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Methods for derivation of orthogonal leads from 12-lead electrocardiogram: A review

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ABSTRACT

Vectorcardiography (VCG), as an alternative to standard 12-lead electrocardiography (ECG), represents the electrical activity of the heart. Previous studies on VCG document that VCG criteria for the diagnosis of, for example, myocardial infarction (MI), ventricular hypertrophy and ischemic diseases, are superior to the corresponding 12-lead ECG criteria. Its use in clinical practice is not common because it requires the placement of additional electrodes. However, VCG leads can be derived from standard ECG by using mathematical transformations.

This paper reviews the published works on transformation techniques for derivation VCG from 12-lead ECG, their historical evolution and their importance in today's clinical practice. Different kinds of criteria for evaluation accuracy of transformations are briefly described and the accuracy of individual techniques discussed.

1. Introduction

The history of vectorcardiography dates back to 1920, when Mann introduced the concept of representing the cardiac vector using a loop constructed manually from three Einthoven's leads. He also mentioned the possibility of three-dimensional depiction of cardiac cycle [1]. For direct measurement of orthogonal leads, Schellong et al. presented the first non-corrected orthogonal system in 1937 [2]; their work was followed by other authors who defined new lead systems [3–6]. These lead systems differ by placing the electrodes on the torso and are represented by signals that are mutually orthogonal. However, they do not take account of the different geometry of the torso or inner inhomogeneity of tissues. The first corrected lead system was derived by Frank based on a mathematical model [7]. Today, this lead system is called Frank's lead system and is the most common VCG system. Other lead systems, including that of McFee and Parungao [8], SVEC III [9] and hybrid lead system [26], were also published and in use for a short period.

Although VCG is considered as a diagnostic method in many fields with higher sensitivity compared to conventional ECG, it was gradually replaced by 12-lead ECG in common clinical practice [10,11]. However, today VCG still predominates in specific cases [12]. Current research in this field is focused on the development of new computational algorithms using directly measured or derived VCG in the field of MI detection [13,14,31,32,33] or ventricular hypertrophy [15,16,86], where VCG achieves significantly higher sensitivity than 12-lead ECG.

VCG based features are usually used for automatic classification by using machine learning algorithms. Many VCG based features were designed. For example authors in [14] use 27 different spatial features computed from directly measured and derived VCG, which are used for automatic classification presence/absence of MI scar. Designed Support Vector Machine (SVM) model achieves sensitivity 82.36% and specificity 77.36%. Another robust classification algorithm presented authors in [17]. For detection MI scar, they used complex model based on SVM and using ECG and derived VCG features. This model achieves sensitivity 76% and specificity 87.5%. Even higher accuracy of detection MI published authors in [18]. By using regression tree based model (CART) and VCG based features is published sensitivity 97.28% and specificity 95%. Authors in [19] introduced Self Organizing Map based model using VCG features for localisation of the MI scar. For separating MIs and Healthy controls this model achieves sensitivity 94.9% and specificity 95.7%. For classification of individual localisations this model achieves sensitivity and specificity around 90% depending on the localisation of the MI.

An additional prognostic information in acute phase of MI provides continuous VCG, which can be used in ambulance or already during transportation of patients. Some published works describe importance of VCG during acute phase of the MI [20–23].

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The greatest potential offered by computational VCG is also in the diagnostics of ischemic heart disease [29,30]. Authors in [24,25] published set of VCG based features for monitoring ischemic patients. For detection of acute ischemia achieve sensitivity 99.5% and specificity 99.4%. For standard Holter monitoring of patients with unstable angina pectoris compared authors in [26] ECG and derived VCG approach. The authors claim that dynamic VCG monitoring seems to be more efficient and more sensitive than conventional Holter monitoring. For localisation and estimation of ischemia size used authors in [27] derived VCG. The exercise test is used in work published in [28]. Authors measured VCG and computed 21 different features for classification by using artificial neural network (ANN).

Some of the studies document that a combination of both 12-lead ECG and VCG significantly improves sensitivity and specificity in ischemia detection [11,25]. For this purpose it is necessary to directly measure VCG and 12-lead ECG. This is impractical especially during exercise tests. Some studies therefore use only derived VCG.

Derived VCG is suitable for estimating some meaningful features which represent high diagnostic information such as QRS-T angle or TCRT. These features can be estimated from derived VCG with sufficient accuracy [35–39].

Numerous transformation techniques have been published. In this review, we would like to highlight the methodology and evolution of individual methods.

2. History and development of transformation methods

The first considerations of possible transformations between individual lead systems were described in a paper by Burger et al. [40]. Kornreich et al. described that 12-lead ECG and Frank's leads were very similar in terms of their information contents, and their mutual transformation was thus possible [41].

The first attempts at transforming lead systems were based on VCG transformation to 12-lead ECG by Dower et al. [42,43]. Later, Wolf et al. derived transformation matrices for the bidirectional transformation of conventional 12-lead ECG to VCG and vice versa [44]. Other transformation methods focused predominantly on transforming 12-lead ECG to VCG. So-called quasi-orthogonal leads were initially used in clinical practice but their accuracy was not sufficient. Therefore, Levkov derived 4 transformation matrices and in addition, one simplified transformation matrix, which he implemented as a hardware solution as an electrical circuit [45]. Uijen et al. published their own transformation matrix [46], and Edenbrandt et al. designed a transformation matrix based on a mathematical model of the torso, which is still used today and is known as the inverse Dower transformation (IDT) [47]. The second most commonly used transformation matrix today was derived by Kors using the regression analysis method [48].

New transformation matrices were developed with the rising importance of derived VCG, which take account of interpatient variability, particularly for paediatric patients, as published in the paper by Edenbrandt et al. [49]. Furthermore, transformation matrices focusing on specific patient groups were designed, divided e.g., according to pathologies [50].

Most transformation matrices were derived only for the QRS complex. The authors of transformation methods consider the difference between transformations derived for various segments as insignificant. Despite that, Guillem et al. focused on the possibilities of optimizing the transformations also for other VCG segments; these authors designed a modified transformation matrix optimized for the P wave, whereby achieving an improvement in the transformation of this ECG segment [51].

The derivation of orthogonal leads may serve to obtain indications that provide a significant diagnostic value. For example, QRS-T or the planar angle can be mentioned as two of the frequently used and explored indications. Cortez et al., and Man et al. demonstrated that the QRS-T angle derived from the Kors transformation was not significantly different from the angle obtained from directly measured VCG [37,38]. Transformations play an important role in this respect because unlike direct measurement of VCG leads, they can be used in common clinical practice. Currently, other methods can be used to derive VCG indications; these methods do not provide direct transformation to Frank's leads, but produce three non-correlated orthogonal leads. For example, Acar et al. used an optimized SVD transformation to derive orthogonal leads [52], and the thus derived leads were used by Karsikas et al. and Hasan et al. to obtain the QRS-T angle and other indications of diagnostic importance [35,39].

Individualized transformations have recently been developed in the field of lead system transformations, based on minimizing the error between the measured and reconstructed ECG [53,54].

3. Evaluation criteria

Although it is very important, there is no standardization of how to evaluate the accuracy of derived VCG. Published papers and comparative studies evaluate accuracy by different criteria. For the objective comparison of new methods it is important to use the right criteria. In this section we provide the most common criteria and evaluation techniques used in individual studies.

The comparison of morphological characteristics of the measured VCG and derived DVCG signal, or semantic evaluation based on diagnosis interpretation and from the measured and derived signal, can be used to evaluate the quality of the transformation.

Various parameters are evaluated by individual authors when comparing the morphological characteristics.

The mean absolute percentage deviation (MAPD) was used in [48]:

$$\mathrm{MAPD} = \frac{1}{n}\sum\left|\frac{\mathrm{VCG}-\mathrm{DVCG}}{\mathrm{VCG}}\right| \qquad (1)$$

The root mean squared error (RMSE) for QRS complex, P wave or for the entire cardiac revolution was used in [51,55–58]:

$$\mathrm{RMSE} = \sqrt{\frac{1}{n}\sum_{\mathrm{QRS},P}(\mathrm{VCG}-\mathrm{DVCG})^2}. \qquad (2)$$

Mean squared error (MSE) was used in [54]:

$$\mathrm{MSE} = \frac{1}{n}\sum(\mathrm{VCG}-\mathrm{DVCG})^2. \qquad (3)$$

Normalized Euclidean distance used in [45] is a relative measure for the mean squared error between signals:

$$D = \sqrt{\frac{\sum(\mathrm{VCG}-\mathrm{DVCG})^2}{\sum\mathrm{VCG}^2}}. \qquad (4)$$

Pearson's correlation coefficient r, used in [45,51,55,58], gives the rate of similarity between two signals and is independent of differences in their amplitudes $r \in [-1;\quad 1]$; for identical signals $r = 1$. Although a frequently used parameter, a high value of the correlation coefficient by itself does not provide any information about the quality of the transformation, as discussed in [55], and therefore it is often used only as a supplementary parameter:

$$r = \frac{\sum(\mathrm{VCG}\times\mathrm{DVCG})}{\sqrt{\sum\mathrm{VCG}^2\sum\mathrm{DVCG}^2}} \qquad (5)$$