Inverse Localization of the Latest-Activated Areas in the Ventricles from Body Surface Potential Maps

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Abstract

In this simulation study an identification of the latest depolarized site of the ventricles from integral body surface potential maps (BSPMs) using an inverse solution in terms of one or two dipoles was tested on models of a normal heart.

The input data for the inverse solution were integral BSPMs computed from the interval of the last 5 or 10 ms of depolarization. It was assumed that such integral BSPMs represents a small activated area so that they can be approximated by a single dipole. The BSPMs were produced by two types of normal heart-torso models. The very last activated points on the surfaces of the ventricular models were known.

If there was a single latest activated area, the localization error was between 0.5 and 3.5 cm. If there were two distinct latest activated areas, the localization error was between 1.7 and 2.9 cm.

The proposed method could be used for the preliminary noninvasive assessment of the latest-activated ventricular areas, which are of great interest for cardiac resynchronization therapy.

1. Introduction

Heart failure is one of the most common cardiovascular diseases. It is usually associated with some type of contractile dyssynchrony which yields an impaired cardiac systolic function [1]. During the last decades cardiac resynchronization therapy (CRT) has become a standard nonpharmacologic approach for improvement of the heart function. The cardiac dyssynchrony is caused by delayed activation sequence between atria and ventricles and/or within the ventricles. With CRT, selected parts of the myocardium are paced artificially to reduce the delays. Knowledge of the latest depolarized site of the ventricles can have direct clinical applicability for positioning of the pacing lead in the CRT.

The inverse solution to one dipole for identification of local ventricular lesions with changed repolarization was suggested by Tysler et al [2]. Later this approach was extended to identification of two distinct local lesions [3]. The method seems to be suitable for finding local events in the myocardium. In this simulation study the method was applied for the assessment of the latest activated areas in the ventricles using heart models with normal depolarization sequence.

2. Methods and Materials

The basic assumption for the suggested method is that during the very last period of depolarization only small areas of the ventricles are activated and that the electrical activity in each of them can be represented by a single dipole. In normal activation such areas are either on the lateral sides at the base of both ventricles, or at the lateral base of one of them [4].

A normal heart depolarization was simulated on two types of the heart model: The first type was a dipole layer model in the simulation tool ECGSIM [5], the second was Propag-4, a high-resolution reaction-diffusion model of the human heart and torso developed at Université de Montréal [6], [7]. In each heart model the position of the latest-activated areas was known.

First, for each heart model simulated BSPMs were computed at 65 points on the surface of a corresponding inhomogeneous torso model according to the Amsterdam 62-lead system plus extremity electrodes [8]. The realistically shaped torso model was considered to be a piecewise homogeneous volume conductor surrounded by air. Ventricular cavities with electrical conductivity three times higher than the average torso conductivity as well as lung lobes with electrical conductivity four times lower than the average torso conductivity were defined in the torso models.

The very last depolarization of the ventricles is reflected in the final part of the QRS complex in the ECG signals. The integral of the signals during this period represents the activation of the last-depolarized areas. It can be assumed that at the very end of the depolarization these areas are so small that their electrical activity can be

approximated by one dipole. Therefore the integral BSPMs of the last 5 ms or the last 10 ms interval of the QRS complex (interval before the J point) were used as the input for the inverse localization of the latest-activated areas.

Using the boundary element method [9] the potential generated by a fixed dipole on the torso surface model can be expressed by:

$$p = \mathbf{A}d \tag{1}$$

where p is a vector of potential values on the torso surface, $\mathbf{A}$ is a transfer matrix representing the relation between the specific dipole and the potentials assuming the torso as an inhomogeneous volume conductor and d is the vector of three components (moments) of the dipolar generator.

In the inverse solution the components of the dipole are searched that best represent the measured potentials on the torso. If the position of the dipole is unknown it yields a nonlinear problem [10].

For a fixed position of the dipole the dipole moments can be computed from (1) as:

$$D = \mathbf{A}^{-1}p \tag{2}$$

where $\mathbf{A}^{-1}$ is a pseudoinverse of the transfer matrix $\mathbf{A}$.

Because the input data were the integral BSPMs the integral (summed) dipole moments were obtained.

Possible positions of the searched dipole were defined in a 5 mm grid within the whole volume of the ventricular myocardium model. Then for each position the inverse solution was computed using equation (2). The integral dipole moments were computed that best represented the input ECG data. The quality of the inverse solution for each dipole position was rated by the value of the relative residual rms difference RMSDIF between the input integral BSPM and the map computed from the inversely obtained integral dipole in a particular position within the myocardium:

$$RMSDIF = \frac{\sqrt{\sum_i (p_i - r_i)^2}}{\sqrt{\sum_i p_i^2}} \tag{3}$$

where p_i is the value of the input map at i-th electrode position on the torso and r_i is the value computed from the inversely estimated dipole at the same electrode position.

The position of the integral dipole with the smallest value of RMSDIF was assumed to be the location of the searched activated area.

If two simultaneously activated areas were assumed, a modification of equations (1) and (2) was used. The transfer matrix was computed for all combinations of two dipole positions and parameters of the dipoles (6 in total) were computed in each case. The best pair of positions was found according to the criterion of minimal value of RMSDIF, similarly as for one dipole.

The geometry of each heart model was described by a triangulated surface. The time of depolarization was known for each vertex. True position of the latest-activated area was defined as the gravity centre of the vertices depolarized during the last 5 ms of the QRS complex. The localization error of the inverse solution was evaluated as the distance between the true position of the latest-activated area and the position of the inversely found dipole. In the case of two simultaneously latest-activated areas the true position of each of them was calculated. Then the localization error was evaluated for each of them as the distance between the true position and the closer dipole from the inversely found pair of dipoles.

3. Results

Using the ECGSIM simulation software the integral BSPMs from the last 5 ms and 10 ms intervals of depolarization were computed for three heart models: the normal_male, the normal_male2 and the normal_young_male. The individual heart and torso geometry was available for all cases. In all three cases a single latest-activated area was situated at the base of the right ventricle. The example for the normal_male case can be seen in Figure 1.

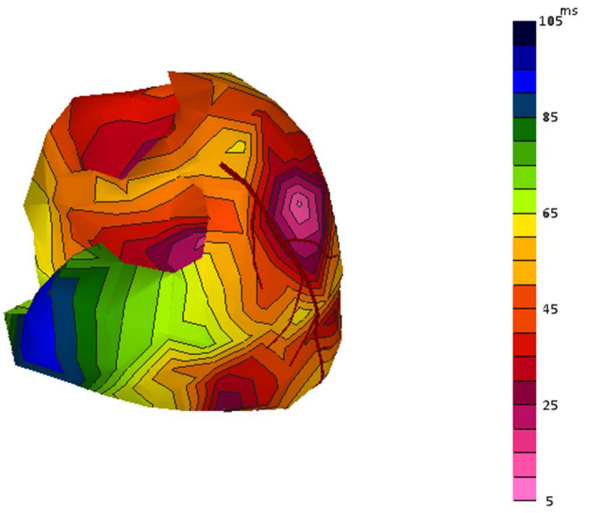

Figure 1. The depolarization times on the surface of the normal_male heart model from the ECGSIM software tool [5]. The latest depolarized area is blue.

The localization error of the inverse solution from BSPMs from the last 5 ms and 10 ms intervals of depolarization was evaluated to the true position for each model and is summarized in Table 1.

Table 1.

Localization error [cm]		
	Last 5 ms	Last 10ms
Normal male	1.4	2.0
Normal male2	2.2	3.5
Normal young male	0.9	0.5

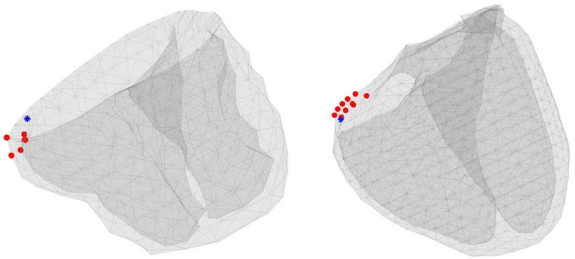

Figure 2. Examples of inversely localized latest-activated areas for the normal_male2 (left) and the normal_young_male (right) models from ECGSIM. Red dots indicate the points on the model surface activated during last 5 ms of depolarization, blue asterisks indicate the inversely found locations of these areas from integral BSPMs computed from the same time interval.

In the Propag-4 model two simultaneously latest-activated areas were present; one was on the lateral side of the right ventricle, the second was on the lateral side of the left ventricle. Again, the integral BSPMs were computed for the last 5 ms and 10 ms interval of depolarization. The localization errors for the last 5 ms were 2.7 cm and 1.7 cm, respectively (mean 2.2 cm) and the localization errors for the last 10 ms were 2.9 cm and 1.8 cm resp., (mean 2.4 cm).

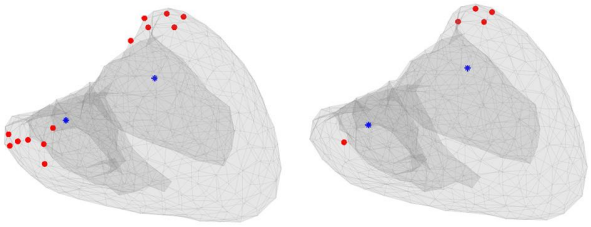

Figure 3. The results for the model Propag-4, where two latest activated areas were present. Left: the inverse solution from the last 10 ms interval of depolarization, Right: the inverse solution from the last 5 ms interval. Red dots indicate the latest activated points on the surface of the model during the corresponding time interval, blue asterisks indicate the localization of these areas by the inverse solution to two dipoles.

4. Discussion

The suggested inverse method allowed a localization of the latest-activated areas in the ventricles using simulated normal ECG data.

The localization error was up to 3.5 cm for a single activated area and up to 2.9 cm if two areas were present. The localization error could be influenced by the density of the grid of predefined positions for the searched dipoles (a 5 mm grid was used in this study) as well as by the precision of the description of triangulated ventricular surfaces. The normal_male model was described by 257 vertices, the normal_male2 model and the normal_young_male model by 576 or 1500 vertices, respectively. We can assume that in the last, refined model the description of depolarization times was more precise so that the latest-activated area was better defined.

All results for the single latest-activated areas in ECGSIM models were correctly localized at the base of the lateral side of the right ventricle. This part of the heart is the area that is best reflected in BSPM, because it is very close to the chest surface. In failing heart with LBBB behavior/markers the latest-activated area is expected on the lateral side of the left ventricle, which is not well reflected on the chest. Therefore in future work we plan to test the suggested method on the failing heart model, too.

In real data there can be a problem to estimate the J point (as the point at the termination of the QRS complex) and the associated very last time interval of depolarization in the ECG signal. The accuracy of the J point estimation can be limited also by additional diagnoses of patients with heart failure disease. In this study two time intervals (5 ms and 10 ms) were tested and the results were similar. The integral BSPM computed from the interval longer than 10 ms before the J point could characterize an area that is too large for the inverse assessment by one dipole. The integral BSPM computed from an interval shorter than 5 ms before the J point may consist of very small ECG values and is therefore sensitive to noise in real situation.

If we assume the usual sampling frequency of the ECG signal of at least 500 Hz the integration of the ECG signal improves the signal to noise ratio, because the summation maintains the useful signal and suppresses the added random noise with zero mean value.

A requirement for obtaining reliable results is the knowledge of the individual heart and torso geometry from MRI or CT scan.

A modified inverse method with two dipoles was used for the model with two latest-activated areas because of the a priori knowledge about such a situation. If the number of activated areas is not known a priori it can be assessed e.g. from the morphology of BSPM as it was suggested by Teplan et al. [11]. On the other hand, in failing heart with LBBB behavior/markers a single latest-

activated area can be expected.

5. Conclusion

A method for localization of the latest-activated ventricular areas was suggested and tested on simulated data in 62-lead BSPMs from four normal heart models. The localization error obtained from integral BSPMs from the last 5 ms of depolarization were up to 2.2 cm for a single latest depolarized area and up to 2.7 cm for two such areas. The localization error from integral BSPMs from the last 10 ms was up to 3.5 cm and up to 2.9 cm, respectively.

The method could be useful for preliminary noninvasive assessment of the latest-activated ventricular areas and for suggesting the pacing site for CRT.

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