Usability Evaluation of Body Surface Potential Mapping in Resolution of Ventricular Ectopic Pacemaker Separation and Lead Density

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Abstract—**Based on our constructed whole heart electrophysiological model, we investigated the usability of body surface potential mapping（BSPM) in two aspects. One was to find the resolution of separating ventricular ectopic pacemakers. Another was to determine the influence of lead density on BSPM. We selected 24 ventricular ectopic pacemakers in all, 18 in a horizontal ventricular section within 12.5 mm×16 mm and 6 a vertical line with the length of 7.5 mm. The two selected ventricular ectopic pacemakers were considered to be separable if the correlation coefficient of their QRS integral map of BSPMs was less than a threshold. For each ectopic pacemaker in the same region, correlation coefficients were calculated between itself and each of the other ones, and the resolution were obtained based on these correlation coefficients. Lead density was reduced by evenly deleting the columns or rows in the lead array under the condition that the remaining leads covering the same area as the original ones. Using the method of statistical inverse deduction, we estimated the values of the whole leads based on the potentials on the leads with lower density. And the correlation coefficients between the estimated potentials and the simulated ones were calculated. Results showed that the resolution for horizontal ventricular section was (2.80±0.62) mm. And the resolution for the vertical line was (3.25±0.39) mm. When the lead numbers were changed from the original 252 to 132, 72 and 36, the correlation coefficients of the estimated potentials and the simulated ones were 0.9865±0.0.0503， 0.9457±0.0596 and 0.8521±0.0790, respectively. At the same time, resolution of separating ventricular ectopic pacemakers decreased with the reduction of lead density. In addition to proving the validation of our constructed model, the usability tests provide delighting information about the influence of lead density on the performance of BSPM.**

Keywords—**body surface potential mapping（BSPM), ventricular ectopic pacemaker, spacial resolution, lead density**

I. Introduction

Body surface potential mapping (BSPM) has been demonstrated in many cardiac disease researches, for its noninvasive and higher spatial resolution compared to the 12-lead electrocardiogram [1-4]. One of the regular applications for BSPM is the investigation on non-invasive localization of cardiac ectopic pacemakers in radiofrequency catheter ablation (RFCA). Another application is to recognize different activation patterns during atrial fibrillation (AF) for its better treatment. Furthermore, a newly developed technique called electrocardiographic imaging (ECGI), combining BSPM and individual cardiac structure reconstructed based on computerized tomography (CT), rebuilt the potential distribution of endocardium and epicardium noninvasively[5]. Moreover, magnetic resonance imaging (MRI) is now available for personalized heart modeling [6]. All of these bring bright clinical application for BSPM.

We constructed a whole heart electrophysiological model simulating the normal and abnormal activation conduction of heart activities [7]. Using this model we could acquire simulated normal and abnormal 12-lead ECGs and BSPMs resulted from some pathological states such as ventricular ectopic pacemakers, conduction blocks and so on. This study utilized the simulated BSPMs in two ways. The first was to assess the spatial resolution of BSPM in separating the ventricular ectopic pacemakers; The second was to investigate the influence of lead density on the quality of BSPMs and spatial resolution. The proposed study concerns the evaluation of the constructed whole heart electrophysiological model and its further applications.

II. Materials and Methords

The flow diagram of our work was displayed in Fig. 1. Based on our constructed whole heart electrophysiological model and the selected ventricular ectopic pacemakers, simulated abnormal BSPMs in one heart cycle were acquired for each ectopic pacemaker. Using QRS integral map of BSPM ($BSPM_{QRS}$) and correlation coefficient, the morphological differences of $BSPM_{QRS}$ between each pair of ectopic pacemakers were measured and the spatial resolution was assessed for the pacemakers. Reducing the lead density, the potentials on the leads with lower density were used to estimate the potentials on the leads with higher density. Coefficient correlation was employed to evaluate the similarity of the estimated potentials to those simulated ones. And at the same time, the influence of lead density on

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the spatial resolution for separating ventricular ectopic pacemakers was studied.

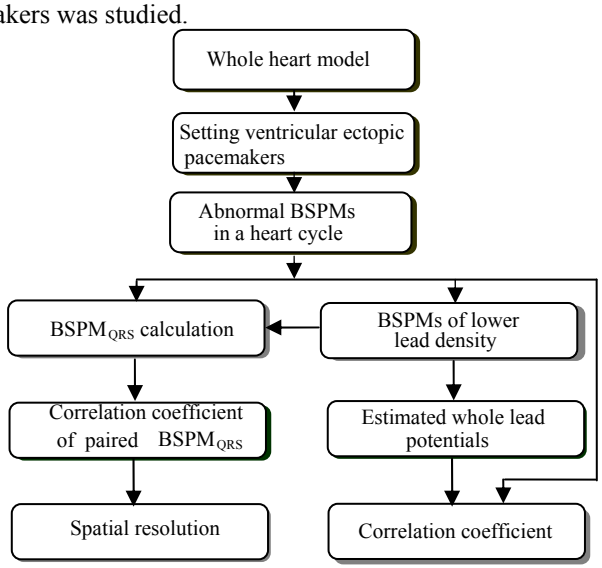

Fig. 1 The flow diagram of our work

A Simulated BSPM and QRS integral maps

Using the visible human project dataset (http://www.nlm.nih.gov/research/visible/visible_human.html), and a microcomputer, we constructed a geometric heart model with a resolution of 0.5 mm×0.5 mm×0.5 mm. Methods involving this procedure included image enhancement, tissue segmentation and three-dimensional reconstruction. Based on cellular action potential simulation, the propagation of electrical activation in heart special conducting system, atrium and ventricle was simulated using different algorithms, including a modified formalized algorithm, the isotropic and anisotropic wavefront propagation algorithms according to Huygens's principle, with a time accuracy of 1 ms. Meanwhile, the normal and abnormal BSPMs were produced by means of using dipole to represent the cardiac current source, combined with the bidomain model and a thorax model. The body surface chest leads for detecting BSPMs were 252 in all, placed at an interval of 10 mm with 21 columns and 12 rows [7].

In this study, the BSPMs were simulated at a 5 ms increment. So there were 41 BSPMs in a QRS interval lasting 200 ms, resulting in too much computational load. So, BSPM$_{QRS}$ [8] was used to represent the whole BSPMs during ventricular activation. For each signal $f_i(t)$ at the i'th electrode, the integral value of this electrode was calculated as

$$F_i = \int_{t\in \mathrm{QRS}} f_i(t)\mathrm{d}t = \sum_{t\in \mathrm{QRS}} f_i(t) \qquad (1)$$

here i=1, 2, ⋯, 252. For each ventricular ectopic pacemaker, we finally got a BSPM$_{QRS}$ with 252 integal potentials during an activation sequence of the ventricle.

B Selection of ventricular ectopic pacemakers

We selected the ventricular ectopic pacemakers on Purkinje fiber systems. The layout of sites in horizontal ventricular section covered a region of 12.5 mm ×16mm at an interval of 1.5 mm, containing 18 horizontal ectopic pacemakers. We also selected 6 vertical ectopic pacemakers at the same interval in a vertical line of 7.5 mm.

C Spatial resolution calculation

For those selected ventricular ectopic pacemakers in the same region (horizontal or vertical region), each of them was taken as a central pacemaker and was paired to every remaining pacemaker. So for each ectopic pacemaker in horizontal region, there were 17 paired pacemakers. And for each ectopic pacemaker in vertical region, there were 5 paired pacemakers.

For every paired ectopic pacemakers, the correlation coefficient (CC_1) of their corresponding BSPM$_{QRS}$ was calculated as

$$\mathrm{CC}_1 = \frac{\sum_{i=1}^{n} X_i Y_i}{\sqrt{\sum_{i=1}^{n} X_i^2 \sum_{i=1}^{n} Y_i^2}} \qquad (2)$$

here n=252, indicating the number of whole leads, X_i is the value of BSPM$_{QRS}$ on the i'th lead for a given ectopic pacemaker, Y_i is the other BSPM$_{QRS}$ except the given one. When one of the 18 horizontal ectopic pacemakers was selected as central one, The CC_1 was calculated between this central one and each of remaining ectopic pacemakers, forming a matrix of 18×18. The same method was applied to the 6 vertical ectopic pacemakers, acquiring a matrix of 6 ×6.

According to Reference [9], a correlation coefficient value of 0.95 was used as the threshold. If the CC_1 corresponding to two ectopic pacemakers was larger than the threshold, these two ectopic pacemakers were thought inseparable.

Finally, the resolutions of horizontal and vertical ectopic pacemakers were calculated according to the method introduced in Reference [10], respectively.

D The influence of lead density

1. The alteration of lead density

Lead density was reduced by evenly deleting the columns or rows in the lead array under the condition that the whole area of the lead array remained the same as that of the initial 252 leads. In this way, the number of leads was altered from 252 to 132, 72 and 36, respectively.

2. Implementation of estimation algorithm

The aim of this estimation was to acquire the whole body surface potentials from the subset leads, and then evaluated its acquisition ability for total information. Using the method of statistical inverse deduction, the values of the whole leads were estimated based on the values on the leads with lower density. The estimation algorithm was carried out referred to Reference [11].

The lead subset with lower density was defined as "known" leads, and the remaining leads whose values were to be estimated were defined as "unknown" leads.

The first component was to build a covariance matrix **K** according to equation (3)

$$\mathbf{K} = \frac{(\mathbf{A} - \bar{\mathbf{A}})(\mathbf{A} - \bar{\mathbf{A}})^{\mathrm{T}}}{M} \quad (3)$$

where the matrix **A** is composed of *N* activation maps and each containing *M* values. As mentioned before, *M*=252 and *N*=41. $\bar{\mathbf{A}}$ is a matrix with identical columns, each of which is the mean activation vector across all maps.

Then we portioned matrix **K** and **A** into blocking one as

$$\mathbf{A} = \begin{bmatrix} \mathbf{A}_{KK} & \mathbf{A}_{KU} \\ \mathbf{A}_{UK} & \mathbf{A}_{UU} \end{bmatrix} \quad (4)$$

where $\mathbf{A}_{KK}$ and $\mathbf{A}_{UU}$ are autocovariances and $\mathbf{A}_{UK}$ and $\mathbf{A}_{KU}$ are cross-covariances of known and unknown activation time values. Finally the transformation matrix **T** was formed as

$$\mathbf{T} = (\mathbf{K}_{KU})^{\mathrm{T}} (\mathbf{K}_{KK})^{-1} \quad (5)$$

Then, the value of an "unknown" lead was obtained according to

$$A_{\mathrm{U}}^{i} = \mathbf{T} \times (A_{\mathrm{K}}^{i} - \bar{A}_{\mathrm{K}}) + \bar{A}_{\mathrm{U}} \quad (6)$$

where A_{U}^{i} and A_{K}^{i} are the estimated and simulated values, respectively, of a single activation time vector.

The correlation coefficient (CC_2) was taken to compare A_{K}^{i} and A_{U}^{i}

$$CC_2 = \frac{\sum_{i=1}^{N} (A_{\mathrm{K}}^{i} - \bar{A}_{\mathrm{K}})(A_{\mathrm{U}}^{i} - \bar{A}_{\mathrm{U}})}{\sqrt{\sum_{i=1}^{N} (A_{\mathrm{K}}^{i} - \bar{A}_{\mathrm{K}})^2} \sqrt{\sum_{i=1}^{N} (A_{\mathrm{U}}^{i} - \bar{A}_{\mathrm{U}})^2}} \quad (7)$$

where *i* is different time instances.

3. The assessment of spatial resolution with different lead density

The horizontal and vertical resolutions concerning the same regions as mentioned before were calculated with every altered lead density.

III. RESULTS

A Spatial resolution of the ventricular ectopic pacemakers

The resolutions for each ventricular ectopic pacemakers (24 in all) were listed in Table 1. At last we got the horizontal and vertical resolutions of (2.80±0.62)mm and (3.25±0.39)mm, respectively.

Table 1 Horizontal and vertical resolutions of selected ventricular ectopic pacemakers

Horizontal ectopic pacemakers	Resolutions (mm)	Vertical ectopic pacemakers	Resolutions (mm)
1	2.50	1	3.75
2	2.15	2	3.00
3	3.41	3	3.00
4	2.52	4	3.75
5	3.75	5	3.00
6	2.50	6	3.00
7	2.12		
8	2.12		
9	2.12		
10	1.96		
11	1.80		
12	3.91		
13	4.07		
14	2.92		
15	2.52		
16	2.58		
17	3.58		
18	3.20		

B The influence of lead density

By picking leads out in the columns or rows equidistance, we acquired an incomplete BSPM, containing known leads (with simulated potentials) and unknown leads (with estimated potentials). Then, correlation coefficient (CC_2) was calculated between this incomplete BSPM and the BSPM with complete simulated potentials. As showed in Table 2,

correlation coefficient (CC_2) between the simulated and estimated BSPMs declined with the reduction of lead density. When the lead number was changed from the original 252 to 132, the CC_2 was relatively high, while for 72 leads, the CC_2 was acceptable and for 36 leads, CC_2 was quite low. As we expected, the spatial resolution of the selected ventricular ectopic pacemakers appeared the same tendency.

Table 2 The influence of lead density on BSPM and spatial resolution

Number of leads	CC_2	Horizontal /Vertical Resolutions (mm)
252	1	2.80±0.62/3.25±0.39
132	0.9865±0.0503	2.92±0.51/3.83±1.81
72	0.9457±0.0596	3.01±0.36/4.00±1.82
36	0.8521±0.0790	3.01±0.41/4.25±1.75

IV. Discussion and conclusions

The application of BSPMs in localizing ventricular ectopic pacemakers includes two aspects. The first is the comparison between the normal and abnormal BSPMs caused by ectopic pacemakers. The second is the comparison of these abnormal BSPMs. Our study concerns the latter. The spatial resolution for ventricular ectopic pacemakers were almost the same as reported in Reference [10, 12], indirectly proving the validation of our constructed whole heart electrophysiological model. Virtually, spatial resolution for ventricular ectopic pacemakers in different regions might appear different. By now we selected ventricular ectopic pacemakers only in limited regions, the comprehensive discussion of spatial resolution may need the selection of more ectopic pacemakers located in various regions. Moreover，the BSPM on back lead array [3] might be simulated for the detection of posterior ventricular ectopic pacemakers

The simulation results showed that when the leads number changed from 252 to 72, the correlation coefficient values remained nearly 0.95, indicating that reduction of lead density was applicable theoretically. From Table 2 we could notice that the decline of lead density has a little affection towards the horizontal spatial resolution for ectopic pacemakers. Although we selected limited ectopic pacemakers in a certain region, our result supported the feasibility for decreasing the leads density in some sense. The lower lead density facilitates the leads installation. Moreover, in practical application, higher lead density could be used in target parts and the rest parts with lower lead density. In this way, the balance between the lead number and BSPM detecting quality might be kept.

In conclusion, the usability tests not only prove the validation of our constructed whole heart model from the point of resolution, but provide delighting information about the influence of lead density on the performance of BSPM.

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