Derivation of Orthogonal Leads from the 12-Lead ECG. Accuracy of a Single Transform for the Derivation of Atrial and Ventricular Waves

MS Guillem[1,3], AV Sahakian[1], S Swiryn[1,2]

[1]Northwestern University, Evanston, IL, USA
[2]HeartCare Midwest, Peoria, IL, USA
[3]Universidad Politécnica de Valencia, Valencia, Spain

Abstract

Vectorcardiograms are not usually recorded in clinical practice and must be derived from the conventional 12-lead ECG, for example by making use of Dower's transform. However, its accuracy for the derivation of the P wave is questionable. We tested the accuracy of Dower's transform on the P-wave and compared with a P-wave optimized transform in a database of 123 simultaneous recordings of ECGs and VCGs. This new transform achieved a lower error when we compared derived vs. true measured P-waves (12.2 ± 7.96 μVRMS) than Dower's transform (14.4 ± 9.5 μVRMS) and higher correlation values (Rx=0.93 ± 0.12, Ry= 0.90 ± 0.27, Rz=0.91 ± 0.18 vs. Dower's: Rx=0.88 ± 0.15, Ry=0.91 ± 0.26 , Rz=0.85 ± 0.23). We concluded that derivation of P-waves and QRS complexes VCGs were optimized by the use of different transform matrices for each wave in this database.

1. Introduction

The vectorcardiogram (VCG) is a useful tool in the study of atrial arrhythmias [1-3]. However, the VCG is not usually recorded in clinical practice, and orthogonal leads need to be derived from the conventional 12 leads.

Previous studies on the atrial VCG have made use of the so-called Dower's inverse transform for the derivation of the VCG from the 12-lead ECG [4]. The accuracy of this derivation has been previously tested for the QRS complex and compared to other derivation methods such as the Least Squares Value (LSV) optimization [5]. Although results from LSV optimization were shown to be superior to Dower's, it is generally accepted that the degree of accuracy of Dower's transform is high enough to be considered as a satisfactory method of derivation of the QRS complex.

As it was initially pointed out by Dower [4], the accuracy of his transform for the derivation of the P wave is compromised by the fact that the spatial location of the origin of the simplified atrial electrical vector should differ from the origin of the ventricular vector. This difference in location of the electrical origin should affect the coefficients of the transform matrix in some extent, resulting in a lack of accuracy when using a QRS-optimized transform for the derivation of atrial waves.

This degree of inaccuracy of derived versus true recorded P-waves was studied by Carlson et al. [6] for a database of 41 subjects. These authors concluded that P waves derived by Dower's transform accurately reproduced P wave morphology by measuring correlations and other morphological parameters. However, they didn't consider the possibility of an optimized derivation for atrial electrical activity.

In this study, we tested the accuracy of Dower's transform for the derivation of P-waves and compared its performance with a new transform optimized for the derivation of the P-wave by a LSV optimization method. Additionally, we compared the relative contribution of inter-patient variability with the variability introduced by the fact that the spatial location of the atria and the ventricles are different in relation to the recording leads.

2. Methods

2.1. Study population

We used the PTB Diagnostic ECG database available on PhysioNet's webpage. This database consists of 15 simultaneously recorded signals: the conventional 12-lead ECG and 3 Frank orthogonal leads. Signals were acquired with 16 bit resolution over a range of ± 16.384 mV and stored with a sampling frequency of 1KHz.

The PTB database contains recordings from 294 subjects with different diagnoses. However, for the purposes of our study, patients with diagnosis of atrial arrhythmias or AV block and patients with implanted pacemakers were excluded. Those diagnoses were established prior to the study phase based on annotations in the database (when available) and by visual inspection of ECG recordings by a cardiologist (SS) blinded to the results of the study. After exclusion, 247 recordings constituted our ECG database.

2.2. Data conditioning and preprocessing

ECG signals were downloaded from PhysionNet, and read and preprocessed using algorithms implemented by our group under Matlab 6.5. (The Mathworks Inc, Natick, USA).

Baseline wander was reduced by subtracting an estimated baseline obtained by low-pass filtering of each ECG lead with a Chebyshev type II filter with cutoff frequency equal to 1 Hz.

Power line interference was evaluated in each lead by the Welch spectrum estimator, using a Hamming window of 8000 points, an overlap of 4000 points and FFT with 16000 points. Leads presenting a power level in the 49-50 Hz band greater than 0.3% of the total power of the lead were further processed in order to eliminate this 50 Hz contribution.

A representative PQRST cycle was calculated for each lead using a template-matching algorithm. First, QRS peaks were detected using a modified version of Pan and Tompkin's algorithm [6]. A window starting 350 ms before each QRS peak detected in lead 1 (QRSp1) and 400 ms after QRSp1 was selected to perform the correlation and subsequent averaging after positive matching. This window size had to be increased in 12 patients with a long PR interval. The correlation coefficient established for positive matching in the algorithm was set to 0.97.

After averaging, templates were low-pass filtered using a Butterworth filter with a cutoff frequency of 50Hz.

2.3. Wave detection

A step prior to wave analysis is the definition of QRS and P wave onset and offset points. Onset and offset points were automatically detected for each lead. among local minima of a function that estimates the radius of curvature, as described in [7]. After automatic wave detection, fiducial points were displayed, resulting in an incorrect detection of either P_{onset} or P_{offset} in 46 patients and incorrect QRS_{onset} or QRS_{offset} in 37 patients, for which fiducial points were edited manually.

2.4. Optimized transforms for P-wave and QRS complex derivation

Half of the patients in the database (every other patient among those not previously excluded, N= 124) were selected as a study set for the computation of optimal matrices for the QRS and the P-wave.

By applying the least squares method over the time interval included between the P_{onset} and the P_{offset}, an individual transform matrix optimized for the recovery of the P wave (PLSVi) was obtained for each patient in the study set. In the same fashion, an individual transform matrix was obtained for the QRS complex (QLSVi) by solving the coefficients of the transformation by the least squares method on the QRS interval.

The optimimal transform matrix for the recovery of the P wave (PLSV) was calculated as the average of all PLSVis. The optimal transform for the recovery of the QRS complex (QLSV) was computed as the mean of all QLSVis. PLSV, QLSV and Dower's matrices are shown in the Appendix.

2.5. Comparison of derived vs. true measured waves

Patients not included in the study set constituted the test set (N=123). For every patient in the test set, derived cardiac cycles of the XYZ leads obtained by the three studied transforms were compared with true recorded XYZ leads.

In order to compare the accuracy of the recovery, we measured for each lead (X, Y and Z), derivation method (Dower, QLSV and PLSV) and wave (P and QRS), the correlation coefficients (Rx, Ry, Rz) between derived and true measured waves for each lead and the mean squared error. Also, we computed the mean squared error of the derived VCG loops.

3. Results

Figure 1 shows true versus derived ECG waveforms for one patient using the three transform matrices described.

Average results for the test set can be observed in Figures 2-5 and Table 1. The PLSV transform globally performed better than Dower and QLSV for the derivation of the P wave (see Figure 2), with a mean loop error of 12.2 ± 7.96 µVRMS (vs. Dower: 14.4 ± 9.5 µVRMS and QLSV: 16.0 ± 7.38 µVRMS). Correlation values (true vs derived P-waves) for leads X and Y were also higher for PLSV than for both Dower's and QLSV, and similar for lead Y. Root mean squared errors showed a similar behaviour. (See Figure 3 and Table 1)

In the derivation of the QRS complex from the 12-lead ECG, QLSV globally performed better than both PLSV and Dower (see Figure 4), with a mean loop error of 84.8 ± 43.8 µVRMS (vs. Dower: 121.3 ± 65.8 µVRMS and PLSV: 91.1 ± 43.8 µVRMS for PLSV). Correlation values (true vs. derived QRS complexes) and root mean squared errors per lead, also showed a better performance of QLSV transform for the derivation of the QRS complex than Dower's and PLSV transforms.

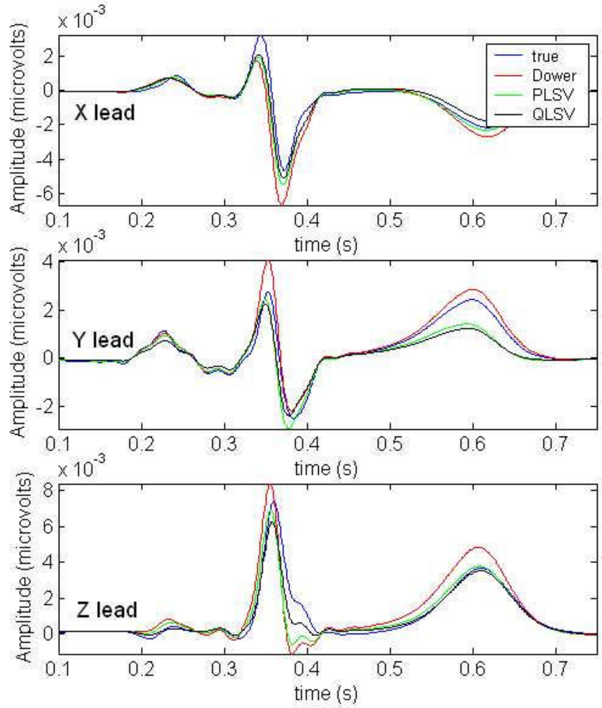

Figure1: True versus derived ECGs with Dower, PLSV and QLSV transforms of patient 2.

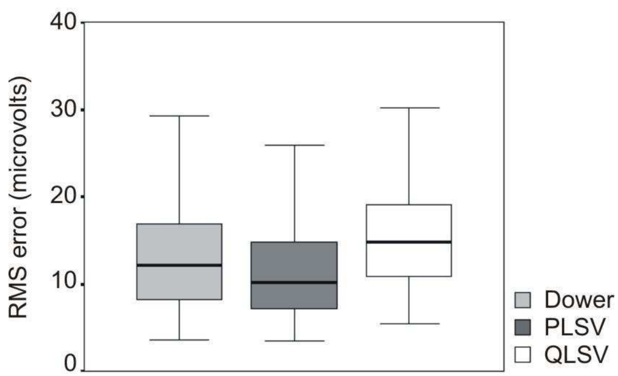

Figure 2: Derived versus true measured P-loops using Dower, PLSV and QLSV transforms

4. Discussion and conclusions

We have shown that it is possible to construct a matrix based on LSV optimization for the P wave that improves on Dower's transform. This P-optimized transform also performs better for the derivation of the QRS complex than Dower's transform for this database.

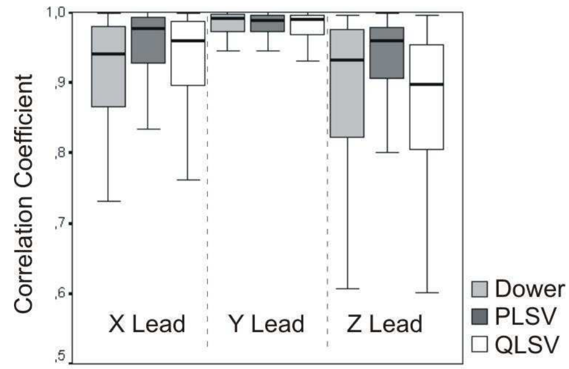

Figure 3: Derived vs. true measured P-waves. Correlation coefficients for Dower, PLSV and QLSV transforms

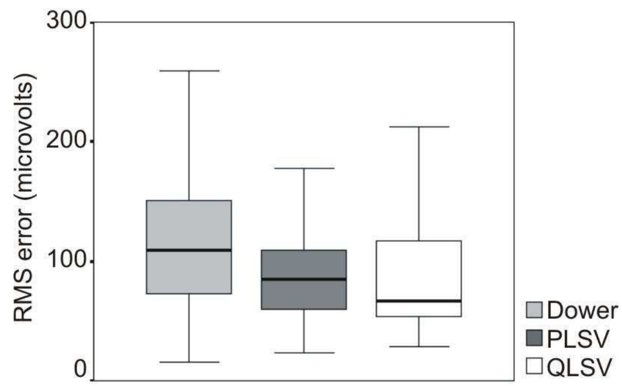

Figure 4: Derived versus true measured QRS-loops. Root mean squared errors for Dower, PLSV and QLSV transforms.

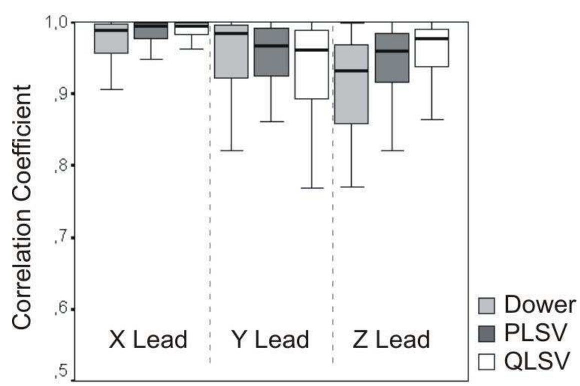

Figure 5: Derived vs. true measured QRS complexes. Correlation coefficients for Dower, PLSV and QLSV transforms.

Therefore, raising the question of whether it was the optimization for the P-wave or only the specific database that resulted in improvement over the Dower's transform, we have shown that, for this same database, the P-wave optimized transform performed better for the P-wave while the QRS-optimized transform performed better for the QRS complex.

We concluded that derivation of orthogonal leads for both the P-wave and the QRS complex can be improved by using separate transform matrices, and consequently, the difference in the spatial position of electrical activation seems to have a significant influence on the optimal derivation method.

5. Appendix

$[V1\ V2\ V3\ V4\ V5\ V6\ I\ II]^T = D\ [X\ Y\ Z]^T$

$[X\ Y\ Z]^T = D^{-1}\ [V1\ V2\ V3\ V4\ V5\ V6\ I\ II]^T$

Dower's inverse transform:

$$D^{-1} = \begin{pmatrix} -0.172 & -0.073 & 0.122 & 0.231 & 0.239 & 0.193 & 0.156 & -0.009 \\ 0.057 & -0.019 & -0.106 & -0.022 & 0.040 & 0.048 & -0.227 & 0.886 \\ -0.228 & -0.310 & -0.245 & -0.063 & 0.054 & 0.108 & 0.021 & 0.102 \end{pmatrix}$$

PLSV inverse transform:

$$D^{-1} = \begin{pmatrix} -0.266 & 0.027 & 0.065 & 0.131 & 0.203 & 0.220 & 0.370 & -0.154 \\ 0.088 & -0.088 & 0.003 & 0.042 & 0.047 & 0.067 & -0.131 & 0.717 \\ -0.319 & -0.198 & -0.167 & -0.099 & -0.009 & 0.060 & 0.184 & -0.114 \end{pmatrix}$$

QLSV inverse transform:

$$D^{-1} = \begin{pmatrix} -0.147 & -0.058 & 0.037 & 0.139 & 0.232 & 0.226 & 0.199 & -0.018 \\ 0.023 & -0.085 & -0.003 & 0.033 & 0.060 & 0.104 & -0.146 & 0.503 \\ -0.184 & -0.163 & -0.190 & -0.119 & -0.023 & 0.043 & 0.085 & -0.130 \end{pmatrix}$$

Acknowledgements

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Address of Correspondence:
Steven Swiryn, M.D.
HeartCare Midwest, 5405 N. Knoxville Ave.
Peoria, IL 61614
Email: s-swiryn@northwestern.edu

		Dower		PLSV		QLSV	
		R	RMSerror (μVRMS)	R	RMSerror (μVRMS)	R	RMSerror (μVRMS)
P	X	0.88 ± 0.15	12.50 ± 7.07	0.93 ± 0.12	9.37 ± 5.63	0.91 ± 0.14	11.29 ± 6.49
	Y	0.91 ± 0.26	13.83 ± 16.77	0.90 ± 0.27	15.32 ± 15.38	0.91 ± 0.26	21.85 ± 14.70
	Z	0.85 ± 0.23	16.70 ± 13.6	0.91 ± 0.18	11.86 ± 8.61	0.84 ± 0.20	14.43 ± 8.22
QRS	X	0.93 ± 0.11	96.39 ± 77.88	0.93 ± 0.11	77.23 ± 65.95	0.97 ± 0.06	70.36 ± 61.23
	Y	0.91 ± 0.21	70.37 ± 68.17	0.88 ± 0.27	72.86 ± 53.19	0.86 ± 0.28	81.50 ± 56.22
	Z	0.84 ± 0.29	194.42 ± 118.87	0.88 ± 0.26	121.26 ± 73.19	0.92 ± 0.19	100.7 ± 67.68

Table 1: Comparison of true vs. derived P-waves and QRS complexes using Dower's, PLSV and QLSV transforms.