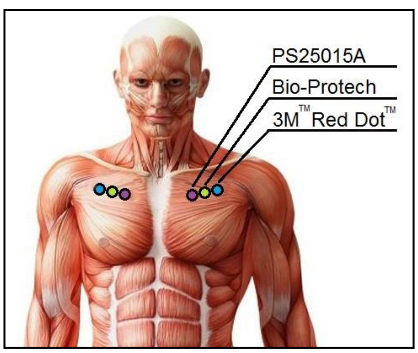

Figure 3: Electrode Placement on the Chest [adapted from 15]

Standard chest electrode positions can also be referred to in a paper authored by P.M. Rautaharju et al [14]. Both elbows were used as ground (not shown in Figure 3).

Once the electrodes were placed on the body, the dry electrodes were fed into the Plessey system, which was connected to a computer, and an offset of 0.1V was implemented. Snap leads were attached to each of the wet electrodes. The snap leads were fed into the input channels 1 and 2 and ground on the CleveMed Bioradio 150 system. The Bioradio was then connected to another computer via a wireless receiver. Moreover, data was acquired from both systems simultaneously; providing the same input to both systems, allowed for the quality and variations in the ECG signals to be analyzed.

The ECG was measured from each subject for 60 seconds, in the sitting position, and three trials were performed on each subject. The data files were converted into CSV files, in order to perform signal processing in MATLAB.

C. Signal Processing

The ECG signals acquired from both systems were sampled at 1000 Hz. Furthermore, the raw ECG data was filtered using low-pass, high-pass, and notch filters.

First, an 8th order low-pass Butterworth filter was used with a cutoff frequency of 180 Hz. The filter was designed based on (1) [1].

$$|H(\Omega)|^2 = \frac{1}{1+(\frac{\Omega}{\Omega_c})^{2N}} = \frac{1}{1+\varepsilon^2(\frac{\Omega}{\Omega_p})^{2N}} \quad (1)$$

Where N is the order of the filter, Ω_c is the corner frequency, Ω_p is the pass-band edge frequency, and $1/(1+\varepsilon^2)$ is the band edge value.

Next a stop-band filter was used for a notch filter at 55-65 Hz, followed by a high-pass FIR filter with a cutoff frequency of 0.002 Hz. In order to detect heart rate, the R waves were made prominent by squaring the entire ECG signal. Peak detection was performed using the thresholding technique, similar to the R-wave detection performed by H. Kew and D. Jeong [16]. A threshold value was used to detect the R-wave peak, as seen in a study by P. Verdecchia et al. [17].

Statistical analysis was performed on the R-wave peak values detected in order to compare the ECG signals obtained through the wet and dry electrode systems. The parameters computed include mean (2), standard deviation (3), variance (4), and standard error (5). The signals were also compared by computing the signal-to-noise ratios (SNR) and the cross-correlation. Cross-correlation (6) was performed on the outputs from each electrode to evaluate the similarity between the signals by obtaining the correlation coefficient [1][18][19].

$$\bar{x} = \frac{\sum x}{n} \quad (2)$$

Where $\bar{x}$ is the mean, n is the number of samples, and x are the data values.

$$\sigma = \sqrt{\frac{\sum_{i=1}^{n}(x_i-\bar{x})^2}{n-1}} \quad (3)$$

Where σ is the standard deviation x_i are the data values, and $\bar{x}$ is the mean of x_i.

$$\sigma^2 = \frac{\sum(x_i-\bar{x})^2}{n-1} \quad (4)$$

Where σ^2 is the variance.

$$SE = \frac{\sigma}{\sqrt{n}} \quad (5)$$

Where SE is the standard error.

$$r = \frac{\sum_i[(x(i)-mx)\times(y(i-d)-my)]}{\sqrt{\sum_i(x(i)-mx)^2}\sqrt{\sum_i(y(i)-my)^2}} \quad (6)$$

 ISBN: 978-1-61208-375-9

Where r is the correlation coefficient, $x(i)$ and $y(i)$ are the two signals, mx and my are their means respectively, and d is the delay.

IV. RESULTS

Figure 4 shows a sample plot illustrating the three ECG signals obtained from the three electrodes, PS25015A dry electrodes, Bio-Protech Ag/AgCl wet electrodes, and 3M Red Dot Ag/AgCl wet electrodes respectively. It is evident from Figure 4 that the dry electrode system shows a lower amplitude, compared to the wet electrode systems. Both of the wet electrode systems show amplitudes of approximately 1 mV.

Thresholding was used to perform R-wave detection in order to detect the heart rate, similar to the techniques used by H. Kew and D. Jeong [16]. The average instant heart rate can be seen in Figure 5.

Table II compares the processed data acquired from the three electrodes. As expected, the two wet electrodes showed higher correlation with each other than with the dry electrodes. The dry electrodes were found to have a negative DC-offset, compared to the wet electrodes, and provided the best SNR. Statistical analysis was performed on the R-wave peak values for each of the three electrodes, similar to analysis performed by G. Crifaci et al [20]. The 3M Red Dot electrodes showed higher mean R-wave peak voltages. For example, subject A had a mean R-wave peak of about 0.99 mV when measured through the 3M Red Dot electrodes and a mean of only 0.39 mV when measured through the dry electrodes.

When comparing the standard errors across the three electrodes for the different subjects, the results seem to vary. Subject A had an error of 0.0011 mV for the dry electrode, and errors of 0.003 mV and 0.0054 mV for the wet electrodes, giving a slight difference of 0.0043 mV between the dry and wet electrodes, with the dry electrode having the lowest error. On the other hand, Subject B had an error of 0.0045 mV for the dry electrode, and errors of 0.0019 mV and 0.0017 mV for the wet electrodes, resulting in a difference of 0.0028 mV, with the dry electrode having the highest error. Similarly, for Subject C, there was an error of 0.01 mV for the dry electrode, and errors of 0.0072 mV and 0.0055 mV for the wet electrodes, resulting in a difference of 0.0045 mV with the dry electrode once again having the highest standard error. In summary, there is no suggestion of consistent differences in the standard errors between electrodes.

It is important to note that there were a few factors which may have affected the results. Although the data was acquired simultaneously from the three electrodes, there was an inter-electrode distance of 3.0 cm. This may have affected the results, as the electrodes were each acquiring ECG data from slightly different positions on the chest. The skin was wiped with alcohol before the electrodes were positioned; however, there may not have been 100% electrode-to-skin contact.

TABLE II. Numerical Analysis

	PS25015A	**3M Red Dot**	**Bio-Protech**
DC-Offset (mV)	-0.2099	0.0205	0.0239
Corr Coef (%)	PS25015A & 3M Red Dot = 5.05		
	3M Red Dot & Bio-Protech = 87.6		
	PS25015A & Bio-Protech = 5.71		
SNR (db)	28.9	19.5	19.3
Subject A			
Mean (mV)	0.3897	0.9940	0.7050
Variance (mV)	0.0013	0.0094	0.0364
Std Dev (mV)	0.0355	0.0925	0.1669
Std Error (mV)	0.0011	0.0030	0.0054
Subject B			
Mean (mV)	0.172	0.7952	0.6320
Variance (mV)	0.0056	0.0066	0.0027
Std Dev (mV)	0.0697	0.0572	0.0510
Std Error (mV)	0.0045	0.0019	0.0017
Subject C			
Mean (mV)	0.0708	0.2490	0.4420
Variance (mV)	0.0010	0.0124	0.0295
Std Dev (mV)	0.0322	0.1110	0.1711
Std Error (mV)	0.0100	0.0072	0.0055

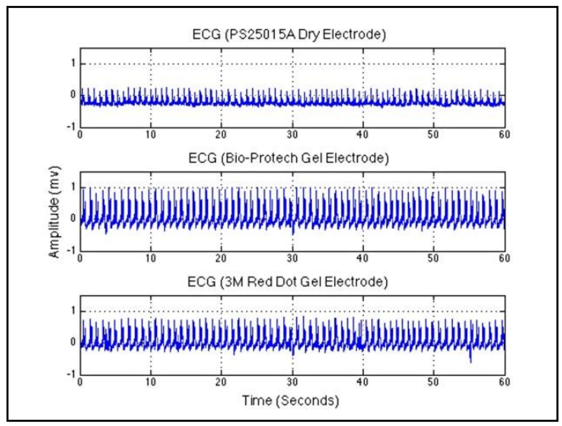

Figure 4: ECG signals acquired from the three electrodes

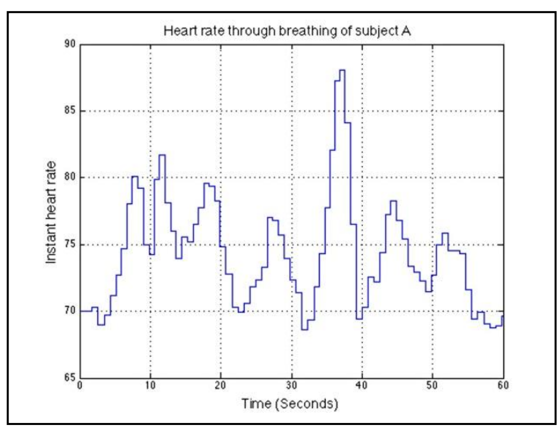

Figure 5: Heart Rate while Breathing

 ISBN: 978-1-61208-375-9

Furthermore, the dry electrodes were attached firmly onto the subject, but the pressure on the electrodes may not have been uniform for the entire duration of the experiment because of the elasticity of the fastening band. Moreover, two individuals were running the two systems on two different computers to start data acquisition. Hence, there may have been a slight delay in start/stop times during acquisition, but this was adjusted in the data analysis by aligning the R-waves.

For future work, the results may be more definitive if more subjects are used.

V. CONCLUSION

The results showed fairly high signal-to-noise ratios and varying mean and variance ranges for each electrode type. However, there were suggestions of differences between the electrodes, such as the SNR, where the dry electrodes seemed to have a better SNR in our subjects, compared to the wet electrodes even though they recorded at lower amplitude. Although both types of electrodes have their own advantages and disadvantages, the determination of the most advantageous option is dependent on the individual user's applications and needs. For example, if the user desires a higher SNR value, dry electrodes should be used. However, if a lower standard error is desired, then wet electrodes should be used. The advantage of this approach consists of clearly defined pros and cons for each system so that the user can make a more informed decision. For future work, these values can be compared to a wider range of dry and wet electrodes and ECG acquisition systems, and can be tested on a larger population for more accurate results. Most importantly, the methods discussed in this paper can be used as a platform for the comparison of electrodes in order to help evaluate different systems and their accuracies.

ACKNOWLEDGMENT

We would like to thank John David Chibuk, Kiwi Wearable Technologies for the Plessey system.

REFERENCES

[1] R.M. Rangayyan, "The electrocardiogram (ECG)," Biomedical Signal Analysis. IEEE Press, pp. 14-28, 2002.

[2] G.P. Pizzuti, S. Cifaldi, and G. Nolfe, "Digital Sampling Rate and ECG Analysis," Journal of Biomedical Engineering, vol. 7, Aug. 1985, pp. 247-250, doi: 0.1016/0141-5425(85)90027-5.

[3] P.R. Rijnbeek, J.A. Kors, and M. Witsenburg, "Minimum Bandwidth Requirements for Recording of Pediatric Electrocardiograms," Circulation: Journal of the American Heart Association, vol. 104, Dec. 2001, pp. 3087-3090, doi: 10.1161/hc5001.101063.

[4] A. Gacek and W. Pedrycz, "The Main Properties of ECG Signals," ECG Signal Processing, Classification, and Interpretation, 2012, pp. 25-26.

[5] Y. Wang et al., "Dry Electrode for the Measurement of Biopotential Signals," Science China, vol. 54, Nov. 2011, pp. 2435-2442, doi: 10.1007/s11432-011-4354-0.

[6] A. Gruetzmann, S. Hansen, and J. Muller, "Novel Dry Electrodes for ECG Monitoring," IOP Publishing, Oct. 2007, pp. 1375-1390, doi:10.1088/0967-3334/28/11/005.

[7] E. Nemati, J. Deen, and T. Mondal, "A Wireless Wearable ECG Sensor for Long-Term Applications," IEEE Communication Magazine, Jan. 2012, pp. 36-43, doi: 10.1109/MCOM.2012.6122530.

[8] A. Searle and L. Kirkup, "A Direct Comparison of Wet, Dry, and Insulating Bioelectric Recording Electrodes," Physiological Measurement, vol. 21, May 2000, pp. 271-283, doi: 0.1088/0967-3334/21/2/307.

[9] X. Pu et al., "A Wireless 8-Channel ECG Biopotential Acquisition System for Dry Electrodes," IEEE International Symposium on Radio-Frequency Integration Technology, Nov. 2012, pp. 140-142, doi: 10.1109/RFIT.2012.6401640.

[10] Y. M. Chi, T. Jung, and G. Cauwenberghs "Dry-Contact and Noncontact Biopotential Electrodes: Methodological Review," IEEE Reviews in Biomedical Engineering, vol. 3, Dec. 2010, pp. 106-119, doi: 10.1109/RBME.2010.2084078.

[11] N. Gandhi, C. Khe, D. Chung, Y. M. Chi, and G. Cauwenberghs, "Properties of Dry and Non-contact Electrodes for Wearble Physiological Sensor," International Conference on Body Sensor Netowrks, May 2011, pp. 107, doi: 10.1109/BSN.2011.39 -112.

[12] Y. M. Chi, Y. Wang, C. Maier, T. Jung, and G. Cauwenberghs, "Dry and Noncontact EEG Sensors for Mobile Brain-Computer Interfaces," IEEE Transactions on Neural Systems and Rehabilitation Engineering, vol. 20, May 2012, pp. 228-235, doi: 10.1109/TNSRE.2011.2174652.

[13] CleveLabs, "Electrocardiography I Laboratory," Cleveland Medical Devices, 2006, pp. 1-14.

[14] P.M. Rautaharju, L. Park, F.S. Rautaharju, and R. Crow. "A Standardized Procedure for Locating and Documenting ECG Chest Electrode Positions," Journal of Electrocardiology, vol. 3, Jan. 1998, pp. 17-29, doi: 016/S0022-0736(98)90003-6.

[15] Cypher Avenue, "Human Muscle Anatomy," 2013, Retrieved March 10, 2014 from < http://cypheravenue.com/wp-content/uploads/2013/01/human-muscle-anatomy.jpg>

[16] H. Kew and D. Jeong, "Variable Threshold Method for ECG R-peak Detection," Journal of Medical System, vol.35, Jun. 2011, pp 1085-1094, doi: 0.1007/s10916-011-9745-7.

[17] P. Verdecchia et al., "The Voltage of R Wave in Lead aVL Improves Risk Stratification in Hypertensive Patients without ECG Left Ventricular Hypertrophy," Us National Library of Medicine National Institutes of Health, vol. 8, Aug. 2009, pp. 1697-704, doi: 10.1097/HJH.0b013e32832c0031.

[18] W. Thalheimer and S. Cook, "How to Calculate Effect Sizes from Published Research Articles: A Simple Mythology," 2002, pp. 1-9.

[19] L. Welch, "Information Theory," IEEE Transactions on Information Theory, vol. 30, 1974, pp 397-399.

[20] G. Crifaci et al., "ECG and GSR measure and analysis using wearable systems: Application in anorexia nervosa adolescents," Image and Signal Processing and Analysis (ISPA), 2013 8th International Symposium on, Sept. 2013, pp. 499-504, doi: 10.1109/ISPA.2013.6703792.