ECG measurements in atypical arm positions

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This study presents an alternative way to measure electrocardiogram (ECG) in order to achieve an easier monitoring of the patient. The idea is to place two electrodes in the left arm and analyse in which positions good results can be obtained, so that a comfortable device capable of performing continuous measures can be introduced. In addition, if the PPG is measured, a further characterization of physiological parameters can be achieved, through the PAT. Signal processing has been applied to optimize results.

I. INTRODUCTION

Electrocardiogram (ECG) is the main tool for cardiologists to diagnose heart pathologies. The standard method requires 10 electrodes and a complicated setup which must be performed at a hospital.

However, new methods are emerging that allow a similar result with increased comfort and repeatability. An example is the ECG app on Apple Watch [1], which measures an ECG-lead that is similar to a single-lead ECG, so that the results obtained have a waveform similar to one of the 12 waveforms obtained with the standard method. With only a single-lead ECG, since the heart creates a three-dimensional electric field, it cannot be guaranteed to have all the necessary information to obtain a correct cardiovascular characterization of the user. In addition, the obtained signal may be different for different users, because the orientation of each person's heart is different. Apart from that, the problem of this method is that the user needs to hold the finger of the opposite hand on the watch and wait for 30 seconds, which implies that no continuous measurements can be performed. It would be important to get continuous monitoring in a patient in order to detect possible instantaneous irregularities. This can be achieved by placing a system with two electrodes in the same arm or leg.

It has been seen that it is possible to perform ECG measurements in only one arm with high enough Signal-to-Noise Ratio (SNR) to be able to detect the characteristic points of the ECG. However, the positioning of the electrodes is critical. Reference [2] shows that that from the upper arm to the wrist, SNR is significantly higher than measurements only on the wrist or from the forearm to the wrist. To obtain a high-quality signal and reduce noise, [3] shows that adaptive filtering using IPG or PPG signal as reference allows to achieve a clean signal from foot to foot ECG measurement.

In this study we aim to obtain a reliable estimation of one or more of the ECG leads from an atypical but more practical measure. We will focus on measures on the left arm with the goal of reducing the distance between the two electrodes to be able to measure ECG from a simple clothing. Nonetheless, reducing distance also reduces the amplitude of the signal, which complicates the analysis of the result due to white noise and muscle contraction, electromyogram (EMG). These artifacts can be reduced using signal processing with adaptive filtering or wavelet transform.

II. THEORETICAL MODEL

The heart can be modeled, on a first approximation, as a three-dimensional dipole which acts as a source that generates an electric field. From this dipole, it is assumed that the unipolar tension in the body surface is a linear combination of each of the three dipole components. This assumption can be made knowing that the heart-torso electrical system is lineal and quasi-static [4].

Franck [5], Waller and Einthoven suggested in 1954 that the electrical activity of the heart could be represented by a single, time-varying current dipole fixed at the center of an equilateral triangle in the frontal plane, and the ECG recordings were projections of this dipole [6]. The dipole can be represented by

$$\mathbf{p} = p_x\mathbf{x} + p_y\mathbf{y} + p_z\mathbf{z} \tag{1}$$

On the other hand, a lead vector can be defined from the position of an electrode to the position of the other electrode, in differential leads. In the case of unipolar leads, the lead vector starts at the center of the dipole vector and ends at the recording electrode. If this vector is denoted as $\mathbf{c}$, then

$$V = \mathbf{p} \cdot \mathbf{c} = p_x c_x + p_y c_y + p_z c_z \tag{2}$$

The 12 ECG positions are well known: 6 in the chest, and 4 in the limbs, with the right leg acting as reference. The unipolar leads (V1,V2, ..., V6) are measured with respect to the WCT (Wilson Central Terminal), which is the average of all the tensions in the limbs. Hence, knowing the dipole components for each user, they can be projected into every lead by computing the scalar product from equation 2. Moreover, the heart-dipole model can also be used to find an estimate of the tension one would measure at any point of the human surface, by creating a lead vector pointing towards such point.

This model allows to obtain an estimate of the ECG recorded at any point of the body surface, and in particular, in the left arm, which is were measures are taken.

It also makes possible to know, for every subject, *a priori*, the best electrode positioning, given the inclination of the equivalent heart dipoles.

III. MATERIALS AND METHODS

To verify the dipole model presented above, and determine the possibility of estimating ECG leads from non-standard positions of the arm, it has been measured the electric signal between two electrodes, in different positions (Figure 1).

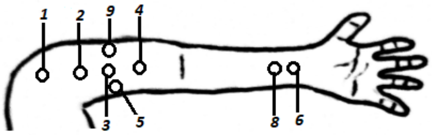

FIG. 1. Location and numbering of the different electrodes in the left arm. Position 7, not showed in the picture, corresponds to the right wrist.

The system used is BIOPAC [7], which provides the hardware and software needed to measure, record and extract the signals. It consists of a monitor unit with four input channels, a 24 bit ADC and an amplifier, which connects directly to the BIOPAC software that adapts, modifies accordingly and extracts the data acquired. Along with this system, a set of wet AgCl electrodes have been employed.

Three signals are recorded simultaneously in each measure; the first and second are two ECG signals and the third is a PPG signal. The proceeding for the ECG acquirement is the following: Two electrodes are placed in the points between which we aim to evaluate the voltage difference, and a third one is placed as a reference to the system in the right wrist, position 7 of Figure 1. These three cables are connected to one of the channels of the BIOPAC device, and the signal is amplified from 1 to 50000 times, depending on the necessity. The PPG signal, likewise, is acquired using a sensor placed on the finger, which connects with a cable to another channel input of the device. The data collected is then processed and treated using MATLAB.

The ECG signals have been extracted in the following atypical positions, referenced in Table 1 from Figure 1.

Measure	Electrodes	Location
1	2-1	Shoulder
	5-3	Upper arm (Horizontal,1)
2	2-1	Shoulder
	8-7	Wrist to wrist
3	6-1	Wrist-shoulder
	8-4	Wrist-Upper arm
4	3-1	Upper arm (Vertical)
	5-9	Upper arm (Horizontal, 2)
5	6-8	Wrist
	5-9	Upper arm (Horizontal, 2)

TABLE I. Location of ECG measurements in the arm

The Signal-to-Noise Ratio (SNR) is used to quantify the quality of the obtained signals. This ratio compares the amplitude of the ECG signal with the standard deviation of the noise that appears in the isoelectric interval.

IV. RESULTS AND DISCUSSION

A. Measurements and signal analysis

Performing different measures with the electrodes in different positions of the arm, it has been checked that it is possible to measure a quality ECG signal in the arm with a local measure with a pair of electrodes separated by a few centimeters. If the electrodes are in the upper arm, the measured ECG shows good quality results. However, the farther the electrodes are from the heart, the smaller the amplitude of the ECG signal. For this reason, at some point the amplitude is so small that it is confused with the internal noise of the measurement. Moreover, it has been checked that it is not possible to measure a quality ECG signal in the lower arm with a local measure in the wrist. The comparison between two measures in the upper arm (3-1 and 5-9) and one in the lower arm (6-8) can be seen in Figure 2.

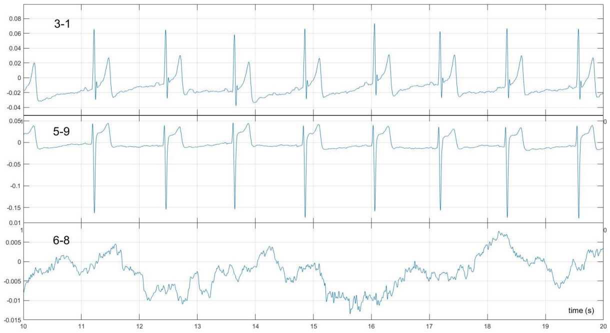

FIG. 2. Comparison of the ECG signal with the electrodes in different positions of the arm

Studying the variability between persons, it has been seen that the optimal position of the electrodes to measure a good quality ECG signal is different in each one. This is tested comparing the SNR of the ECG signal of three subjects in the same position, as shown in Table II. This variability can be easily explained using the dipole model; depending on the orientation of the dipoles, the measured tension in a particular direction can vary, which is exactly what is observed.

A solution to this variability, to ensure a good measure in any subject, could be to position a patch with several electrodes in the upper arm, so that different measures can be performed at the same time and then choose the best one.

Electrodes	Subject 1	Subject 2	Subject 3
2-1	16.76	30.85	35.13
5-3	37.77	36.37	32.62
8-7	39.48	35.01	39.4
6-1	38.77	25.14	30.11
8-4	21.38	0	0
3-1	33.01	26.66	34.34
5-9	48.32	37.44	31.35
6-8	0	0	0

TABLE II. SNR for different measurements (in dB)

We have also checked the validity of the dipole model comparing the estimated and measured waveforms. We have measured a 12-lead ECG on subjects 1 and 2, and from this, calculated the dipoles. Projecting the dipoles into the directions of the two measures, 1-3 and 5-9, we have found that for these two positions, both waveform and amplitude match the measured signals. However, when the electrodes are placed farther, only the waveform is well estimated.

It is also important to know what happens if the arm is situated in different positions. This has been studied measuring the ECG signal with the electrodes in the positions 1-3 and 5-9 and with the arm forming 0º (p1), 80º (p2) and 110º (p3) with respect to the body. The results show that the signal has the same form in each different position of the arm (Figure 3). This implies that to estimate the ECG signal in the arm using the dipole model it is enough to consider the lead vector pointing towards the left (in the positive $\hat{y}$ direction) and then the same result would be valid for any position of the arm.

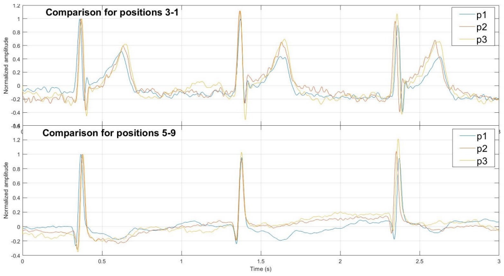

FIG. 3. ECG signal with the arm in 3 different positions

The measured ECG can be used to calculate the different temporal parameters using the Pan-Tompkins algorithm, which detects the temporal position of each characteristic point of the ECG signal (P,Q,R,S,T) [8]. For a measure made on subject 1 in the position 3-1, the mean and standard deviation are shown in Table III. The standard deviation on PR, QRS, ST and QT segments is mainly due to noise, because they are intrinsic for every person and do not depend on heart rate. However, RR shows a higher standard deviation, which is normal, because heart rate variability for a healthy person is typically non-zero.

	Mean (ms)	Standard deviation (ms)
PR	151	10
QRS	111	22
ST	224	3
QT	335	22
RR	1129	132

TABLE III. ECG parameters

In addition, if both ECG and PPG are available, the pusle arrival time (PAT) can be determined. This parameter is defined as the time delay between a characteristic feature of the ECG, typically the R wave, and a point of an arterial pulse waveform, extracted from a photoplethysmography (PPG) measure (Figure 4).

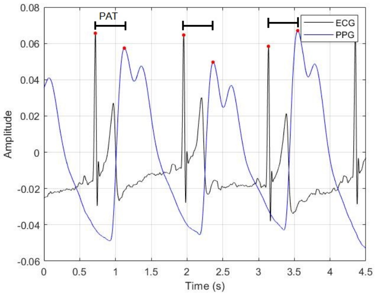

FIG. 4. Time delay between ECG and PPG

The PAT allows to estimate the time it takes for the blood to go from the heart to the hand, which is related with its velocity and can be useful in measures of the blood pressures, even though it is still being studied [9]. In the presented case a PAT of 399 ms and a standard deviation of 20.8 ms has been found.

B. Signal enhancement

Despite the performed measures in the upper arm seem to be good enough, they have been performed at a controlled environment and in a relaxed position. However, if the subject is not relaxed, the muscles are contracted and it can appear an external noise in the ECG signal due to EMG. This effect can be seen in Figure 5. It is of great interest to be able to separate both signals.

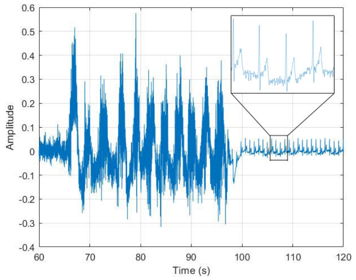

FIG. 5. ECG signal with and without EMG

Most of ECG's frequency content is between 0.05 and 10 Hz, and EMG ranges between 1 Hz and 10 kHz [10]. Hence, using a band-pass filter from 0.05 Hz to 10 Hz would not remove all of EMG and, on the other hand, using a band-stop filter from 1 Hz to 10 kHz to clear out the EMG would also delete most of ECG's frequency content.

The most obvious solution appears to be adaptive filtering. We have measured ECG in positions 3-1 and 5-9, as well as EMG. To record EMG, several tests have been made changing the position of the two electrodes. The channel recording EMG uses the same filters as the ECG ones. The key idea of adaptive filtering is that the EMG component of the reference signal (d(n) in Figure 6) which is the ECG+EMG, must be somehow correlated with the input signal x(n), which is only EMG.

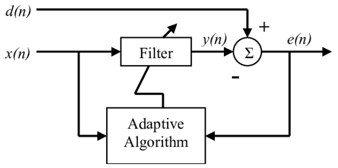

FIG. 6. Block diagram of LMS algorithm. From [11]

The first option is to place the EMG electrodes in the wrist, because in this position it has been shown that no ECG signal can be measured. Hovever, LMS and NLMS algorithms have been tested and are not able to clear the signal, because the EMG in the wrist is not very well correlated with the one measured in the upper arm.

However, if the EMG electrodes are in the upper half of the arm but very close to each other, the measured EMG is very similar to the reference some ECG content is also recorded. Then, when the LMS algorithm is applied, since the input of the filter is also correlated with the ECG part of the reference, the ECG component, as well as the EMG component, is filtered. This shows that the adapting filtering works, but we have not been able to obtain a measure of EMG similar enough to the reference signal without containing some ECG content.

Finally, one last tool commonly used to analyse ECG signals is the Wavelet Transform (WT) (Equation 3). WT are the basis of the frequency analysis of non-stationary signals, which cannot be correctly represented with a simple Fourier Transform, because of its nature changing over time (Fourier does not contemplate the possibility of the spectrum changing over time). Several studies have focused in this topic and show its practical results. Reference [8] shows a comparison of SNR of ECG signals with noise, filtered with different types of wavelet.

$$WT(a,\tau) = \frac{1}{\sqrt{a}} \int_{-\infty}^{\infty} s(t) \cdot \phi(\frac{t-\tau}{a}) dt \tag{3}$$

Regarding the previous problem of EMG noise contamination of the signal, it has been tried to use this Wavelet Analysis to extract parameters of the signal. *Wavelet Toolbox* [12], from Mathworks, provides an easy way to do so. Results are shown in Figure 7.

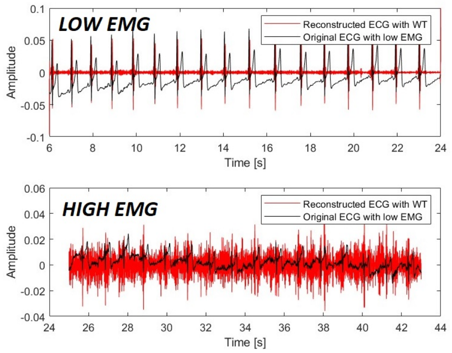

FIG. 7. ECG signal WT analysis with low and high EMG

Two ECG recorded signals in the upper arm have been taken for the analysis. LOW EMG contains the WT reconstruction of an ECG signal with a SNR=33.01 dB. The WT transforms provides a clear representation and location of the R-peak and the cardiac rhythm. HIGH EMG contains the WT of an ECG signal with a SNR=21.38. Comparing with the R peaks of the original ECG, the WT is still able to localize most of them, but fails with others and does not provide a clear result. Therefore, we conclude that signals with a lower SNR cannot be analyzed this way. [14] provides a further WT analysis of noisy signals.

C. 12 lead ECG synthesis

Furthermore, studies such as [3] have shown that from two measures in the upper arm plus one in the chest, it is possible to synthesize the 12-lead ECG with a good correlation (94%) using transformation matrices, which finds the linear combination that transforms the information from three independent standard leads in the shape of the single arm leads or vice versa.

V. CONCLUSIONS

In this paper, a quality ECG signal in the upper arm using two electrodes has been measured. When the signal has a high SNR, the ECG parameters can be obtained. If PPG is also measured, PAT can be calculated and enables to obtain an estimation of blood pressure, even though research on this topic is still in progress. For measures with some noise due to EMG but enough SNR, we have been able to improve clearly the signal using Wavelet Transform and from it, we are able to obtain the ECG parameters. However, the signal processing tools to separate ECG and EMG content when the EMG is significantly larger than ECG still need to be improved.

[1] *ECG app on Apple Watch* https://support.apple.com/en-is/HT208955

[2] O.J.Escalona, L.McFrederick, M.Borges, P.Linares, R.Villegas, G.Perpiñan, J.McLaughlin, D.McEneaney (2017) *Wrist and Arm Body Surface Bipolar ECG Leads Signal and Sensor Study for Long-term Rhythm Monitoring*, Computing in Cardiology, vol.44

[3] R.Cuervo (2017) *ECG signal acquisition and processing for highly wearable devices*, UPC.

[4] R.Plonset, D.B.Heppner (1967) *Considerations of quasi-stationarity in electrophysiological systems*, The bulletin of mathematical biophysics, vol.29, no.4, pp.657-664

[5] E.Franck (1954) *General Theory of Heart-Vector Projection*, Circulation Research, vol.2, no.3, pp.258-270

[6] J.Malmivuo, R.Plonsey (1995) *"Volume Source and Volume Conductor", Bioelectromagnetism - Principles and Applications of Bioelectric and Biomagnetic Fields.* New York, NY, USA: Oxford Univ. Press, pp.133-153

[7] *Biopac Systems, Inc.*. https://www.biopac.com/

[8] J.L.Romero (2015) *Análisis de señales electrocardiográficas usando técnicas de procesamiento digital*

[9] E.Finnegan, S.Davidson, M.Harford, J.Jorge, P.Watkinson, D.Young, L.Tarassenko, M.Villarroel (2021) *Pulse arrival time as a surrogate of blood pressure*, Scientific Reports, vol.11, no.1

[10] R.Martinek, M.Ladrova, M.Sidikova, R.Jaros, K.Behbehani, R.Kahankova, A.Kawala-Sterniuk (2021) *Advanced Bioelectrical Signal Processing Methods: Past, Present, and Future Approach—Part III: Other Biosignals*, Sensors, vol.21, no.18, p.6064

[11] R.Mustafa, M.A.Mohd Ali, C.Umat, D.A.Al-Asady (2009) *Design and implementation of least mean square adaptive filter on Altera Cyclone II Field Programmable Gate Array for active noise control.* Conference: Industrial Electronics Applications, vol.1

[12] *Wavelet Transforms in MATLAB. Analyze signals and images in the wavelet domain.* https://es.mathworks.com/discovery/wavelet-transforms.html

[13] I.Tomasic, R.Trobec (2014) *Electrocardiographic Systems With Reduced Numbers of Leads—Synthesis of the 12-Lead ECG*, IEEE reviews in biomedical engineering, vol.7, pp.126-142

[14] A. Sharma, S. Patidar, A. Upadhyay, U. Rajendra (2019). *Accurate tunable-Q wavelet transform based method for QRS complex detection*