Waveform Phase Shift Study to Compute the Relationship between the Mason-Likar and the Standard Limb Lead Electrode Placements

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Abstract

Variations due to electrode positions are particularly pronounced in the R-wave amplitudes in limb leads between resting ECG and stress ECG records as they are recorded with wrist or shoulder placed electrodes. Since the human torso is not electrically homogenous, the alteration in the morphology due to electrode position also causes a rotation in the phase angle of the waveform. The purpose of the present study is to analyze ECG waveforms, recorded simultaneously at different electrode positions and derive a transformation function that can project the waveform recorded in any electrode position to another shifted position. The computed transformation function provided an almost perfect ECG, visually indistinguishable from actual limb lead systems. A subject-specific transformation is available for interpolating ECG signals corresponding to any intermediate electrode location.

1. Introduction

The standard 12-lead ECG, with frontal plane axes derived from electrodes placed distally on the extremities, has been used in multiple studies. As the standard lead system is affected by motion artifacts easily, Mason and Likar (ML) [1] introduced a modified electrode placement bringing the wrist and ankle electrodes to the base of the limbs. The ML system uses all the conventional precordial electrode sites, but the limb electrodes are connected to sites on the anterior part of the torso instead of to distal limb sites, as is shown in Figure 1. It is well known that the ECG recordings using standard limb electrode placement and the Mason-Likar configuration for stress ECG recordings present differences in the amplitude and waveform morphology especially in the QRS complex. A baseline resting ECG is suggested as an important prerequisite to performing an exercise test [2]. Variations in normal ECG waveform characteristics during stress are studied in [3], which indicated complex changes in the QRS complex, affecting the magnitudes of R, Q and S waves, as exercise activity proceeded. Such variations are compounded by the placement of electrodes. Our present work shows an extrapolation of ML lead configurations to the standard 12-lead positions.

Anisotropic characteristics of the human body contribute to the amplitude and phase difference in the observed ECG waveforms between the two configurations. In this study the authors have investigated the nature of this difference as a function of electrode locations along the limb, between the shoulder and the wrist, to derive a non-linear, space-variant relationship which characterizes both the amplitude and the phase components of the ECG waveform. This relationship can be used to transform one electrode placement to the other, as indicated in (1) below.

$$E_{Std} = L(t,x)\{E_{ML}\} \qquad (1)$$

In the above equation, $L(t,x)$ is a transform that relates the ML ECG signal to the standard ECG signal.

In the present approach, a one dimensional scalar wave equation, eq (2), is used to represent the observed ECG waveform as a complex function of time and location;

$$E(t,j) = A(t,j)\exp[i\omega t + \phi(t,j)] \qquad (2)$$

where $E(t,j)$ is the observed ECG signal, $A(t,j)$ is the amplitude and $\phi(t,j)$ is the phase angle at time t and electrode location j.

Our present objective is to transform ECG waveforms that are recorded in one electrode position (j1) to those recorded at another electrode location (j2) by means of a transform that is a function of amplitude and phase relationship between the waveforms.

2. Methods

In this study, a Cardiac Science Q-Stress® ECG system is used to collect 12-lead ECG data from multiple subjects. The limb electrodes were placed on the torso in Mason-Likar configuration, and the chest electrodes (Vx1-Vx6) were placed along the limb to

observe the waveform transition between the shoulder and the wrist, (Figure 1*)*. ECG data was sampled at 500 samples/second, at 2.5 micro-volts/lsb resolution and had 0.05-150 Hz frequency bandwidth.

The collected data then was analyzed to generate the average beat for each electrode position as in equation (3)

$$Avg(t,j)=\left(\frac{1}{N}\right)\left(\sum_{i=1}^{N}\{E(t,j)\}_i\right) \qquad (3)$$

Figure 2 shows a gradual change in QRS complex morphology as the electrode position along the limb changes. The average beat for each electrode position is used to compute the frequency domain counterparts in terms of amplitude and phase spectra (Figure 3 a-b) using Welch's *Averaged, modified periodogram spectral estimation* method [4]. Matlab was used to analyze, model and compute the transformation function in time and frequency domains.

For display purposes, the ECG waveforms recorded at the electrode positions placed on the shoulder and along the arm "Vx1" through "Vx5" are transformed to that recorded at the wrist electrode position "Vx6".

$$\hat{E}_{Vx6}(f)=T(f,\phi)*(E_{Vxn}(f)) \qquad (4)$$

where $\hat{E}$ is the estimated (transformed) ECG waveform for the wrist electrode position "Vx6", applying "$T(f, \phi)$" transfer function to the ECG waveform recorded at electrode position "Vxn", (n=1:5). The result of the transformation from each electrode position (Vx1,….,Vx5) to the electrode position Vx6 are shown in figure 4.

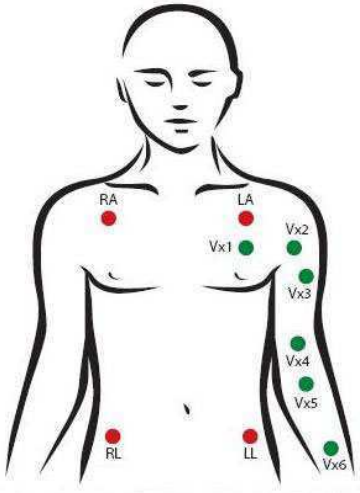

Figure 1: Electrode placement on the torso (Vx1-Vx6) used in the data collection for this study.

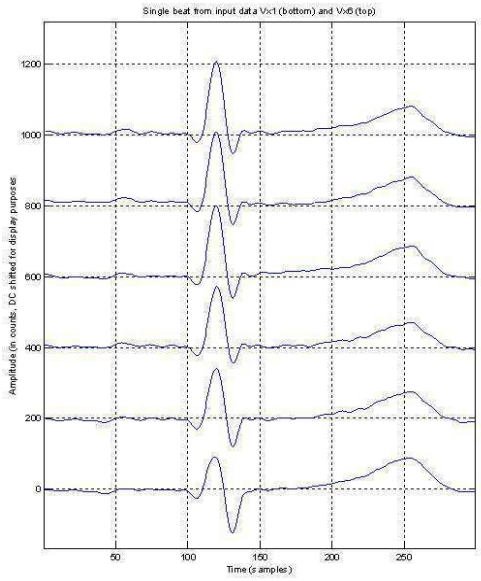

Figure 2.ECG data recorded at Vx1-Vx6 positions

Algorithm Description:

2.1. Input ECG "x" and the desired ECG "y" waveforms from different electrode locations are acquired. Figure 2: ECG Data (subject -1) recorded at electrode positions shown in Figure 1. Data was DC shifted for display purposes.

2.2. Input ECG waveforms x and y are divided into 2048 sample long segments for FFT.

2.3. These ECG segments are then filtered to remove the low frequency noise components (detrended).

2.4. Hamming windowing functions are applied on filtered segments data.

2.5. The cross-power spectrum *P(x,y)* is computed for each segment as the product of the forward FFTs of the input "x" and the desired "y" waveforms.

2.6. The auto-power spectrum *P(x,x)* is computed for each segment as the product of the forward FFTs of the input by itself [5,6]

2.7. Averaging and scaling of both P(x,x) and P(x,y) is done.

2.8. Finally the transfer function to convert "x" to "y" is then computed by

$$T(x,y)=\frac{P(x,y)}{P(x,x)} \qquad (5)$$

2.9. Fourier transform of the input is then multiplied by the transfer function.

2.10. Inverse Fourier transform of the multiplication is taken to retrieve the transformed output, in time domain.

2.11. Equivalent convolution operation can also be performed by IFFT of *T(x,y)* and the input signal *x*.

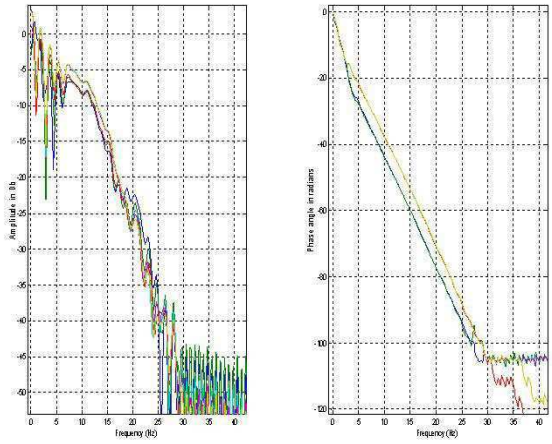

Figure 3. Amplitude (left) and phase spectra of the average beats used for the transformation computed for each electrode position ECG Data (subject -1).

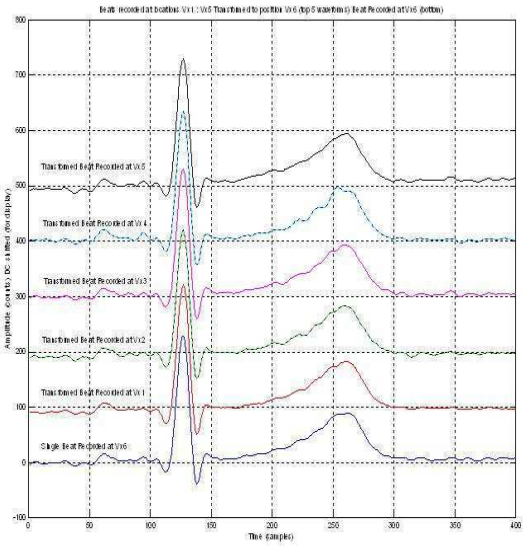

Figure 4. Original beat recorded at electrode position Vx6 (bottom) and the same beat recorded (at the same time) at electrode positions Vx1 : Vx6 and transformed to the electrode position Vx6. Compare to figures 2 and 5.

3. Results and conclusions

The above results confirm that:

3.1. Application of transformation function that introduces phase rotation to ECG waveforms produces waveforms that are similar to those recorded at other electrode locations.

3.2. P, QRS, and T wave components may require different transformation (rotation) function for correct reproduction. The same may be true for other morphologies like PVCs, Couplets, VTs and VFs.

3.3. Random noise contamination may cause additional adjustments in the computation of the transfer function.

3.4. Validity and verification of the approach will need to be tested using a variety of data sets containing NSR and time varying complex ECG morphologies to test the need for time varying transfer functions.

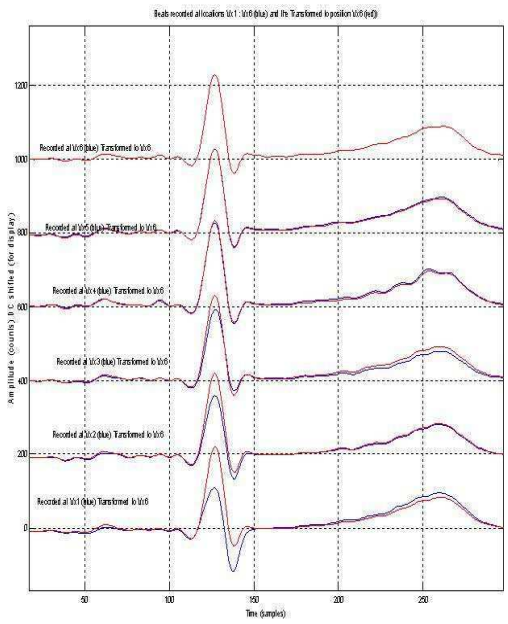

Figure 5. Original beat recorded at electrode positions V1x:Vx6 (blue) and the output of the transformation to the electrode position Vx6 (red) superimposed. Compare to figures 2 and 4.

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