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Lead transformations and the dipole approximation: Practical applications

Jan A. Kors*

Department of Medical Informatics, Erasmus University Medical Center, Rotterdam, the Netherlands

Abstract The transformation of recorded electrocardiographic leads (source leads) into leads that are wanted but were not recorded (target leads) has many practical applications. In general, two transformation methods are put to use, a purely statistical one and a model-based one. They are briefly reviewed and compared. Lead transformations were first used in the early nineteen-sixties to transform the component leads of one vectorcardiographic lead system into those of another. Since then, the use of lead transformations has proliferated and they are currently applied for a variety of purposes. Lead transformations can be grouped according to the source and target leads that are involved. A few applications of lead transformations from the different groups are presented, with a focus on the practicality of the application. The validity and value of the dipole approximation in relation to lead transformations is discussed.

Keywords: Lead reconstruction; Dipole model; Transformation matrix; Vectorcardiography

Introduction

The transformation of recorded electrocardiographic leads (source leads) into leads that are wanted but were not recorded (target leads) has many practical applications. Lead transformations can be carried out as a merely statistical procedure, without any underlying physical model. In an alternative approach a physical model is involved, namely the "dipole approximation". In this review, I will briefly discuss the dipole approximation and its implication for lead transformations. The two main transformation methods mentioned will be presented and compared. I will then review a few applications of lead transformations, grouped according to the source and target leads that are involved, with a focus on the practicality of the applications. The validity and value of the dipole approximation in relation to lead transformations will be discussed.

Dipole approximation

Slightly more than a century ago Willem Einthoven undertook to model the heart's electrical activity [1]. His now classical equilateral triangle represented the body in the frontal plane, the sides being the leads I, II and III, while an arrow through the center (the heart) depicted the "direction and manifest magnitude" of all the potential variations in the heart at a given moment. The voltage in a lead at that moment was given by the projection of the arrow on the lead. With this model he introduced the concept of the heart vector, without using the term, to model the heart's electrical activity. This heart vector, as it is conceived now, describes the behavior of a single ("equivalent"), time-varying dipole (a current source and sink of equal strength, in very close proximity) with fixed location ("stationary"), that Einthoven thought in the center of the equilateral triangle. The dipole model is a first-order approximation of a very complex reality. According to Einthoven's projection rule, lead voltages are proportional to the projection of the three-dimensional heart vector $\boldsymbol{H}(t)$ on the hypothetical line connecting the two electrodes of a lead k (the lead axis):

$$V_k(t) = |\boldsymbol{H}(t)| \cos \alpha,$$

where $|\boldsymbol{H}(t)|$ is the heart-vector magnitude and α the angle between the heart vector and the lead axis.

This model provided an important educational framework for clinical electrocardiography, but has several obvious limitations: man is not an equilateral triangle and the heart is not in the center. Moreover, the body is not electrically homogeneous, as the model assumes.

The Dutch physicist Herman Burger tackled these issues in a series of lucid articles in the late forties of the previous century by introducing the concepts of lead vector and image space [2]. A lead vector defines the relationship between the heart vector and the voltage in a lead, and has not only a direction but, unlike the lead axis, also a magnitude. Each

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* Department of Medical Informatics, Erasmus University Medical Center, P.O. Box 2040, 3000 CA, Rotterdam, the Netherlands.

E-mail address: j.kors@erasmusmc.nl

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point on the body surface corresponds with a lead vector; the tips of the lead vectors form a so-called image surface. Lead voltages now result as the scalar product of the heart vector $\boldsymbol{H}$ and the lead vector $\boldsymbol{L_k}$ corresponding with a given lead k:

$$V_k(t) = \boldsymbol{H}(t) \cdot \boldsymbol{L}_k = |\boldsymbol{H}(t)|\,|\boldsymbol{L}_k| \cos\ \alpha,$$

with α the angle between the heart vector and the lead vector.

It should be noted that a lead vector and its corresponding lead axis are different entities: a lead vector only exists in image space, to be distinguished from anatomical space, which is the realm of a lead axis (although both spaces have a one-to-one relationship) [2].

Since lead vectors have three components, any lead vector $\boldsymbol{L}_k$ can be constructed as a linear combination of three independent given lead vectors $\boldsymbol{L}_1$, $\boldsymbol{L}_2$, $\boldsymbol{L}_3$[3]:

$$\boldsymbol{L}_k = k_1\boldsymbol{L}_1 + k_2\boldsymbol{L}_2 + k_3\boldsymbol{L}_3$$

so that

$$\begin{aligned} V_k(t) &= \boldsymbol{H}(t) \cdot \boldsymbol{L}_k = \boldsymbol{H}(t) \cdot (k_1\boldsymbol{L}_1 + k_2\boldsymbol{L}_2 + k_3\boldsymbol{L}_3) \\ &= k_1 V_1(t) + k_2 V_2(t) + k_3 V_3(t) \end{aligned}$$

This signifies that the voltage of any desired lead can be constructed as a linear combination of three other lead voltages, in as far as the dipole approximation holds.

Lead transformation

In general, a lead transformation is the construction of some target lead **y** by taking a linear combination of a set of source leads $\boldsymbol{x}_j$ ($j = 1..n$):

$$\boldsymbol{y} = c_1\boldsymbol{x}_1 + c_2\boldsymbol{x}_2 + \ldots + c_n\boldsymbol{x}_n$$

A lead **x** is an array of signal samples that vary in time, but the coefficients $\mathbf{c}_i$ are constant. For multiple target leads,

$$\boldsymbol{y}_i = c_{i1}\boldsymbol{x}_1 + c_{i2}\boldsymbol{x}_2 + \ldots + c_{in}\boldsymbol{x}_n, i = 1..m$$

This can conveniently be described in matrix notation:

$$Y = C\ X$$

with $\boldsymbol{C}$ the coefficient or reconstruction matrix of size $m \times n$. To determine $\boldsymbol{C}$, there are two main approaches, model-based transformation and statistical transformation.

Model-based transformation

The model-based approach to lead transformation rests on the dipole approximation, with the concepts of lead vector and image space as its corollaries. It then follows, as shown above, that an arbitrary lead can be constructed as a linear combination of three other, independent leads [3]. Given their lead vectors, the coefficients can be determined for any lead transformation. The lead vectors can be derived from a physical or mathematical torso model.

Model-based transformation was first applied by Gordon Dower to reconstruct the standard 12-lead electrocardiogram (ECG) from the vectorcardiogram (VCG) [4]. He used the lead vectors that had been derived by Frank from a homogeneous torso model [5]. The resulting matrix of reconstruction coefficients was called the “Dower matrix”. Remarkably, Dower claimed that the interpretations of derived 12-lead ECGs by an automatic ECG computer program were more accurate than the interpretations of the original ECGs [6]. A possible explanation might be that electrode positioning for recording the VCGs was done more carefully than for recording routine ECGs, with the result that reconstructed ECGs had on average a closer resemblance to the “true” ECG than the directly recorded leads.

Statistical transformation

The statistical approach to derive the transformation coefficients requires a training set of data that contains both the source leads and the target leads. With the use of standard multivariate regression, the estimated target leads are fitted to the original target leads, yielding the reconstruction coefficients. The first to apply this statistical approach, in 1962, were Burger and coworkers [7], who searched for transformations between the VCG lead systems of Burger, Frank, McFee, and Schmitt. The work was done in the precomputer area. Although “a simple electric calculator was utilized” [7], the calculations still took months of work. Today, these computations can be done instantly using a statistical software package. The authors concluded that any well-founded VCG system can be satisfactorily adapted to any other system desired.

Comparison of methods

Several studies have compared the performance of model-based and statistical lead transformations. In my research group, we evaluated both approaches for reconstructing the Frank VCG from the standard 12-lead ECG, using the inverse of the Dower matrix [8] and a statistically derived matrix (called the “Kors matrix” in later studies) [9]. When comparing the diagnostic accuracy of the reconstructed and original VCGs, the two approaches turned out to be comparable [9]. Several other groups compared the reconstruction performance of the inverse Dower and Kors matrices at the level of the measured variables, in particular the spatial QRS-T angle as derived from the 12-lead ECG, and showed that the Kors matrix performed better than the inverse Dower matrix [10–12]. This may not come as a surprise: the Dower matrix was based on a single, simplified torso model, whereas the Kors matrix was derived from simultaneously recorded ECGs and VCGs of a group of individuals, which is likely to produce a more accurate transformation on average. That a higher accuracy at the variable level did not translate into higher diagnostic accuracy may be explained by the fact that diagnostic VCG interpretation is typically “pattern-based”, i.e., cardiologists base their judgment on combinations of variables that produce relatively stable patterns. Individual variables may then change to some extent without essentially affecting the interpretation.