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Transformation of the Mason-Likar 12-Lead Electrocardiogram to the Frank Vectorcardiogram*

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***Abstract*— Vectorcardiograpic (VCG) parameters can supplement the diagnostic information of the 12-lead electrocardiogram (ECG). Nevertheless, the VCG is seldom recorded in modern-day practice. A common approach today is to derive the Frank VCG from the standard 12-lead ECG (distal limb electrode positions). There is, to date no direct method that allows for a transformation from 12-lead ECGs with proximal limb electrode positions (Mason-Likar (ML) 12-lead ECG), to Frank VCGs. In this research, we develop such a transformation (ML2VCG) by means of multivariate linear regression on a training data set of 545 ML 12-lead ECGs and corresponding Frank VCGs that were both extracted surface potential maps (BSPMs). We compare the performance of the ML2VCG method against an alternative approach (2step method) that utilizes two existing transformations that are applied consecutively (ML 12-lead ECG to standard 12-lead ECG and subsequently to Frank VCG). We quantify the performance of ML2VCG and 2step on an unseen test dataset (181 ML 12-lead ECGs and corresponding Frank VCGs again extracted from BSPMs) through root mean squared error (RMSE) values, calculated over the QRST, between actual and transformed Frank leads. The ML2VCG transformation achieved a reduction of the median RMSE values for leads X (13.9μV; *p<.001*), Y (15.1μV; *p<.001*) and Z (2.6μV; *p=.001*) when compared to the 2step transformation. Our results show that the 2step method may not be optimal when transforming ML 12-lead ECGs to Frank VCGs. The utilization of the herein developed ML2VCG transformation should thus be considered when transforming ML 12-lead ECGs to Frank VCGs.**

I. Introduction

The vectorcardiogram (VCG) is a representation of the cardio-electrical activity as projected onto three orthogonal axes (x, y, z). The most popular lead system for recording the VCG is that developed by Frank [1]. Nonetheless, the Frank VCG has not prevailed over the 12-lead ECG as a recording format of choice [2]. Despite the fact that Frank VCGs are seldom recorded in clinical practice [3], the measurements that can be extracted from them (e.g. the spatial QRS-T angle and the spatial ventricular gradient) are still often valuable as a supplement to the 12-lead ECG [4], [5]. Recognizing that the 12-lead ECG contains electrocardiographic information that is largely linearly related to that of the Frank VCG, investigators have proposed ways for transforming 12-lead ECGs to Frank VCGs [6], [7].

Specifically, several sets of transformation matrices have been proposed that derive the Frank VCG from the standard (distal limb electrodes) 12-lead ECG [8] and a number of recent studies have used measurements from derived Frank VCGs (such as the spatial QRS-T angle) to predict risk of ventricular arrhythmias and sudden cardiac death [3], [9].

Nonetheless, the standard 12-lead ECG is not suitable for exercise testing, monitoring and prolonged Holter recordings. This is due to the susceptibility of the distal limb leads to artifacts. Instead, recording of Mason-Likar (ML) 12-lead ECGs (recorded using proximal limb ML electrode placement [10]) is preferred. Although a growing number of 12-lead ECGs are being recorded using the ML configuration it has been shown that the recorded signals do differ between the ML and standard formats [11]. Hence potentially making the utilization of the standard 12-lead ECG to VCG transformation inadequate.

To the best of our knowledge, no transformation method that derives the Frank VCG from the ML 12-lead ECG has previously been published. Thus, the utilization of a two step approach (2step) is required when deriving the Frank VCG. In this approach two existing transformations, that are consecutively applied (ML 12-lead ECG to standard 12-lead ECG and subsequently to Frank VCG), are used. As both transformations are afflicted with errors, this 2step approach might not be optimal.

In this research we develop a transformation method (ML2VCG) that facilitates the transformation of ML 12-lead ECGs directly to Frank VCGs. We then compare the performance of the ML2VCG method against the alternative 2step approach. Although the focus of this research is ML 12-lead ECG to Frank VCG transformations, for comparison, we also assess the performance of a transformation method (based on the Kors matrix [6]) that is currently considered to be optimal when transforming the standard 12-lead ECG into Frank VCG.

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II. METHODS

A. Data

We base our study on 726 BSPMs referred to hereafter as the study population dataset (*D_StudPop*). Approximately one third of these BSPMs were recorded from normal subjects, one third from subjects with myocardial infarction (MI) and one third from subjects with left ventricular hypertrophy (LVH). Each BSPM was recorded from a total of 120 leads. All leads were recorded with respect to the Wilson central terminal (WCT). Three of the 120 leads were recorded from electrodes placed on the right and left wrist and the left ankle (VR, VL and VF respectively). The remaining 117 leads were recorded from electrodes placed on the thorax (81 anterior and 36 posterior recording sites). A detailed description of the recording procedure and the data is available in [12], [13].

$D\_StudPop$ was partitioned into a training dataset (D_Train) and a test dataset (D_Test). D_Train was assembled by randomly drawing (without replacement) approximately 75% of the BSPMs of normal subjects and pathologic (MI, LVH) subjects. The remaining BSPMs were subsequently used to assemble a test dataset (D_Test). Table I summarizes the composition of $D\_StudPop$, D_Train and D_Test.

TABLE I
COMPOSITION OF DATASETS

Dataset	*# normal*[a]	*# LVH*[b]	*# MI*[c]	*# total*[d]
$D\_StudPop$	232	229	265	726
D_Train	174	172	199	545
D_Test	58	57	66	181

[a] Number of normal subjects in dataset. [b] Number of subjects with LVH in dataset. [c] Number of subjects with MI in dataset. [d] Total number of BSPMs in dataset.

Not all of the electrocardiographic leads required to conduct our study were available as a direct subset of the BSPM. We therefore expanded out data to provide a higher spatial resolution of the surface potentials. We applied the previously reported two-step interpolation procedure [14]. In the first step we applied a Laplacian 3D interpolation method [15] to expand our data to 352 leads that correspond to the nodes in the Dalhousie torso [16]. In the second step we used linear interpolation [17] to obtain any measurements that were required but fell between the 352 nodes. Inter-electrode interpolation on the used BSPMs has been reported to produce interpolation errors that are smaller than the noise level typically found in precordial leads [17].

From the expanded BSPMs all leads required to conduct the study were obtained as follows:

1) Frank VCG leads

Potentials at the A, C, E, F, H, I and M recording locations, suggested by Frank [1], were extracted from the BSPMs. The published [18] formulae (1) to (3) were then applied to yield the voltages V_X, V_Y and V_Z measured in Frank leads X, Y and Z respectively.

$$V_X = 0.61V_A + 0.171V_C - 0.781V_I. \quad (1)$$

$$V_Y = 0.655V_F + 0.345V_M - 1V_H. \quad (2)$$

$$V_Z = 0.1333V_A + 0.736V_M - 0.264V_I - 0.374V_E - 0.231V_C. \quad (3)$$

Where V_I, V_E, V_C, V_A, V_M and V_F are the potentials at the electrodes of the Frank system measured with respect to the WCT.

2) Standard 12-lead ECG

The eight independent channels of the standard 12-lead ECG were extracted from the BSPMs using signals recorded from the wrists and ankles to yield leads I, and II and signals from thoracic BSPM leads to yield V1-V6.

3) The ML 12-lead ECG

In order to obtain the eight independent channels of the Mason-Likar (ML) 12-lead ECG a new set of limb lead potentials were extracted from locations on the thorax that corresponded to the sites proposed by Mason and Likar in [10]. These potentials were used to calculate ML variants of leads I and II hereafter referred to as I_{ML} and II_{ML}. I_{ML} and II_{ML} where then used to calculate a new ML WCT denoted as WCT_{ML}. WCT_{ML} was then subtracted from all other thoracic leads in the BSPM and, from this, precordial leads $V1_{ML}$ to $V6_{ML}$ with the WCT_{ML} as reverence potential were extracted.

B. ML 12-lead ECG to the Frank VCG transformation matrix

In the following, we refer to the Frank VCG of a subject i as $^{i}\boldsymbol{VCG} = [^{i}\boldsymbol{x}, ^{i}\boldsymbol{y}, ^{i}\boldsymbol{z}]$. Where $^{i}\boldsymbol{x}$, $^{i}\boldsymbol{y}$ and $^{i}\boldsymbol{z}$ are $m \times 1$ vectors containing m samples values of the QRST of the Frank leads and $^{i}\boldsymbol{VCG}$ is a $m \times 3$ matrix.

Correspondingly, the ML 12-lead ECG of a subject i is referred to as $^{i}\boldsymbol{ML12L} = [^{i}\boldsymbol{I_{ML}}, ^{i}\boldsymbol{II_{ML}}, ^{i}\boldsymbol{V1_{ML}}, \dots, ^{i}\boldsymbol{V6_{ML}}]$ where $^{i}\boldsymbol{I_{ML}}$,$^{i}\boldsymbol{II_{ML}}$ and $^{i}\boldsymbol{V1_{ML}}$ to $^{i}\boldsymbol{V6_{ML}}$ are $m \times 1$ vectors containing m sample values of the QRST of eight independent leads of the ML 12-lead ECG and $^{i}\boldsymbol{ML12L}$ is a $m \times 8$ matrix.

We developed the 8×3 transformation matrix $\boldsymbol{A_{ML2VCG}}$ that can be used to derive the Frank leads from a ML 12-lead ECG. $\boldsymbol{A_{ML2VCG}}$ was calculated with data from all n subjects in D_Train by multivariate linear regression through:

$$\boldsymbol{A_{ML2VCG}} = \boldsymbol{Y}^T ((\boldsymbol{X}^T \boldsymbol{X})^{-1} \boldsymbol{X}^T)^T, \quad (4)$$

with $\boldsymbol{Y} = [^{i=1}\boldsymbol{VCG}^T, \dots, ^{i=n}\boldsymbol{VCG}^T]^T$, and X= $[^{i=1}\boldsymbol{ML12L}^T, \dots, ^{i=n}\boldsymbol{ML12L}^T]$. Where $(\cdot)^{-1}$ denotes the inverse of a matrix and $(\cdot)^T$ represents the matrix transpose.

C. 12-lead ECG to Frank VCG transformation

This Subsection details the three 12-lead ECG to Frank VCG transformation methods that have been compared in this research.

1) Kors method

This method transforms the standard 12-lead ECG into the Frank VCG. This is performed through utilization of the so called Kors matrix ($\boldsymbol{A_{Kors}}$) [6]. $\boldsymbol{A_{Kors}}$, is 8×3 matrix of constant transformation coefficients. Equation (5) illustrates the estimation of the Frank leads through $\boldsymbol{A_{Kors}}$.

$$^{i}\boldsymbol{eVCG_{Kors}} = {}^{i}\boldsymbol{Dist12L} \quad \boldsymbol{A_{Kors}}. \quad (5)$$

With ${}^{i}\boldsymbol{VCG}_{Kors} = [{}^{i}\hat{\boldsymbol{x}}, {}^{i}\hat{\boldsymbol{y}}, {}^{i}\hat{\boldsymbol{z}}]$ and $\boldsymbol{Dist12L} = [{}^{i}\boldsymbol{I}, {}^{i}\boldsymbol{II}, {}^{i}\boldsymbol{V1}, \dots, {}^{i}\boldsymbol{V6}]$ where i is a subject index, ${}^{i}\hat{\boldsymbol{x}}$, ${}^{i}\hat{\boldsymbol{y}}$, ${}^{i}\hat{\boldsymbol{z}}$ are $m \times 1$ vectors containing the estimates of the Frank leads, ${}^{i}\boldsymbol{I}$, ${}^{i}\boldsymbol{II}$, ${}^{i}\boldsymbol{V1}$ to ${}^{i}\boldsymbol{V6}$ are $m \times 1$ vectors containing sample values of eight independent leads of the standard 12-lead ECG.

2) The 2step method

In this method a ML 12-lead ECG is first transformed to an estimated standard 12-lead ECG using the 8×8 "Leiden" matrix ($\boldsymbol{A}_{Leiden}$) [19]. Subsequently, the estimated standard 12-lead ECG is transformed to yield the Frank VCG using $\boldsymbol{A}_{Kors}$ as described in II.C.1). Equation (6) illustrates the estimation of the Frank leads through the 2step method.

$${}^{i}\boldsymbol{eVCG}_{2step} = {}^{i}\boldsymbol{ML12L}\ \boldsymbol{A}_{Leiden}\ \boldsymbol{A}_{Kors}. \quad (6)$$

With ${}^{i}\boldsymbol{eVCG}_{2step} = [{}^{i}\hat{\boldsymbol{x}}, {}^{i}\hat{\boldsymbol{y}}, {}^{i}\hat{\boldsymbol{z}}]$ and ${}^{i}\boldsymbol{ML12L}$ is as defined in Subsection II.B. Where i is a subject index and ${}^{i}\hat{\boldsymbol{x}}$, ${}^{i}\hat{\boldsymbol{y}}$, ${}^{i}\hat{\boldsymbol{z}}$ are $m \times 1$ vectors containing the estimates of the Frank leads.

3) The ML2VCG method

This method transforms ML 12-lead ECGs into Frank VCGs by utilization of the 8×3 matrix $\boldsymbol{A}_{ML2VCG}$. The development of $\boldsymbol{A}_{ML2VCG}$ has been described in Subsection II.B. Equation (7) illustrates the estimation of the Frank VCG through the ML2VCG method.

$${}^{i}\boldsymbol{eVCG}_{ML2VCG} = {}^{i}\boldsymbol{ML12L}\ \ \boldsymbol{A}_{ML2VCG}. \quad (7)$$

With ${}^{i}\boldsymbol{eVCG}_{ML2VCG} = [{}^{i}\hat{\boldsymbol{x}}, {}^{i}\hat{\boldsymbol{y}}, {}^{i}\hat{\boldsymbol{z}}]$ and ${}^{i}\boldsymbol{ML12L}$ is as defined in Subsection II.B. Where i is a subject index, ${}^{i}\hat{\boldsymbol{x}}$, ${}^{i}\hat{\boldsymbol{y}}$ and ${}^{i}\hat{\boldsymbol{z}}$ are $m \times 1$ vectors containing the estimates of the Frank leads.

D.Estimation error assessment

The estimation errors of the previously described VCG transformation methods $\mathcal{M} = \{\text{Kors}, \text{2step}, \text{ML2VCG}\}$ were assessed by means of the root mean squared error (RMSE) as it is defined in (8).

$${}^{i}_{l}RMSE_{m} = \sqrt{E\left[\left({}^{i}_{l}\boldsymbol{VCG}_{m} - {}^{i}_{l}\boldsymbol{eVCG}_{m}\right)^{2}\right]}. \quad (8)$$

Where $E[\cdot]$ is the expectation operator, ${}^{i}VCG_{l}$ is a vector containing the sample values of an actual Frank lead, ${}^{i}_{l}eVCG_{m}$ is a vector containing the sample values of an estimated Frank lead, i is a subject index, $l \in \mathcal{L}$ with $\mathcal{L} = \{X, Y, Z\}$ is a lead index and $m \in \mathcal{M}$ denotes the estimation method that has been used.

First, we calculated ${}^{i}_{l}RMSE_{m}$ for all the ordered triples $(i, l, m) \in D\_Test \times \mathcal{L} \times \mathcal{M}$. After that, the first quartile, the median and the third quartile of the ${}^{i}_{l}RMSE_{m}$ values were calculated across all $i \in D\_Test$ this was performed separately for each of the ordered pairs $(l, m) \in \mathcal{L} \times \mathcal{M}$.

Secondly, differences between the ${}^{i}_{l}RMSE_{m}$ values of different transformation methods were calculated through:

$${}_{l}\Delta RMSE_{d1,d2} = {}^{i}_{l}RMSE_{d1} - {}^{i}_{l}RMSE_{d2}. \quad (9)$$

This was performed for all ordered triples $(l, (d1, d2), i) \in \mathcal{L} \times \mathcal{D} \times D\_Test$ with $\mathcal{D} = \{(2step, ML2VCG), (Kors, ML2VCG), (2step, Kors)\}$. Where ${}_{l}\Delta RMSE_{d1,d2}$ denotes the RMSE differences of all $i \in D\_Test$ for a Frank lead $l \in \mathcal{L}$ between two transformation methods defined by the ordered pair $(d1, d2) \in \mathcal{D}$.

Subsequently, the first quartile, the median and the third quartile of each ${}_{l}\Delta RMSE_{d1,d2}$ was calculated separately for each of the ordered pairs $(l, (d1, d2)) \in \mathcal{L} \times \mathcal{D}$.

The distribution of the paired RMSE differences of each ${}_{l}\Delta RMSE_{d1,d2}$, defined by an ordered pair $\left(l, (d1, d2)\right) \in \mathcal{L} \times \mathcal{D}$, was found to be skewed (non-symmetric) and not normal (Jarque–Bera test for normality, significance level alpha = 0.05).

A two sided sign test (significance level alpha = 0.05) was used to test whether the median values of each ${}_{l}\Delta RMSE_{d1,d2}$, that can be defined by an ordered pair $\left(l, (d1, d2)\right) \in \mathcal{L} \times \mathcal{D}$ were statistically significantly different from zero. This non-parametric test was chosen as it does not require a symmetric distribution.

III. Results

Below we provide the transformation matrix $\boldsymbol{A}_{\boldsymbol{ML2VCG}}$ that has been obtained through (4).

$$\boldsymbol{A}_{\boldsymbol{ML2VCG}} = \begin{bmatrix} 0.5169 & -0.2406 & -0.0715 \\ -0.0722 & 0.6344 & -0.1962 \\ -0.0753 & 0.1707 & -0.4987 \\ 0.0162 & -0.0833 & -0.0319 \\ 0.0384 & 0.1182 & -0.2362 \\ 0.0545 & 0.0237 & -0.0507 \\ 0.1384 & -0.1649 & -0.2007 \\ 0.4606 & 0.2100 & 0.4122 \end{bmatrix}$$

Table II details the first quartile, the median and the third quartile of the ${}^{i}_{l}RMSE_{m}$ values that were calculated across all $i \in D\_Test$ this was performed separately for each of the ordered pairs $(m, l) \in \mathcal{M} \times \mathcal{L}$.

TABLE II
RMSE VALUES BETWEEN DERIVED FRANK LEADS AND ACTUAL FRANK LEADS CALCULATED ACROSS ALL SUBJECTS OF D_Test

	VCG ESTIMATION METHOD		
Lead	***ML2VCG***	***2step***	***Kors***
	median [1st quartile; 3rd quartile][a] RMSE (μV)		
X	28.3 [18.1; 42.6]	39.2 [25.3; 59.8]	36.0 [24.3; 49.9]
Y	45.6 [30.9; 62.3]	58.0 [41.2; 83.5]	33.6 [24.9; 46.1]
Z	37.4 [28.5; 56.2]	43.4 [30.5; 58.4]	37.9 [25.8; 66.7]

[a] calculated over the QRST between estimated and actual VCG leads

It can be seen in Table II, that the median RMSE values associated with transformation method ML2VCG are lower than those associated with the 2step transformation method.

Table III presents the results of the two sided sign test (significance level alpha = 0.05) for the null hypothesis of zero median RMSE differences for each ${}_{l}\Delta RMSE_{d1,d2}$ that is defined by an ordered pair $\left(l, (d1, d2)\right) \in \mathcal{L} \times \mathcal{D}$.

TABLE III

TWO-SIDED SIGN TEST FOR THE NULL HYPOTHESIS OF ZERO MEDIAN RMSE DIFFERENCE BETWEEN TWO VCG TRANSFORMATION METHODS

Paired RMSE differences[a]	median [1st quartile; 3rd quartile] RMSE[b] (μV)	p^c
${}_X\Delta RMSE_{2step,ML2VCG}$	13.9 [0.0; 23.8]	<0.001
${}_Y\Delta RMSE_{2step,ML2VCG}$	15.1 [-1.0; 33.8]	<0.001
${}_Z\Delta RMSE_{2step,ML2VCG}$	2.6 [-2.6; 10.5]	=0.001
${}_X\Delta RMSE_{Kors,ML2VCG}$	6.3 [-3.9; 18.5]	<0.001
${}_Y\Delta RMSE_{Kors,ML2VCG}$	-7.7 [-27.1; 6.4]	<0.001
${}_Z\Delta RMSE_{Kors,ML2VCG}$	-0.1 [-12.1; 17.8]	=0.88
${}_X\Delta RMSE_{2step,Kors}$	4.0 [-23.8; 10.4]	=0.074
${}_Y\Delta RMSE_{2step,Kors}$	22.2 [-41.9; -8.4]	<0.001
${}_Z\Delta RMSE_{2step,Kors}$	1.7 [-14.0; 10.8]	=0.137

[a] as defined in (8) in Subsection II.D. [b] median [1st quartile, 3rd quartile] are calculated for the corresponding ${}_l\Delta RMSE_{d1,d2}$. [c] p-value returned by two-sided sign test.

As it can be seen in Table III, the median RMSE differences between the 2step and the ML2VCG transformation method are, for each of the Frank leads (${}_X\Delta RMSE_{2step,ML2VCG}$, ${}_Y\Delta RMSE_{2step,ML2VCG}$ and ${}_Z\Delta RMSE_{2step,ML2VCG}$), statistically significantly different from zero.

IV. Discussion

In this paper we reported on the development and performance of a transformation matrix $\boldsymbol{A_{ML2VCG}}$ that allows for the derivation of Frank VCGs form ML 12-lead ECGs.

Our results have shown that $\boldsymbol{A_{ML2VCG}}$ performs more favorably than an alternative 2step approach where ML 12-lead ECGs are first transformed to standard 12 lead ECGs and then transformed to the Frank VCG. Further analysis of the results indicated that both ML2VCG and the 2step method perform worst when deriving Frank lead Y. This is more so the case for the 2step approach.

In contrast, all Frank leads were derived with a similar level of error (median RMSE value of 36.0μV, 33.6 μV and 37.9 μV for Frank leads X, Y and Z respectively) when the Kors transformation method, that utilizes standard 12-lead ECGs, was used. As the ML2VCG and 2step rely on the ML 12-lead ECG we speculate, that the increased RMSE in Frank lead Y in both methods, is caused by the loss of frontal plane information which may be better captured by the standard 12-lead ECG.

V. Conclusion

Our results show that the 2step method may not be optimal when deriving Frank VCGs from ML 12-lead ECGs. The utilization of the herein developed transformation matrix $\boldsymbol{A_{ML2VCG}}$ should thus be considered, when Frank VCGs are to be derived from ML 12-lead ECGs.

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