Two Approaches for Inverse Localization from Clinical ECG Data Using Heart Surface Potentials

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Abstract

The standard approach for the inverse problem of electrocardiography computes the extracellular potentials on the closed epicardial or endo-epicardial surface. In the case of premature ventricular contractions (PVC) localization, the point with the earliest activation time (AT) is considered the PVC origin. In this study, we studied a different approach, assuming that at the beginning of the PVC (thus also EGM) signal, only a small area of the ventricles is activated.

The inverse localization of the PVC origin using a homogeneous and inhomogeneous torso and two methods (standard and point) for epicardial potentials was performed on the measured body surface potential maps of ten patients who underwent a successful radiofrequency ablation procedure. The true PVC location and the patient-specific torso geometry from the CT scan were known. The localization error (LE) between both methods' estimated and true PVC origins was evaluated and compared.

For the homogeneous torso and the standard method, the mean LE was 37.2±15.9 mm and 37.6±17.8 mm for epicardial and endo-epicardial surfaces, respectively. The corresponding values for the point method were 25.6±10.5 mm and 31.2±16.5 mm. For the inhomogeneous torso and the standard method, the mean LE was 38.6±18.9 mm and 31.3±11.1 mm. The mean LE improved to 27.6±7.2 mm and 29.5±9.6 mm, respectively, for the point method.

A simplified assumption of a single-point equivalent electrical generator can improve the LE for identifying local events on the heart.

1. Introduction

Heart surface potential distribution is one of the forms of equivalent electrical generator searched in the inverse solution of electrocardiography. It is also used to assess the position of the starting an undesired electrical activity called premature ventricular contraction (PVC). This technique has been applied to simulated [1], [2] and clinical data [3].

A different approach to finding the PVC origin represents the method using a geometrical constraint based on the apriori knowledge that the PVC starts in a single area of the ventricles. Therefore, a single-point equivalent electrical generator is assumed, usually as a single dipole [4].

Recently, the potential-based and single dipole methods were applied to body surface potential maps (BSPMs) measured on the patients with PVC and compared [5]. The present study assumed a single-point potential as the equivalent heart generator instead of a single dipole. The localization error (LE) between the estimated PVC origin and its true position was evaluated and compared for potential-based and single-point potential methods.

2. Materials and Methods

2.1. Patients

In cooperation with the National Institute for Cardiovascular Diseases in Bratislava, ten spontaneous premature ventricular contraction (PVC) patients indicated for radiofrequency ablation (RFA) underwent a body surface potential mapping procedure. There were eight men and two women, mean age of 49 years (17-72). The successful RFA was performed in RVOT for six patients, in the left ventricle for two patients, and for two patients in the right ventricle or septum, respectively. All patients subscribed the written consent with the procedure.

2.2. Measurements

ECG was measured by 128 electrodes placed on the patient's torso in 16 vertical strips with 8 electrodes. The signal was recorded with the sampling frequency of 1 kHz using the ProCardio8 measuring system developed in the Department of Biomeasurements [6], Institute of Measurement Science, Bratislava. The recording duration

varied from 5 to 20 minutes for each patient. The measured ECG signal was first filtered by a high-pass filter designed by Blackmann-Harris [7]. Then, the ECG cycles were identified according to their R-peaks and clustered to normal and PVC morphology. The averaged signal from the PVC cluster was computed and used as an input for an inverse solution. After the BSPM procedure, the patient's chest with the electrodes still stuck on it was scanned by a CT. The scan was later used to create the 3D patient's specific geometrical model.

2.3. Inverse solutions

The usual potential-based inverse solution is finding the potential distribution on the whole epicardium, or endo-epicardium in each time step of the PVC signal.

The potentials on the torso can be computed from epi or endo-epicardial surface potentials as:

$$y(t) = Ax(t) + v(t),\ t = 1,2,3,\dots T \qquad (1)$$

where x(k) ∈ N×1 are the heart surface potentials and y(k)∈M×1 are the corresponding BSPMs at time instant k; A∈M×N is the forward transfer matrix, and v(k) represents a noise in the measurements. The transfer matrix A between the potentials on the heart surface and the torso was computed using a boundary element method.

From the known measured BSPMs the unknown heart potentials are then computed using the equation (1):

$$x(t) = \arg\min_{x(t)}\{\|Ax(t) - y(t)\| + \lambda_t^2 \|Lx(t)\|\} \qquad (2)$$

where λ_t is a regularization parameter that controls the tradeoff between the residual norm $\|Ax(t) - y(t)\|$ and the constraint norm $\|Lx(t)\|$, and L is a regularization matrix based on the chosen constraint. In this study, L is chosen to be the identity matrix (zero-order Tikhonov regularization method).

From the computed heart potential, the activation time (AT) is derived from the potential course in each point of the heart surface by the spatiotemporal method (spTemp). The point with the minimal AT value is considered the PVC's origin.

The method that assumes a geometrical constraint of the heart sources works with the same equation (1). However, it works with different presumptions instead of regarding the whole PVC time interval in BSPMs and reconstructing the potential distribution on the whole heart surface. First, PVC starts in a single point/area of the ventricles. Second, during the initial QRS time interval, the activated area around the PVC origin is small. Third, a single-point equivalent electrical generator can represent such a small area. This approach has been used in the localization of PVC origin by an inverse solution using a single dipole.

This study's geometrical constraint is analogical to the single dipole approach. The point with a heart potential leading to the torso potentials with the best agreement with the measured BSPM was chosen for each time step. The agreement between the measured and computed BSPM on the torso was evaluated by a relative residual error (RRE):

$$RRE(t) = \frac{\|measBSPM(t) - compBSPM(t)\|}{\|BSPM(t)\|}$$

The point with minimal RRE value from all heart surface positions and all time steps from the early QRS time interval up to 30 ms was considered the estimated PVC origin. This method will be referred to as a point potential method (pointPot).

The true position of the PVC origin was estimated manually on the endo-epicardial ventricular model by a physician using the results of the successful RFA procedure. The Euclidean distance (localization error LE) between the true PVC origin and the estimated one by the inverse method was used for quantitative evaluation of the method. The results obtained by spTemp and pointPot methods were compared.

3. Results

For each patient, two types of the heart surface were modeled. The epicardial surface had a closed convex shape surrounding the ventricular cavities. The endo-epicardial surface was a closed concave shape representing only the ventricular myocardium with ventricular cavities out of it.

Regarding the torso model, the results were computed either for a homogeneous torso or for the inhomogeneous torso, where a different conductivity of some inner organs like lungs and ventricles was considered. The conductivity of the lungs was assumed to be four times lower, and of the blood in cavities three times higher than the conductivity of the torso (Figure 1).

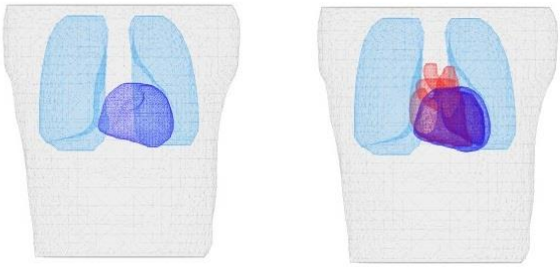

Figure 1. Heart-torso setup for inhomogeneous torso case. Left – for epicardial surface; right - for endo-epicardial surface.

In the inhomogeneous case and the epicardium surface, the presence of the lungs was assumed between the heart and torso surface. In the inhomogeneous case and endo-epicardium surface, the ventricular cavities, together with

the lungs, were included in the computation of the transfer matrix.

The results for both methods and four considered torso setups are summarized in Table 1 and Table 2.

Table 1. LE in [mm] of the inverse methods for the homogeneous torso.

	epicardial		endo-epicardial	
pat	**spTemp**	**pointPot**	**spTemp**	**pointPot**
P1	27.9	**24.9**	29.2	68.3
P2	58.2	**29.0**	55.2	**30.6**
P3	20.4	25.0	23.0	24.2
P4	20	29.8	12.1	28.0
P5	59.2	**29.1**	49.2	**26.2**
P6	16.5	38.9	23.3	34.0
P7	42.1	**17.4**	53.7	**38.9**
P8	36.2	**17.4**	56.5	**18.6**
P9	51.9	**39.7**	19.1	38.6
P10	39.9	**4.7**	55.1	**4.4**

Table 2. LE in [mm] of the inverse methods for the inhomogeneous torso.

	epicardial		endo-epicardial	
inh	**spTemp**	**pointPot**	**spTemp**	**pointPot**
P1	27.7	**27.9**	29.2	**21.8**
P2	51.6	**25.1**	40.6	**33.6**
P3	20.8	22.0	19.1	22.8
P4	20	29.8	28.6	30.1
P5	40.7	**32.6**	39.6	**22.3**
P6	16.5	33.0	23.4	34.0
P7	42	**21.5**	49.8	**32.1**
P8	78.5	**30.7**	20.5	29.5
P9	51.9	**39.7**	19.2	51.5
P10	36.4	**14.1**	42.9	**17.4**

The results when the LE for the pointPot method was smaller or comparable with the spTemp method are highlighted in bold font. For the epicardial heart surface, more than half of the pointPot method's results improved compared to the standard method, and for the endo-epicardial surface, the LE was better for 5 out of 10 cases. The improvement of the LE for pointPot method is also visible in the graphs in Figure 2 and Figure 3.

The mean LE decreased from 37.2±15.9 mm to 25.6±10.5 mm for homogeneous torso and epicardial surface. If the endo-epicardial surface was considered in the homogeneous torso, the mean LE decreased from 37.6±17.8 mm to 31.2±16.5 mm. In the inhomogeneous torso and epicardial surface, the mean LE decreased from 38.6±18.9 mm to 27.6±7.2 mm, and for the endo-epicardial surface, the mean LE decreased from 31.3±11.1 mm to 27.0±8.1 mm.

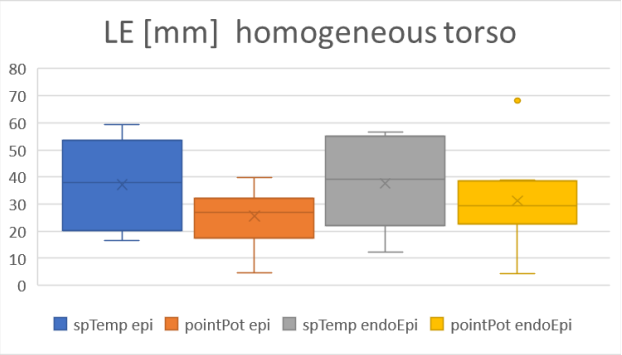

Figure 2. Box plots of LE of the PVC estimation for ten patients for a homogeneous torso model assuming closed epicardial or endo-epicardial surface of the ventricles using standard spTemp and alternative pointPot inverse method.

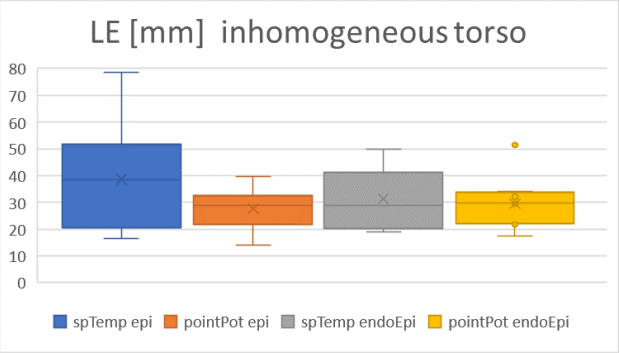

Figure 3. Box plots of LE of the PVC estimation for ten patients for an inhomogeneous torso model assuming closed epicardial or endo-epicardial surface of the ventricles using standard spTemp and alternative pointPot inverse method.

4. Discussion and Conclusion

This study compared two approaches for assessing the PVC origin using the heart surface potential in an inverse solution of electrocardiography. Both used the presumption that the PVC starts in a single ventricle area. The first was based on finding the earliest AT from the inversely computed time flow of the heart surface potential, and the second was based on finding a single point potential best approximating the measured BSPM within the starting PVC time interval up to 30 ms. Such an assumption was used in our previous studies [8] using a single dipole as an equivalent heart generator. The geometrical constraint in inverse localization of the PVC origin was also investigated for various equivalent electrical heart generators on the simulated data in [9]. It was shown there that the models of a single point equivalent heart generator led to similar LE of the inverse results.

According to the results of this study, the LE of the second method outperformed the method based on the AT. The mean LE was smaller for all four heart-torso setups.

However, for endo-epicardial surface, one outlier appeared in homogeneous and also in inhomogeneous cases. Similar findings were obtained on these data comparing the spTemp method with the inverse method using a single dipole published in [5]. The reason can lie in too many steps needed in spTemp method and assessment of many parameters: order of the Tikhonov regularization, λ parameter, smoothening of the computed time flow of the heart potential, finding the AT. On the other hand, while the pointPot method asses only the origin of PVC activation, spTemp method gives more complex information about the potential distribution on the heart surface.

However, the geometrical constraint of the ventricular activation related to the starting time interval of the ECG signal appears to be very helpful a priori information for the PVC origin assessment.

Acknowledgments

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