

Optimizing Electrode Positioning in 3-lead ECG Chest Devices

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Abstract. Although the 12-lead electrocardiogram has become an essential medical and research tool, many current and envisaged applications would benefit from simpler devices, using 3-lead ECG configuration. This is particularly true for Ambient Assisted Living (in a broad perspective). However, the chest anatomy of female patients, namely during pregnancy, can hamper the adequate placement of a 3-lead ECG device and, very often, electrodes are placed below the chest rather than at the precise thoracic landmarks. Thus, the aim of this study was to compare the effect of electrode positioning on the ECG signal of pregnant women and provide guidelines for device development. The effect of breast tissue on the ECG signal was investigated by relating breast size with the signal-to-noise ratio, root mean square and R-wave amplitude. Results show that the 3-lead ECG should be placed on the breast rather than under the breast and indicate positive correlation between breast size and signal-to-noise ratio.

1 Introduction

The electrocardiogram (ECG) was introduced in clinical practice in 1942 and nowadays is one of the most used non-invasive techniques in medicine. For extracting the ECG signal, the placement of multiple electrodes in specific anatomic regions is typically required. The patient is traditionally connected to the ECG monitoring system using 10 wires, which allow a 12-lead ECG reading; with this configuration, the depolarization and re-polarization of the heart are recorded as five typical waves (P, Q, R, S and T) [1]. The most analyzed feature of the ECG trace is the QRS complex, which reflects the ventricles' depolarization. The R-wave is the most widely used for extracting important cardiac parameters, such as the Heart Rate ($HR = 1/(R_{i+1}-R_i)$) and the Heart Rate Variability ($HRV = R_{i+1}-R_i$). With those parameters, the physician can identify and possibly predict several cardiac pathologies [2].

However, the quality of the signal depends strongly on the electrode placement

since noise or presence of artifacts on the ECG can induce important diagnosis errors [3]. Therefore, a strong knowledge of the correct ECG acquisition procedures is required to conduct a proper diagnosis. It is usually assumed that a major variation on ECG signals results from chest lead misplacement, which can cause attenuation of ECG amplitudes due to abundant breast tissue [4, 5]. This is a problem, namely in women and obese patients, and has given rise to many studies because there is an uncertainty about the standardized procedures for the placement of ECG chest electrodes in these patients. In 1998, Pentti [6] studied the effect of breast tissue protuberance on ECG signals using a 12-lead ECG and concluded that the volume of breast tissue had no effects on ECG amplitudes. In this paper, they also recommended the placement of the chest electrodes on the breast in detriment of placing them under the breast. Five years later, Marcfarlane [3] studied the precordial electrode placement in women, using 12-lead ECG. As well as Pentti et al., the authors of this study have not found variability in the ECG signal related to the anatomical positioning of the electrodes namely on lead V3 and V4.

In recent years, we have witnessed a clear tendency for miniaturization of medical devices, either for remote monitoring purposes or for ambulatory usage. With the ECG being an important signal to be monitored and taking into account the needs of the new medical and social areas such as Ambient Assisted Living (AAL), the 12-lead configuration has a tendency to be abandoned and replaced by 3-lead solutions at breast level. In particular, considering the most recent developments in AAL devices, the 3-lead ECG is clearly a major current application and many such devices are expected to enter the market in the upcoming years [7]. Therefore the knowledge of the correct ECG–electrode placement is extremely important in the particular case of 3-lead configuration devices. The 3-lead ECG is more prone to the effects of misplacement than the 12-lead ECG due to the reduced number of electrodes, which increase the probability of getting a noisy signal in one of them. It is very important to obtain clean ECG signals from all ECG-electrodes. On the other hand, the generalization of these devices makes them prone to be used in a variety of different scenarios and by a higher number of professionals than the traditional ECG. These small and, currently, wireless devices can be employed in disaster scenarios, transit of patients, home-care environments and many other situations. As the general purpose 3-lead sensor must be placed on the left side of the chest, an improved understanding of the effect of the breast shape and volume on the ECG signal is vital.

1.1 Motivation and Goals

The main goal of this study was to verify if (and how) breast size affects the ECG signal and which is the best electrode placement using a 3-lead sensor in order to acquire a signal with high quality and without compromising the medical diagnostic.

The effects of ECG-electrode placement and breast size on the acquired signal were investigated by analyzing the differences in signal-to-noise (SNR), root mean square (RMS) and R-wave amplitude that resulted from positioning the sensor on the breast and under the breast. The correlation between breast size and SNR, RMS and R-wave amplitude were also ascertained.

2 Methods

2.1 ECG Signal Processing

From the collected ECG signals, the signal-to-noise ratio (SNR), root mean square (RMS), R-wave amplitude and Heart Rate (HR) were extracted.

To obtain the SNR, some steps were followed:

1) A low-pass filter, with 50 Hz cut-off frequency, was applied to the raw ECG.

The ECG spectrum contains frequencies in the range from 0.05 Hz up to 40 Hz [8]. Frequencies higher than 50 Hz are considered as noise. Thus, a Butterworth digital filter, with cut-off frequency of 50 Hz, order 2 and sampling frequency of 1000 Hz, was applied to the ECG raw signals. No band pass filter was used, since frequencies lower than 0.05 Hz have negligible impact on the signal.

2) Noise was calculated as the difference between raw and filtered signal (eq. 1).

$$\text{Noise} = \text{ECG}_{\text{raw_signal}} - \text{ECG}_{\text{filtered_signal}} \quad (1)$$

3) Both for raw signal and noise, the energy index (EI) was calculated (eq. 2).

$$EI(t) = \frac{1}{N} \sum_{n=0}^N x(t)^2 \quad (2)$$

4) Using EI, the RMS both for raw signal and noise was calculated (eq. 3).

$$RMS = \sqrt{EI} \quad (3)$$

5) Finally, with the RMS values, the SNR was calculated (eq. 4).

$$SNR = 20 \times \text{Log} \left(\frac{RMS(\text{raw_signal})}{RMS(\text{noise})} \right) \quad (4)$$

The R-wave amplitude and HR were obtained through an ECG algorithm that uses an exponential order to seek the R-peaks. The implemented algorithm was based on Pan & Tomkins [15] to assure that the R-peaks are correctly extracted.

2.2 Breast Size Estimation

The breast size (Bs) was estimated based on the transversal area of the entire breast, measured for each subject from a lateral digital image collected at the time of the ECG data acquisition, as schematically represented in Figure 1 (left). Image processing software was employed to manually draw a spline over the previously captured digital image, creating a closed region that encloses the entire breast. The software measures the area of that region automatically.

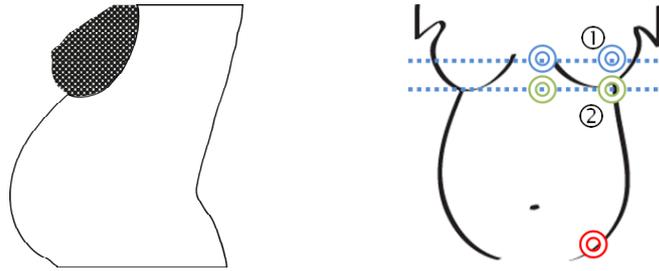


Fig. 1. Estimation of breast size (left), and precordial electrode location for the ECG measurements; the two channels are indicated by double concentric circles, in blue and green, and the ground is shown at the iliac crest, in red. (right).

2.3 ECG Features Analysis

The extracted parameters (described in Sections 2.1 and 2.2) were statistically analyzed. In the present work, a t-test was used and all results with p-value less than 0.05 were considered as statistically significant and with R-value larger than 0.5 linearly related. The statistical study was divided in two analyses:

1) Comparison between ECG-electrode placement and signal parameters. SNR, RMS and R-wave amplitude were compared concerning the ECG-electrode placement in two different anatomic regions: on the breast (Figure 1-right, placement 1) and under the breast (Figure 1-right, placement 2), which correspond to the V2 and V4 standard positions. The mean and standard deviation were calculated for each signal parameter and then compared regarding the referred anatomic regions.

2) Effect of Breast size on ECG signal

A regression equation and the correlation coefficient were calculated in order to investigate if the breast size affects the ECG signal.

3 Experimental Setup

To acquire biosignals in this study, electrocardiography sensors [9] and Kendall/Tyco ARBO disposable surface electrodes (48x34mm) were used. For the signal's analog to digital conversion and Bluetooth transmission to the computer a wireless signal acquisition system, certified for clinical ECG usage, was used (bioPLUX research) which has 12 bit ADC and a sampling frequency of 1000 Hz [10]; see Figure 2.

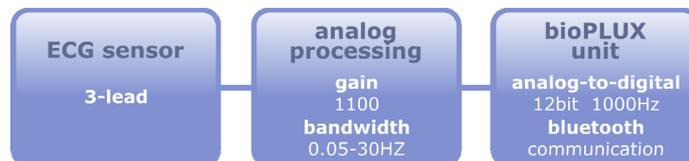


Fig. 2. System architecture.

The ECG trace has been collected for each patient in 2 different chest locations. In order to enable comparison between the two ECG traces, they were recorded simultaneously in two different channels of the signal acquisition system. A pair of electrodes (ECG channel 1) was placed at the nipple level and another (ECG channel 2) at the infra-mammary level. The ground electrode was placed at the left iliac crest. The setup is shown in Figure 1-right.

The study was conducted in a clinical setting, in a temperature-controlled room. Measurements were conducted with subjects resting in a sitting position, which was considered the most representative of continuous (and remote) monitoring scenarios. In each measurement, the ECG signal was recorded for 2 minutes to enable processing and analysis. The study subjects were pregnant patients of the Hospital of Braga (Braga, Portugal), with 30 to 39 weeks of gestation, and who volunteered to participate in the study and have their vital signals monitored and registered. Informed consent forms have been collected from all subjects. The study was approved by the Hospital ethics committee. The test group included 17 subjects. No subject was known to have cardiac problems that should be taken into consideration in the study.

4 Results and Discussion

4.1 Effect of Electrode Placement

Table 1 lists the statistical results (t-test) obtained for SNR, RMS and R-wave amplitude with respect to the two anatomic ECG electrode placements.

Table 1. Statistical values for SNR, RMS and R-wave, for the two ECG-electrode placements.

Anatomic Regions	SNR (dB \pm SD)	RMS (mV \pm SD)	R-wave (mV \pm SD)
On the Breast (Wn)	21.2 \pm 1.8	0.29 \pm 0.1	1.6 \pm 0.5
Under the Breast (Wt)	19.9 \pm 2.9	0.17 \pm 0.1	1.0 \pm 0.3
p-value	0.1	< 0.001	< 0.001

From the results of Table 1, it can be observed that RMS and R-wave values decrease when comparing the electrode placement on (Wn) with under (Wt) breast. The same trend is observed for SNR outcomes; however this decrease is not statistically significant (p-value >.05), demonstrating that it is indifferent to place the ECG-electrode on or under breast concerning the level of noise. Despite this decrease not being significant, the ECG-electrode placement does influence the signal, since there is a statistically significant decrease in RMS and R-wave values under the breast (p-value < .05). Thus, the results show that the decrease of signal amplitude is not due to the decrease of the SNR value, but due to the distance between electrode and heart, which is lower when the electrode is placed on the heart than when it is placed under the heart. In fact, about two-thirds of the heart volume are at the left of the mid-sternal line, in the direction of the left breast [1]. As a consequence, by placing the ECG-electrode on the breast the amplitude of ECG signal is higher than under breast be-

cause this last placement is more distant from the heart, leading to a decrease of the ECG RMS value and R-wave amplitude.

These results are not in accordance with the traditional concept. It is believed that adipose tissue, due to its biologic features, attenuates the ECG amplitudes and decreases the SNR value. The obtained results show the opposite behavior, i.e., on the breast, where the adipose tissue is abundant, the SNR is higher than under the breast. The same is verified for the RMS value and the R-wave amplitude. Thus, the conducted study does not support the traditional concept, and for a 3-lead ECG configuration, it is recommended to place the ECG-electrode on the breast rather than under.

4.2 Effect of Breast Size

Table 2 lists the regression results for SNR, RMS and R-wave with Breast Size. Results reveal poor correlation of RMS and R-wave with Breast Size since the correlation's coefficient (R^2) is less than 0.5 for both parameters.

Furthermore, it can be also verified that despite the R^2 for SNR being less than 0.5, it seems to have a positive linear correlation trending between SNR values and Breast Size ($R > 0.5$). This can mean that these two variables are somehow correlated, and SNR can improve with the increase of breast size. However, when these two variables are categorized, it can be ascertained that there is an increase of the SNR value with the rise of the Breast Size but only up to a certain breast size value. From that threshold on, a stabilization of SNR values is observed, i.e., the SNR maintains its value ($\approx 23\text{dB}$) with further increase of breast size.

The obtained results reinforce that the SNR is positively influenced by adipose tissue, with the RMS and R-wave of ECG signal being unchanged with the breast size. Once more, the results are not supporting the traditional idea that adipose tissue influences negatively the ECG signal. Other authors have also found this trend, when they were studying the relationship between breast protuberance and placement of electrodes on breast. In face of this situation, some authors [11] have suggested that, physiologically, an increase of chest size is associated with an increase of left ventricular mass (LVM), which is related to the body weight, an important factor on LVM. Following this line of thought, other studies related to chest size, body weight and LVM have been published in order to find out a consolidated relationship between chest size/body weight and LVM. For example, in 1977, Horton [12] studied the distance for precordial ECG measurement estimating LVM using an echocardiogram. In this study, the researchers observed a positive relationship between precordial voltage and echo LVM, concluding also that ECG amplitudes could be strongly influenced by the thoracic size. Also, in 2001, Mahommad [13] tried to determine the LVM from echocardiogram, and he has verified a positive linear correlation between LVM and body weight both for males and females. Similar results were obtained by Jose Peralta-Huerstas in 2008 [14], when investigating LVM differences between overweight and normal-weight pre-adolescents.

Despite the fact that, in this work, an echocardiogram was not used, the outcomes suggest that, in fact, the increase of chest size, and breast as well, can positively influence the ECG signal. However, it is necessary to significantly increase the study population to establish better statistical significance and obtain more accurate results.

Table 2. Linear Regression coefficients relating the parameters SNR, RMS and R-wave with Breast size (x) (Parameters = $a \cdot x + b$).

Parameters	a	b	R ²
SNR	0.0056	19.20	0.3
RMS	0.0001	0.24	0.1
R-wave	0.0007	1.38	0.1

5 Concluding Remarks

Over the years, electrode placement has been studied to determine if chest size has an effect on the ECG signal. This is a critical point in standard ECG procedures, particularly in women or obese patients. In women, the conventional procedure is to place the ECG-electrode under rather than on the breast, since it is believed that adipose tissue attenuates the signal and introduces noise. In this work, the ECG signals acquired with a 3-lead ECG sensor positioned on and under the breast were compared, and the effect of breast size on the signal was determined.

Results indicate that the ECG-electrodes should be placed on the breast rather than under the breast because there is a statistically significant difference in the RMS value and R-wave between the signals acquired at these two anatomic regions. These parameters were found to be higher on the breast than under the breast. In terms of SNR, no statically significant differences were found. Concerning the effect of breast size on the ECG signal, there seems to be a positive correlation between SNR and breast size; however, no relationship was found between ECG amplitudes and breast size. The intensification of SNR with the increase of breast volume can be explained by the relationship between LVM and chest size (LVM increases with chest size).

In the future, work will focus on confirming the results and extend the number of subjects to increase statistical significance. Also, new form factors for 3-lead ECG devices will be pursued in the context of AAL. An improved understanding the parameters under study in this paper will provide valuable information for the future development of wearable sensor devices.

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References

1. Tortora, G. J., Grabowski, S. R., (2001). Introduction of Human Body – The essentials of anatomy and Physiology. John Wiley & Sons, INC, 5th Edition.
2. Paoletti, M., Marchesi, C., (2006). Discovering dangerous patterns in long-term ambulatory ECG recordings using a fast QRS detection algorithm and explorative data analysis. *Computer Methods and Programs in Biomedicine*, 82:20-30.
3. Macfarlane, P., Colaco, R., Stevens, K., Reay, P., Beckett, C., and Aitchison, T., (2003). Precordial electrode placement in women. *Netherlands Heart Journal*, 11(3):118.
4. Soliman, E. Z., (2008). A simple measure to control for variations in chest electrodes placement in serial electrocardiogram recording. *Journal of Electrocardiology*, 41:378-379.
5. García-Niebla, J., Llontop-García, P., Valle-Racero, J. I., Serra-Autonell, G., Batchvarov, V. N., (2009). Technical mistakes during the acquisition of the Electrocardiogram. *Journal compilation, Willey Periodicals, Inc*, 14(4).
7. Muhlsteff, J., Such, O., Schmidt, R., Reiter, H., Lauter, J., Thijs, J., Musch, G., Harris, M., (2004). Wearable approach for continuous ECG – and Activity Patient-Monitoring. *Proceedings of the 26th Annual Internat. Conf. of IEEE EMBS, San Francisco, CA, USA*:1-5.
8. Mahmoud, S. S., Fang, Q., Davidovic, D. M., Cosic, I., (2006). A Time-Frequency approach for the analysis of Normal and Arrhythmia Cardiac Signals. *Proceeding of the 26th IEEE EMBS Annual International Conference, New Work City, USA*.
9. PLUX, ecgPLUX, PLUX Wireless Biosignals. Available from: www.plux.info [Accessed August 8, 2011].
10. PLUX, bioPLUX Research, PLUX Wireless Biosignals. Available from: www.plux.info [Accessed Aug 8, 2011].
11. Rautaharju, P., Park, L., Rautaharju, F., and Crow, R., (1998). A standardized procedure for locating and documenting ecg chest electrode positions: consideration of the effect of breast tissue on ecg amplitudes in women. *Journal of electrocardiology*, 31(1):17–29.
12. Horton, J., Sherber, H., and Lakatta, E., (1977). Distance correction for precordial electrocardiographic voltage in estimating left ventricular mass. *Circulation*, 55(3):509.
13. Mohammed, M. (2001). Determination of left ventricular mass by echocardiography in normal Arab people. *morbidity and mortality*, 4:6.
14. Peralta-Huertas, J., Livingstone, K., Banach, A., Klentrou, P., and O’Leary, D., (2008). Differences in left ventricular mass between overweight and normal-weight preadolescent children. *Applied Physiology, Nutrition, and Metabolism*, 55.
15. Pan, J, Tompkins, W. J., (1985). A real-time QRS detection algorithm. *IEEE Transactions on Biomedical Engineering*, 3:230-236.