NONINVASIVE LOCALIZATION OF CARDIAC ARRHYTHMIA SOURCES FROM MULTICHANNEL ECG MEASUREMENTS

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Abstract

Results of noninvasive localization of arrhythmogenic tissue in the heart from multichannel ecg measurements are presented. Location of initial preexcitation was estimated by inverse computations using multiple dipole (MD) or jumping dipole (JD) model of equivalent heart generator. First, the influence of error factors frequently met in practice was analyzed on simulated ecg data. Mean localization error of 1.7 cm with 14 % of failures was achieved for MD and 1.1 cm without any failures for JD method. Using only 24 leads the localization error and occurrence of failures increased, particularly for MD method the rate of failures raised almost to 40%.
The localization procedures were tested on 10 WPW patients who later underwent successful radio-frequency catheter ablation of single accessory pathway. In 9 patients ecg potentials were measured in 24 leads and the preexcitation site on atrio-ventricular ring was located in correct region in 7 cases using the JD method, in 4 cases using the MD method and in 8 cases using a modified MD method. For 1 patient body surface potentials were measured in 63 leads and his individual shape of torso with lungs and cavities was used in inverse computation. In this patient, both methods localized the accessory pathway in correct region.

Keywords: multichannel ecg measurement, body surface potential map, noninvasive localization of preexcitation in the heart

1. Introduction

Some types of arrhythmias are initialized in a small confined region of heart. Especially it is the case of Wolff-Parkinson-White (WPW) syndrome when anatomical substrate of preexcitation is a presence of abnormal structural connection between the atria and the ventricles - an atrio-ventricular (AV) accessory pathway (AP).

The most precise localization of the substrate has been provided invasively during catheterization from electrograms measured directly on the heart before radio-frequency catheter ablation (RFCA). However, noninvasive prediction of the location of accessory AV path substrate can substantially shorten and simplify the invasive procedure. While standard 12 lead ecg can correctly determine the location of bypass tract in about 60% of patients, more complete information obtained from body surface potential maps allows correct localization on the basis of map patterns categorization up to about 90% of cases [1]. Nowadays, methods of inverse localization of initial activation are proposed, which use body surface potentials (BSP) and torso geometry as input data for solution of the inverse problem.

In most WPW patients, single site of initial activation occurs, which can be approximated by a dipole located at that region. Only about 15% of patients have more then one AP [1].

In this study, methods of inverse localization based on multiple dipole and so called jumping dipole are discussed. The accuracy of both methods was first examined on simulated data using realistic computer model, then the procedures were tested on a group of patients with single AP.

2. Method

Two types of equivalent cardiac generator based on current dipole source were considered to find the position of the AP on AV ring:

Multiple Dipole. The MD model [4] is composed of a number of segmental dipoles. Heart ventricles are partitioned to several segments and the dipoles are located at the centers of these

segments. Orthogonal components of segmental dipoles $\boldsymbol{M}$ in time $\boldsymbol{t}$ are estimated using the formula $\boldsymbol{M(t)=T^{+}\Phi(t)}$, where $\boldsymbol{\Phi(t)}$ are body surface potentials. Transfer matrix $\boldsymbol{T}$ represents the relation between positions of the dipoles and the potentials. The inverse problem is ill posed and pseudo-inverse $\boldsymbol{T^{+}}$ obtained by truncated singular value decomposition is used.

Segmental dipoles were computed during the initial interval of activation. As a criterion for identification of the segment with initial activation a segment with maximal dipole magnitude was proposed. Integration of dipole moments over selected short interval of activation (20-25 ms) stabilized the inversely determined segment (IDS).

Jumping dipole. In jumping dipole (JD) method [5] the components $\boldsymbol{D_i(t)=T_i^{+}\Phi(t)}$ of each segmental dipole $i=1,2,\ldots n$ are inversely computed from surface potentials $\boldsymbol{\Phi(t)}$ one by one ($\boldsymbol{T_i}$ is transfer matrix characterizing the relationships between the i-th segmental dipole and potentials on torso surface). For each dipole $\boldsymbol{D_i}$, the BSP were computed and compared with original potentials. Origin of activation was localized into the segment for which computed surface potentials are the closest to original ones. As a criterion for IDS, minimal relative root mean square error (RMSE) between original and computed potentials was used. To fix the IDS in time, summation of the relative RMSE over initial interval of activation (7.5-25 ms) was computed.

Testing on simulated data. A realistic torso model comprising lungs and heart ventricles with conductivity equal to 0.25 and 3.0 times the torso conductivity, respectively, was used. Simple model of activation spread in ventricles was used for simulation of BSP and testing of the proposed inverse solutions. The shape of ventricles was analytically defined by ellipsoids and partitioned into 39 segments. The longitudinal measures of 16 segments on the AV ring were from 1.3 to 2.2 cm, mean 1.54 cm [4].

A set of 8 activation sequences, each started at a single point on AV ring was simulated. Locations of simulated APs were selected in physiologically defined regions (anterior septum, right ventricle, posterior septum and left ventricle) on epicardial side of the AV ring [4].

The localization error (LE) was defined as the distance between the center of upper epicardial edge of IDS and the correct starting point. Cases with the LE greater then 3 cm were regarded as localization failures.

The mean localization error (MLE) caused by the size of the heart segments (if all 8 simulated APs have been detected in the correct segment) was 0.4 cm and represents the resolution of the methods.

Influence of error factors. The influence of some error factors was analyzed for both inverse methods. Incomplete knowledge of the thorax geometry was represented by neglecting of lungs and cavities. Errors in determining of the heart position were simulated by shifts and rotations of equivalent generator (misplacements of starting points were about 1 cm). A noise with known σ from 3 to 20 μV was added to simulated surface potentials. To suppress the influence of noise, Pipberger low pass filter with 50Hz notch was used. Inverse computations from potentials simulated in 198 points defining the whole surface of the model torso and in two practically used mapping lead systems (24 lead system according to Barr with 20 anterior and 4 posterior electrodes and 63 lead system according to Savard were compared.

Verification on real data. Described methods of inverse localization were applied to BSP measured in 10 WPW patients.

BSP from 9 patients (3 male, 6 female, age from 18 to 51) were measured in Bratislava (5 patients) and in Vienna (4 patients) by the ProCardio mapping system developed in the Institute of Measurement Science. For practical reasons, only 24-lead measurements were used. The shape of thorax was not measured and standard geometry (the same realistic torso and analytically defined shape of heart ventricles as in model simulations) were used for all patients. The site of AP was confirmed by successful RFCA.

For one WPW patient complete data measured by Shadidi *et al.* [2] were used. Ecg potentials in 63 mapping leads and the shape of thorax with lungs and ventricles including cavities (based on CT scans) were available and used in the inverse computations. Intraoperative measurements of pericardial potentials localized the preexcitation site at the base of the lateral wall of the left ventricle.

3. Results

Simulated data. Results of localization from 63

leads, influence of particular error factors and their combination are summarized in Table 1.

ERROR FACTORS (number of cases)	mean localization error [cm] (failures in %)	
	MD method	JD method
no (8)	0.6	0.5
homogeneous torso (8)	1.1	0.8
noise 5 μV (40)	0.8	0.5
heart misplacements (40)	0.9	1.0
combined factors (200)	1.7 (14 %)	1.1

Table1. Results of simulated localization from 63 leads influenced by different error factors.

The influence of heart misplacement was similar for both method. On the other hand, the influence of torso inhomogeneities and especially noise in BSP and was higher in MD method.

In Fig. 1, the sensitivity of the MD method to the noise and to decreasing number of measured leads is demonstrated for BSP measured in 198 points over the whole torso and in 63 mapping leads. Up to the noise of 5 μV the performance of both methods was similar. When the noise rose, the localization error for MD method increased faster, especially for 63 leads.

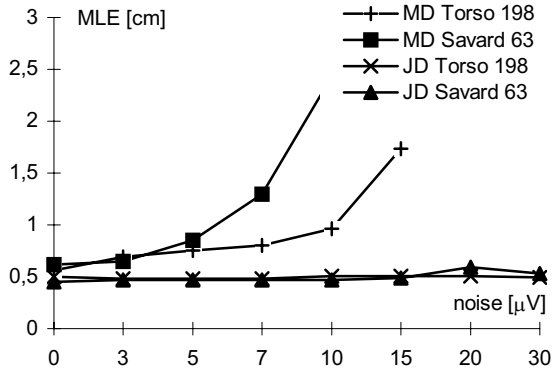

Figure 1: Influence of noise in BSP on the mean localization error when potentials simulated in 198 or 63 leads were taken as input for MD or JD method.

When only 24 leads were taken, homogeneous torso was used and no noise and heart misplacements were present, the localization using the MD method has brought unsatisfactory results: the MLE reached 3 cm and the localization failed in almost 40% of cases. The MLE obtained using the JD method was about 1 cm and no failure occurred.

Measured data. For 9 patients measured in 24 leads, the same geometry data as in the simulation study were used. The segmentation of ventricles in the basal level and its physiological partitioning are shown in Fig. 2.

In Table 2, results of localization are shown. For MD method, in 5 cases (marked by *) the dipole with largest magnitude was found out of the AV ring. In these cases we have used an a priori knowledge about the position of the AP so that the second or third segment (by dipole magnitude) laying on the AV ring was taken. Using this modification of MD method, all IDS were localized on the AV ring: in 4 cases into the correct segment, in 4 cases into the first or second neighboring segment and in 1 case the localization failed. For the JD method all segments were localized on the AV ring. Correct segment was identified in 4 cases, the first or second neighboring segment in 3 cases and in 2 cases the detected segment was in different part of the AV ring.

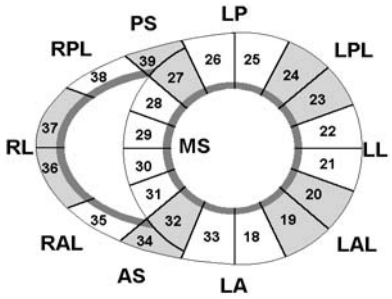

Figure 2: Segments and physiological regions of the heart model in the AV plane.

Patient	AP site	correct segment	localized by MD	localized by JD
FA45	LPL	23-24	21 *	23
F460	LL	21-22	21	22
F530	LL	21-22	19 *	20
F780	LL	21-22	21	20
AF49	LAL	19-20	20 *	22
BISC	LL	21-22	21	21
SCHN	LAL	19-20	21 *	20
FICH	RL	36-37	35	33
BICH	MS	28-31	35 *	18

Table 3: Results of localization in the analytically defined heart using MD and JD model. In cases marked with *, the modified MD method was used, failures are shaded.

Both methods were also applied to 63 lead BSP data with real geometry. The heart ventricles were segmented into 39 segments (like the heart model). According to [3], the correct segment indices were 20 and 21. The JD method localized

the AP into neighboring segment 19. MD method indicated segment 7 in middle level of the heart for interval 20-25 ms, but the correct segment 20 for more appropriate earlier interval. Centers of the inversely localized segments are shown in Fig. 4.

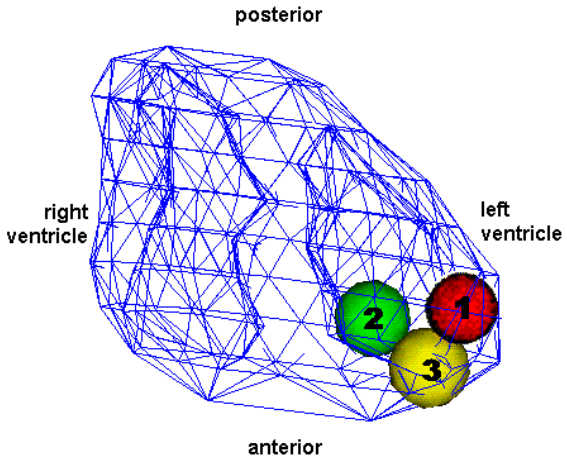

Fig. 4: Upper view of the triangulated real heart with AP:
1- real position of AP, localized also by MD method using an earlier interval
2- position in segment 7 (out of AV ring) localized by MD method using interval 20-25 ms
3- position in segment 19 localized by JD method.

4. Discussion and Conclusions

In model simulations, dipole moments at times between 10 and 35 ms after the activation onset were tested. In most cases the maximal dipole criterion was pointing to the same segment over the whole interval but in some cases it changed. Integral of the dipole moment over selected time interval stabilized the solution. Interval from 20 to 25 ms gave the least mean localization error for MD method and interval from 8.5 to 25 ms was used for JD method. Including earlier part of activation where signal to noise ratio is lower caused increased influence of noise, particularly for the MD method. Further prolongation of the interval did not improve localization results because the activation can spread to far from the initial point or normal activation can start in other areas and distort the localization in real heart. However, the intervals proposed in the simulation study are only approximate and in practice it is recommended to set individual intervals based on actual signal to noise ratio and prolongation of the preexcitation. For example, in one patient from our 9 patient study group the localization at proposed time interval failed, while individual time interval until the end of preexcitation gave the correct result. Similar situation appeared in the patient measured in 63 leads where the IDS moved from the AV ring in direction to the apex when 20-25 ms interval was used. In correspondence with these results, individual selection of analyzed time interval can improve the localization.

Presented results of localization in real patients were in good agreement with the simulation study. With both, MD and JD methods, the localization from 63 measured leads and using individual torso geometry was successful.

In most cases both methods were able to localize the position of AP within 11 regions on the AV ring even if only 24 leads were measured. The success rate was in correspondence with the results obtained in the simulation experiments. Better results were achieved with the JD method which was sensitive only to insufficient geometry data. For MD method, satisfactory results were achieved only with a modified method supposing the AP site on AV ring, so this method can be used only for WPW patients.

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