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Partial Linear Transformation of Vectorcardiogram to 12 Lead Electrocardiogram Signals

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***Abstract*—The ability to transform orthogonal 3-lead Vectorcardiogram (VCG) to 12-lead Electrocardiogram (ECG) enables the use of fewer leads for computer visualization, signal analysis and wireless transmission of signals. This can also improve mobility, albeit limited, to the patients. We presented a least square (LS)-based approach to transform 3-lead Frank VCG to 12-lead ECG signals and vice versa, using partial linear transformation. Also our partial linear transformation function would be compared with Dower and affine transformation functions. The VCG and ECG signals of 40 healthy persons are acquired in this study. The results show that for healthy subjects, our partial linear LS method that is maps 3-lead VCG to12-lead ECG more accurately than both Dower and affine transformations of the ECG recordings**.

***Keywords*—VCG, ECG, partial linear transformation, least square estimation method.**

I. Introduction

Electrocardiogram (ECG) is the primary tool in cardiac diagnosis and it acts through assessment of cardiac function using measurement of electrical potentials derived from body surface leads [1]. Automatic analysis of this signal (introduced since the late 19th century) is one of the first areas in medicine that computational methods have been employed in order to facilitate biomedical signals interpretation.

A number of lead configuration systems had developed with standard electrode positions, but the most attention had focused on 12-lead ECG system. By now, many lead systems for measuring the Vectorcardiogram (VCG) have been developed. The orthogonal Frank lead system is one of the most common procedures to measure VCG [1]. It is based on the torso model and theoretical mathematic considerations [2-3]. Although the information contained in VCG leads has been found useful in many clinical situations [4], the 12-lead ECG has remained the preferred lead system in the clinical environments due to the existence of well-established criteria for its interpretation. However, the synthesizing of VCG from standard 12-leads ECG has been implemented with success [5-6]. Synthesized VCGs have contributed to the improved detection of certain electrocardiographic abnormalities.

VCG determines the direction and magnitude of the heart dipole. In VCG, electrodes are placed in x,y,z directions, therefore it can provide total information from all sides of the heart, specially the posterior orientation in z direction.

One reason for the slow progress in clinical application of VCG might be attributed to the three-dimensional nature of VCG which was developed too early without any comparable methods to understand its meaning. Lack of powerful computational and 3-dimensional monitoring devices in that time has also been suggested for such slow progression [7].

Specific advantages of the VCG were the recognition of undetected atrial and ventricular hypertrophy, greater sensitivity in identification of myocardial infarction, and superior capability for diagnosis of myocardial infarctions in the presence of fascicular and bundle branch blocks [8]. VCG has shown its capabilities during the last decade in concurrence with high design and development of software and hardware medical signal processors. It provides accurate diagnostic clues toward right ventricular hypertrophy, combined left and right ventricular hypertrophy, right bundle branch block and myocardial infarction [9-11]. Furthermore, VCG had a greater sensitivity than ECG in detecting atrial enlargements [10]. Therefore, many novel vectorcardiographic parameters have been implemented and applied in clinical studies during the last decade.

In addition, with the recent advances in wireless and microelectromechanical systems (MEMS) sensor technologies, there has been a renewed interest in advancing ambulatory heart monitoring systems that uses these technologies. Bandwidth constraint has been the chief limitation of the wireless technologies for on-patient heart monitoring and advanced clinical diagnostic applications. ECGs that use fewer leads without affecting diagnosis was critical for minimizing bandwidth requirements, thus, leading to practical on-patient diagnostic systems. In such scenarios, VCGs can be preferred over conventional 12-leads ECG systems.

Since the standard 12- leads ECG is the most common way to measure electrical function of the heart, the main question is the possibility of using VCG instead of ECG in order to get more accurate results? When standard 12- lead ECG is measured, all the chest leads are on the front side of the body, compared to Frank lead systems, where one of the chest lead locates on the back. Therefore the measurement by Frank lead system is more volumetric comparing to standard 12- leads ECG.

As a result 3-lead VCG [3] provides 3D information of the heart, by showing the 3D vector of the heart. Some projections of this vector in 2D-pages will prepare the information about all sides of the heart. Since the VCG signals are less popular than the ECG signals amongst cardiologists and it is hard to analyze by them, therefore, we aimed to introduce a new

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method to convert VCG to ECG signals using partial linear transformation. In this trend for each part of VCG and ECG signals like P, QRS or ST segments new sets of coefficients are obtained. In this method we extract the ECG data of each patient using partial conversion on VCG data based on partial linear least square (LS) method. Therefore, using conversion of VCG to ECG signals, the data would be more understandable and useful for cardiologists. Indeed, the information about posterior wall (V7, V8, V9) would be prepared if necessary.

II. DOWER AND AFFINE TRANSFORMS

The preliminary data on lead transformation have been derived from the seminal investigations of Dower [12-13]. This conversion method made it possible to derive the12-leads ECG datafrom the Frank XYZ leads. Dower has used geometric transformation principles to obtain a matrix based on Frank's torso model, widely referred as the Dower transformation matrix. In Dower transformation method, the matrix is multiplied to VCG samples for extraction of ECG signals from that, as showed below:

$$S=D\times V \qquad (1)$$

where,

$$D=\begin{bmatrix} -0.515 & 0157 & -0.917 \\ 0.044 & 0.164 & -1.387 \\ 0.882 & 0.098 & -1.277 \\ 1.213 & 0.127 & -0.601 \\ 1.125 & 0.127 & -0.086 \\ 0.831 & 0.076 & 0.230 \\ 0.632 & -0.235 & 0.059 \\ 0.235 & 1.066 & -0.132 \end{bmatrix}$$

$S(n)=[V1(n)\ V2(n)\ V3(n)\ V4(n)\ V5(n)\ V6(n)\ I(n)\ II(n)]^T$
$V(n)=[X(n)\ Y\ (n)\ Z(n)]^T$

S contains the voltages of the corresponding leads, n denotes sample index and D represents the Dower transformation matrix. From S = D×V it follows that the VCG leads can be synthesized by the 12-leads.

The other method to derive ECG data from VCG was developed based on the transformation matrices using statistical least squares fitting of an affine function [14]. Every derived lead is a linear combination of the known lead values plus a constant coefficient. The Affine transformation structure provides a convenient mean for automatic compensation of some of these constant biases. Thus, the resultant empirical transformation scan would be more consistent and accurate.

Linear regression model assumes that every derived lead (the individual 8-lead values (V1,V2,…..,V6, I,II) denoted as $Y = [y1, y2,\ldots, y8]^T$ could be obtained from a linear combination of the 3 Frank VCG values (the 3 leads are denoted as X = [x1, x2, x3]).

$$Y = AX + e = a0 + a1x1 + a2x2 + a3x3 + e \qquad (2)$$

where a0, a1…an are the columns of the transformation coefficients, A is the transformation matrix and e is the error. Thus, knowing the input lead values, the corresponding coefficient vectors can be used to derive each of the 8 leads from VCG.

III. MATERIALS AND METHODS

In this study, we have used 40 healthy volunteers. The sampling rate was 500 Hz, and the samples were typically gathered for 16- second duration. The recorder device was Cardiax recorder. The 12-leads ECG and VCG signals were used in this study. We have compared the overall accuracies of Dower and Affine transformations with partial linear transformation method for correctly deriving the 12-leads from the known 3-leads Frank XYZ, just for healthy cases.

In this trend (partial linear transformation) at first step, two signals (ECG & VCG) for each case must be synchronized. Thus using differential threshold method we can find the R peak of each signal and synchronize the ECG and VCG signals for each case. During recording VCG signals the position of the subject varies from the position in ECG recording [4].Cardiax recorder had the ability to give some information about duration of the P, QRS and ST segments of the ECG and VCG signals of each special case. So, we have measured the duration of these segments in milliseconds. Moreover, we knew that the sampling frequency is 500 HZ. Then, having this data we can measure exactly the number of samples in each segment of our signals.

For example:

QRS segment = 40 ms Sampling rate = 500 HZ

$$\frac{1000(ms)}{500(sample)} = \frac{40(ms)}{x\ sample}$$

Thus, after synchronization of ECG and VCG, it would be possible to extract each segment of both signals. Then, the least square fitting method [15-16] to find partial coefficients for each segment of ECG & VCG signals should be used. This formula would be as follow:

$$\begin{bmatrix} a \\ b \\ c \end{bmatrix} = (U^T U)^{-1} U^T Y \qquad (3)$$

where

U= (VCG data)

Y= (ECG data for just one lead)

These coefficients (a-b-c) are provided for each segment of the signal.

In order to test this method, we have calculated a,b,c coefficients for 5,10,20,30,40 cases. We have observed that when the number of cases increased from 20 persons, the coefficients are approximately instant. Then, we found this method as a reliable one. To compare our method with Dower

and Affine transformations, we have used Dower and Affine matrixes to convert VCG signals to ECG ones. Then, we have calculated some statistical parameters to compare the precision of our method and others.

R2 is a statistic parameter that has been used to quantify the extent to which a transform captures the trends in the relationship between the inputs (3 VCG leads) and each of the measured data. R2 statistic of 100% indicates that the transform is able to correctly reproduce the actual measured data (lead value). R2 statistic is given by:

$$R^2 = \{1 - \frac{\sum_{All\ \ ECG\ \ samples}[Derived(samplek\quad k) - Measured(samplek\quad k)]^2}{\sum_{All\ \ ECG\ \ samples}[Measured(samplek\quad k)]^2}\} \times 100 \qquad (4)$$

R2 is used to evaluate how close the outputs are calculated from the model relative to the actual measured lead values. Furthermore, we have evaluated the correlation coefficients between original ECG and derived ones from VCG for each method to assessed the accuracy and precision of our method.

IV. RESULTS

By comparison of some statistical parameters of the partial linear method with Dower and Affine transformations like R2 and correlation coefficients, we have observed that our recommended method was much more reliable and accurate than their methods. Thus, for healthy subjects, the partial linear transformation presented here yields improved accuracy (R2 values and correlation coefficients (C.C)) over Dower and Affine transforms (see Table 1 for details).

Table 1: Comparison between R2 values and correlation coefficients (C.C) of various methods

lead	**R^2** ***partial linear***	**R^2** ***Dower***	**R^2** ***Affine***	**C.C** ***partial linear***	**C.C** ***Dower***	**C.C** ***Affine***
I	0.607	0.209	0.370	0.791	0.674	0.809
II	0.686	0.346	0.574	0.798	0.685	0.439
V1	0.684	0.561	0.593	0.843	0.433	0.641
V2	0.751	0.355	0.673	0.694	0.544	0.224
V3	0.585	0.356	0.536	0.768	0.316	0.404
V4	0.781	0.172	0.781	0.703	0.105	0.796
V5	0.753	0.743	0.747	0.770	0.166	0.502
V6	0.430	0.232	0.333	0.776	0.356	0.726

These results show that for healthy subjects, our method (partial linear LS method), maps 3-lead VCG to12-lead ECG more accurately than Dower and Affine methods. The following figure shows the similarity of real ECG and derived ones from VCGs using various methods. they are unavoidable.

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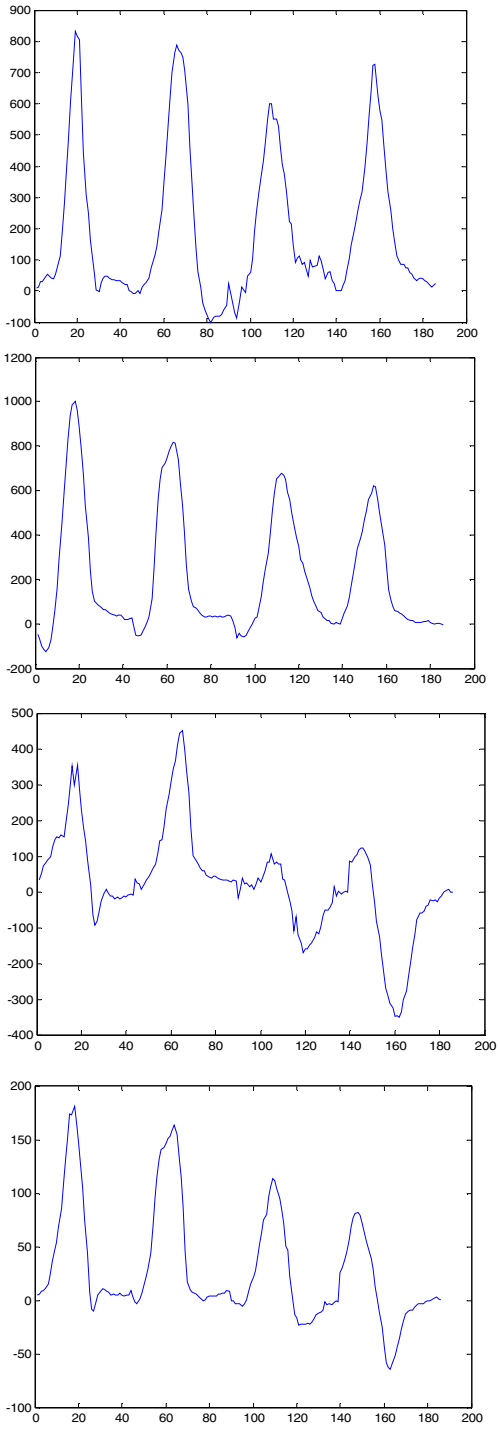

Figure 1: From top to bottom: original ECG (lead 2), the ECG signal derived from VCG by using partial linear transformation, the ECG signal derived from VCG using Dower transformation, the ECG signal derived from VCG by using affine Transformation.

V. DISCUSSION

Based on our results, ECG signals derived from VCG using our method (partial linear transformation) has more

correlation and similarity with general ECG leads compared with ones derived using Dower and affine transformations. As a result, this method provides accurate general information about the underlying heart diseases compared with data derived from linear transformation function.

Providing total information from all sides of heart walls for cardiologists just through 3-leads VCG, it could be actually a helpful tool for better recognition of patient diseases. It also decreases dramatically the time to diagnosis. Indeed, it would be possible to use this method of transformation between VCG and ECG to get posterior information of the heart too [17].Moreover by using this method it would be possible to use telemetric techniqe for sending more accurate heart data from ambulance to hospitals just from 3 leads (VCG leads).

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