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Geometrical constraint of sources in noninvasive localization of premature ventricular contractions

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ABSTRACT

The inverse problem of electrocardiography for localization of a premature ventricular contraction (PVC) origin was solved and compared for three types of the equivalent cardiac electrical generator: transmembrane voltages, epicardial potentials, and dipoles. Instead of regularization methods usually used for the ill-posed inverse problems an assumption of a single point source representative of the heart generator was applied to the solution as a geometrical constraint.

Body surface potential maps were simulated from eight modeled origins of the PVC in the heart model. Then the maps were corrupted by additional Gaussian noise with the signal-to-noise ratio (SNR) from 20 to 10 dB and used as the input of the inverse solution. The inverse solution was computed from the first 30 ms of the ventricular depolarization. It was assumed that during this period only a small part of the heart volume is activated thus it can be represented by a single point electrical source.

Generally, the localization error was more dependent on the PVC origin position than on the type of the used heart generator. The most stable localization error between the inversely found results and the true PVC origin was not larger than 20 mm for PVC origins located in the left ventricular wall and on the right ventricular anterior side. For such cases, the localization was robust to the noise up to SNR of 10 dB for all studied types of the cardiac generator. For SNR 10 dB the results became unstable mainly for the PVC origins in the septum and posterior right ventricle for the dipolar heart generator and for epicardial potentials defined on the pericardium when the range of the localization error increased up to 50 mm. When the results for different electrical heart generators were considered altogether, the mean radius of the cloud of results did not exceed 20 mm and the localization error of the cloud center was smaller than that obtained for a particular type of the cardiac generator.

Combination of results from different models of a single point cardiac electrical generator can provide better information for the preliminary noninvasive localization of PVC than the use of one type of the generator.

Introduction

Preliminary noninvasive estimate of the origin of premature ventricular contraction (PVC) could help to shorten the invasive ablation procedure. Solutions to this problem have been the aim of various research groups. The problem leads to the inverse problem of electrocardiography [1], which is, in general, an ill-posed problem, i.e. the solution is not unique. Therefore, additional constraints should be applied for obtaining a meaningful solution. The regularization methods used for obtaining the unique solution differ in dependence on the type of the used model of the equivalent electrical heart generator. Usually, such generator is modeled in the form of epicardial potentials, transmembrane voltages [2] or an equivalent double layer [3]. For these generators, the activation of the whole heart model is reconstructed. The regularization methods are based on expected physical and physiological properties of the solution [4]. Tikhonov regularization methods impose the smoothness of the potential distribution over the heart [5], the spatiotemporal approach used in [6] includes also the time development of the heart activation. A different approach represents the inverse solution using a single dipole shown in [7]. Here, it is assumed that at the beginning of the premature ventricular activation only a small area of the heart volume is activated that can be approximated by a single dipole. Instead of the distribution of the heart sources over the whole heart volume, only the position of the point dipolar source is searched that represents the small activated area. This approach can be interpreted as a geometrical constraint of the inverse solution.

Recently, the internet-based archive EDGAR (Experimental Data and Geometric Analysis Repository) was created [8] in order to share the data between the research groups interested in noninvasive electrocardiographic imaging. Together with the body surface potential maps (BSPMs) the geometrical models of the measured subjects are provided as well as lead field matrices for various equivalent electrical heart

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sources. The data provided in the EDGAR database allow for the application of various methods on the same data as it was realized also in [9–11].

The aim of this study was to apply the methodology of finding the position of the single point elementary equivalent electrical generator (single point source) representing the activated area to different models of the heart generator described by different transfer matrices. The inverse solution was computed for simulated ectopic beats with their origins in eight different positions in the heart and for three types of equivalent heart generators. The robustness of the method was studied by adding the Gaussian noise with the signal-to-noise ratio (SNR) 10, 15 and 20 dB. The suitability of various types of heart generator for such inverse solution was tested as well as the dependence of the quality of the results on the type of the generator, on the position of the PVC origin, and on the added noise level.

Materials and methods

Data

Simulated BSPMs used as input data for inverse solutions have been contributed to EDGAR database by the Institute of Biomedical Engineering, Karlsruhe Institute of Technology (KIT), Germany and the First Department of Medicine (Cardiology), University Medical Centre Mannheim, Germany [8]. The simulations were performed on the realistic heart and torso geometry obtained from MRI images from a patient with premature ventricular contractions (PVCs) [12]. Eight different BSPMs were computed by starting the simulation in eight different positions of pacing points imitating the origins of PVCs (Fig. 1 left): septum center (SEPCEN), left ventricle lateral (LVLAT), left ventricular apex (LVAPX), left ventricle anterior (LVANT), right ventricle posterior (RVPOS), right ventricle anterior (RVANT), left ventricle lateral epicardial (LVLEP) and left ventricle lateral endocardial (LVLEN) position. The activation propagation was simulated using a cellular automaton principle [13]. The BSPMs were computed using a tetrahedral mesh in the thorax model by finite element method. ECG signals were simulated in 163 positions on the torso model representing the positions of the measuring electrodes (Fig. 1 right).

Together with simulated BSPMs two types of the equivalent electrical heart generator – transmembrane voltages (TMV) and epicardial potentials (EP) were derived. The transfer matrices that project the single point sources described by the equivalent electrical heart generators to signals in 163 electrodes positions on the torso were also provided. For each type of the equivalent heart generator the transfer matrix with two sets of positions of generators was provided in the EDGAR database:

- Transmembrane voltages (TMV_vol) on tetrahedral mesh inside the heart volume (in 2223 points);
- Transmembrane voltages (TMV_enep) on the endo-and-epicardial surface mesh (in 502 endo-epi points). Epicardial potentials (EP_enep) at the nodes of the endo-and-epicardial surface (in 502 endo-epi points);
- Epicardial potentials (EP_peri) at the nodes of the pericardial surface (in 502 peri-points; different from endo-epi points).

As the third type of equivalent electrical heart generator was assumed a multiple dipole. Again, two transfer matrices for two sets of dipoles positions within the myocardium were computed for such generator using the boundary element method [14] and available homogeneous torso model:

- Dipoles (DIP_enep) on the endo and epicardial surface mesh (in 502 endo-epi points).
- Dipoles (DIP_vol) on tetrahedral mesh inside the heart volume (in 2223 points).

Inverse solutions

The simulated BSPMs were provided by the EDGAR database. In this study the input data for the inverse solution representing the initial phase of the PVC activation were the integral BSPMs computed by the formula:

$$\mathrm{BSPM} = \int_{t\_start}^{t\_end} \mathrm{BSPM}(t), \tag{1}$$

where BSPM(t) is the map in time step t of the simulation. The first 30 ms were assumed as the initial phase of the premature ventricular activation.

The integral BSPMs were computed for all time intervals from the beginning of the PVC *t_start* up to 30 ms, so that *t_end* varied from 1 to 30, what was altogether 30 maps. The simulated ECG signals started with very small noisy values with a constant mean value close to zero, therefore the first time instant with the relevant signal *t_start* was defined as the time step when the signal-to-noise ratio of the simulated BSPM was larger than 3. From that time instant 30 input integral BSPMs were computed. The root-mean-square (RMS) signals of the maps for the first 20 time steps are depicted in Fig. 2, where the time instants with the first relevant signal are marked by the asterisk.

To study the robustness of the inverse method to the perturbations in the measured signals three levels of Gaussian noise with the signal-to-noise ratio (SNR) 20, 15 and 10 dB were applied to original signal similar as in [15]. In each time step the root-mean-square (RMS) signal of the BSPM was computed and then the Gaussian noise with the zero

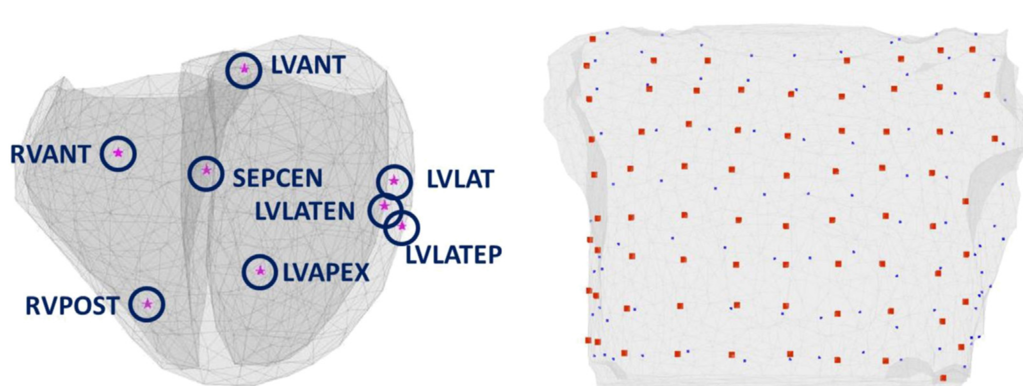

Fig. 1. Left: Heart model with eight positions of modeled PVC origins. Right: Torso model with 163 positions of measuring electrodes (large dots indicate frontal and small dots posterior positions of electrodes).