Derivation of McFee-Parungao Orthogonal Leads from Standard Electrocardiogram

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Abstract. *The study aim was to construct linear transformations for derivation of McFee-Parungao vectorcardiogram (VCG) from 12 standard ECG or Frank VCG and to assess the accuracy of derived electric cardiac signals (ECS) and secondarily derived VCG parameters. A large archive of VCG data recorded in the McFee-Parungao lead system have been accumulated and analyzed in the Cardiology Research Complex (Moscow). To apply this experience to ECSs recorded in the Frank system or standard 12-lead system, linear transformations were constructed basing on sequentially recorded McFee-Parungao VCGs and standard 12-lead ECGs. These transformations provide sufficiently accurate VCGs and secondary vectorcardiographic parameters derived from 12 standard leads.*

Keywords: derived orthogonal ECG, McFee-Parungao lead system, VCG, dipole electrocardiotopography

1. Introduction

For efficient use of clinical experience accumulated with various lead systems, algorithms of ECG transformation are being developed, significantly expanding the armamentarium of diagnostic tools for ECG analysis and integrating disparate facts.

Diagnostic criteria based on orthogonal ECG or VCG findings are widely used in clinical practice. For example, spatial ventricular gradient (SVG) and spatial QRS-T angle are used as indicators of serious pathological changes in the heart. Vectorcardiographic lead systems allow for visual dipolar electrocardiotopographic data presentation, where the time series of instantaneous spatial vectors are converted into time series of areas of activation on a spherical image surface enveloping the heart [1, 2, 3]. Synchronously measured standard ECGs allow for approximate derivation of VCGs and, hence, make benefit from additional possibilities provided by vectorcardiography and decartography.

Various algorithms of standard ECG transformation into the Frank VCG have been proposed [4, 5]. However, some medical centers use another system of corrected orthogonal leads, i.e., the McFee-Parungao system.

Burger et al. [6] compared various systems of orthogonal leads and calculated matrices of linear transformation from one orthogonal system to another, particularly from Frank to McFee-Parungao system. This study was conducted with the original McFee-Parungao lead placement scheme that was subsequently altered.

The aim of the present study was to construct linear transformations for derivation of McFee-Parungao VCG from standard 12-lead ECG or from Frank VCG.

2. Subject and Methods

The Cardiology Research Complex (Moscow) collected a large archive containing standard 12-lead ECGs and McFee-Parungao VCGs. This database contains 50,000 standard ECGs and 10,000 McFee-Parungao VCGs covering a wide range of cardiopathology. The study enrolled 215 patients with paired records of standard ECGs and McFee-Parungao VCGs made sequentially with electrodes replacement from one system to another. These paired records were used to derive approximate linear transformations between ECSs measured in different lead systems.

First of all, we aimed at the construction of linear transformations to derive McFee-Parungao VCGs from standard 12 leads and vice versa. Also of great interest are mutual linear transforms from McFee-Parungao VCGs and true or derived Frank VCGs.

ECSs for the two lead systems were recorded sequentially, therefore, for ECGs to be compared and regression methods to be applied, the measured signals were time-aligned. Functionally relevant time intervals (P, PQ, QRS, ST, and T) obtained via automatic ECG segmentation were aligned by piecewise time interpolation in such a way that the number of points in 12-lead ECG time intervals coincided with the number of points on the corresponding time intervals of VCGs. In some cases, such alignment was impossible due to essential differences in structural, time, and morphological characteristics of ECSs recorded in different lead systems. After exclusion of these cases, the sample contained 195 aligned pairs ($\mathbf{m}_i$, $\mathbf{s}_i$), $i = 1\ldots195$, where $\mathbf{m}_i = [x_i \ y_i \ z_i]$ is McFee-Parungao VCG presented as matrix composed of X, Y, and Z components, and $\mathbf{s}_i = [\mathbf{l}_{\mathrm{I},i} \ \mathbf{l}_{\mathrm{II},i} \ \mathbf{v}_{1,i} \ \mathbf{v}_{2,i} \ \mathbf{v}_{3,i} \ \mathbf{v}_{4,i} \ \mathbf{v}_{5,i} \ \mathbf{v}_{6,i}]^{\mathrm{T}}$ is standard ECG presented as matrix composed of 8 linearly independent components.

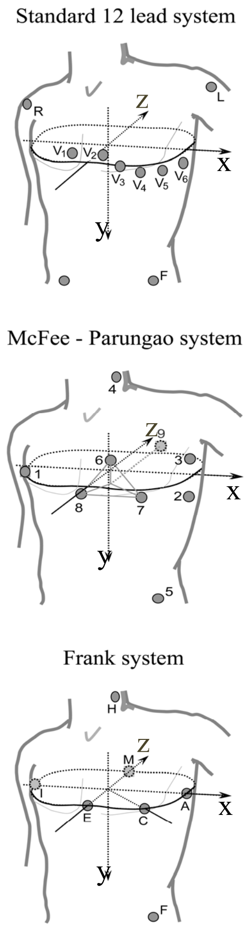

Fig. 1. Lead systems under investigation

The required linear transformation $\hat{\mathbf{T}}$ minimizes the mean squared distance between VCG $\mathbf{m}_i$ and their estimates $\hat{\mathbf{m}}_i = \hat{\mathbf{T}}\mathbf{s}_i$ for standard ECG $\mathbf{s}_i$ in the whole sample:

$$\hat{\mathbf{T}} = \arg\min_{\mathbf{T}} \left(\frac{1}{n} \sum_{i=1}^{n} \left\| \mathbf{m}_i - \mathbf{T}\mathbf{s}_i \right\|^2 \right), \qquad (1)$$

where || . || is Euclidean norm for discrete representation of the 3d vector function.

A different approach is possible, that is, first, we derive the Frank VCG from standard ECG using one of the previously proposed transformations ($\mathbf{T}^{\mathrm{S\to F}}_{\mathrm{Bemmel}}$, $\mathbf{T}^{\mathrm{S\to F}}_{\mathrm{Dower}}$, $\mathbf{T}^{\mathrm{S\to F}}_{\mathrm{Kors}}$ [3, 4]) and then apply the correcting linear transformation of Frank VCG to McFee-Parungao VCG. Approximate transformation $\hat{\mathbf{T}}^{\mathrm{F\to M}}$ is defined using the minimum mean square error estimator (MMSE):

$$\hat{\mathbf{T}}^{\mathrm{F\to M}} = \arg\min_{\mathbf{T}:\,\mathrm{F\to M}} \left(\frac{1}{n} \sum_{i=1}^{n} \left\| \mathbf{m}_i - \mathbf{T}^{\mathrm{F\to M}} \cdot \mathbf{T}^{\mathrm{S\to F}}_{\mathrm{A}} \cdot \mathbf{s}_i \right\|_2^2 \right) \qquad (2)$$

Unbiased estimates of ECS approximation accuracy were computed using Leave One Out cross-validation approach, where VCG approximation $\mathbf{m}_j$ was performed with the use of transformation matrix $\hat{\mathbf{T}}_j$ obtained from MMSE analogous to (1), but on the sample with excluded j^{th} pair of ECS.

3. Results

Using the sample comprised of 195 aligned pairs $(\mathbf{m}_i, \mathbf{s}_i)$ of McFee-Parungao VCG and standard ECG and the least square method, we obtained estimates of linear transformation between $\mathbf{m}_i$ and $\mathbf{s}_i$ for some ECG intervals. Transformation from standard ECG to McFee-Parungao VCG for QT interval is given in the Appendix, and unbiased mean squared approximation errors are listed in Table 1. For the sake of comparison, approximation errors of transformation from standard ECG to Frank VCG with subsequent correcting transformation obtained from (2) are also presented. The correcting transformation from the Frank VCG, derived by Kors matrix, to McFee-Parungao VCG is given in the Appendix.

Accuracy of the secondary derived VCG parameters was assessed using Lin's concordance coefficient [7] (see Table 2). For correct estimation of Lin's concordance coefficients, the sample was randomly divided into training (98 cases) and testing (97 cases) subsamples.

Table 1. RMSE estimates of QRST interval approximation (mean and standard deviation in μV)

Transformation	X Lead	Y Lead	Z Lead	VCG
$\mathbf{T}^{S\to F}_{Dower} * \hat{\mathbf{T}}^{F\to M}_{QT}$	90.1 ± 46.1	59.2 ± 28.5	109.5 ± 51.2	91.2 ± 37.3
$\mathbf{T}^{S\to F}_{Bemmel} * \hat{\mathbf{T}}^{F\to M}_{QT}$	94.0 ± 47.8	50.8 ± 26.2	94.4 ± 50.1	84.9 ± 37.3
$\mathbf{T}^{S\to F}_{Kors} * \hat{\mathbf{T}}^{F\to M}_{QT}$	70.5 ± 37.4	51.4 ± 25.4	91.8 ± 47.8	75.1 ± 33.9
$\hat{\mathbf{T}}_{QT}$ (S→M)	69.3 ± 37.0	49.6 ± 25.9	84.7 ± 45.8	71.4 ± 33.1

Table 2. Lin's concordance coefficient [7] and 95% two-side confidence interval of agreement between true McFee-Parungao VCG parameters and those for derived VCG's (peak spatial QRS-T angle; SVGM, magnitude of spatial ventricular gradient; IRVH, Index of Right Ventricle Hypertrophy[3]; ILVH, Index of Left Ventricle Hypertrophy [2]).

Transformation	QRS-T angle	SVGM	IRVH	ILVH
$\mathbf{T}^{S\to F}_{Dower} * \hat{\mathbf{T}}^{F\to M}_{QT}$	0.89 (0.84, 0.92)	0.93 (0.90, 0.95)	0.93 (0.89, 0.95)	0.86 (0.81, 0.90)
$\mathbf{T}^{S\to F}_{Bemmel} * \hat{\mathbf{T}}^{F\to M}_{QT}$	0.86 (0.80, 0.90)	0.92 (0.88, 0.94)	0.95 (0.92, 0.96)	0.80 (0.73, 0.86)
$\mathbf{T}^{S\to F}_{Kors} * \hat{\mathbf{T}}^{F\to M}_{QT}$	0.94 (0.92, 0.96)	0.96 (0.94, 0.97)	0.97 (0.95, 0.98)	0.93 (0.90, 0.95)
$\hat{\mathbf{T}}_{QT}$ (S→M)	0.95 (0.93, 0.97)	0.96 (0.95, 0.97)	0.96 (0.95, 0.98)	0.92 (0.89, 0.95)

4. Discussion

All systems of vectorcardiographic leads are designed to evaluate the electric dipole moment of the heart, but the results of measurements are not equivalent due to different placement of leads, and correcting transformations allow for significant reduction of distance between VCG as spatial curves.

We have demonstrated that standard ECG to McFee-Parungao VCG transformations provide sufficiently accurate approximation of the components, spatial VCG loops, and secondarily derived vectorcardiographic parameters. Our study, however, had some limitations, including asynchronous data recording and lack of stratification by gender, age, and diagnosis, which will be the aim of our future investigations. Moreover, it is important to analyze special transformations for other cardiocycle phases, depending on specific cardiopathology.

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Appendix

The linear transformation matrix to derive McFee-Parungao VCG from standard ECG for QT interval:

$$\hat{\mathbf{T}}_{\mathrm{QT}}^{\mathrm{S}\to\mathrm{M}} = \begin{bmatrix} 0.555 & -0.265 & -0.137 & 0.054 & 0.118 & -0.098 & 0.498 & 0.411 \\ -0.275 & 1.213 & 0.155 & -0.060 & 0.032 & 0.009 & -0.082 & 0.088 \\ 0.140 & -0.251 & -0.324 & -0.157 & -0.452 & -0.319 & -0.112 & 0.292 \end{bmatrix};$$

$$[\mathbf{x}\ \mathbf{y}\ \mathbf{z}]^{\mathrm{T}} = \hat{\mathbf{T}}_{\mathrm{QT}}^{\mathrm{S}\to\mathrm{M}} \cdot [\mathbf{l}_{\mathrm{I}}\ \ \mathbf{l}_{\mathrm{II}}\ \mathbf{v}_1\ \mathbf{v}_2\ \mathbf{v}_3\ \mathbf{v}_4\ \mathbf{v}_5\ \mathbf{v}_6]^{\mathbf{T}}.$$

The correcting transformation matrix from the derived Frank VCG $[\mathbf{x}_{\mathrm{F}}\ \mathbf{y}_{\mathrm{F}}\ \mathbf{z}_{\mathrm{F}}]^{\mathbf{T}}$ to McFee-Parungao VCG for QT interval:

$$\hat{\mathbf{T}}_{\mathrm{QT}}^{\mathrm{F}\to\mathrm{M}} = \begin{bmatrix} 1.346 & -0.093 & -0.482 \\ -0.291 & 1.300 & 0.205 \\ -0.084 & -0.174 & 1.662 \end{bmatrix}; \quad [\mathbf{x}\ \mathbf{y}\ \mathbf{z}]^{\mathrm{T}} = \hat{\mathbf{T}}_{\mathrm{QT}}^{\mathrm{F}\to\mathrm{M}} \cdot [\mathbf{x}_{\mathrm{F}}\ \mathbf{y}_{\mathrm{F}}\ \mathbf{z}_{\mathrm{F}}]^{\mathbf{T}}.$$

$$[\mathbf{x}_{\mathrm{F}}\ \mathbf{y}_{\mathrm{F}}\ \mathbf{z}_{\mathrm{F}}] = \mathbf{T}_{\mathrm{Kors}}^{\mathrm{S}\to\mathrm{F}} \cdot [\mathbf{l}_{\mathrm{I}}\ \ \mathbf{l}_{\mathrm{II}}\ \mathbf{v}_1\ \mathbf{v}_2\ \mathbf{v}_3\ \mathbf{v}_4\ \mathbf{v}_5\ \mathbf{v}_6].$$

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