Effect of Elimination of Noisy ECG Leads on the Noninvasive Localization of the Focus of Premature Ventricular Complexes

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Abstract

High frequency of the premature ventricular complexes (PVCs) can lead to the development of the left ventricular dysfunction. Preoperative noninvasive localization of the PVC focus can decrease the time of the invasive electrophysiological study and improve the success rate of the radiofrequency ablation. Body surface potential (BSP) maps, patient-specific inhomogeneous torso model and inverse solution in terms of single dipole model were used for noninvasive localization of the PVC focus in five patients. BSP maps were computed for the initial 20 ms time interval of the ventricular activation (QRS complex in the ECG) from five selected PVCs in each patient. The inhomogeneous torso model included surfaces of torso, lungs, heart cavities and outflow tracts. To investigate whether the exclusion of the noisy ECG leads improves the accuracy of the inverse solution, the leads with the signal-to-noise ratio (SNR) less than the defined threshold value were excluded from the inverse computations. Four levels of the SNR were defined: 10, 20, 30, 40 dB. Locations of the PVC foci were computed by the inverse solution and compared with the catheter positions during successful radiofrequency ablation performed within invasive electrophysiological study. Removal of noisy ECG leads did not improve the PVC localization when the noisy ECG leads were located in left anterior torso region.

Keywords

Body surface potential mapping • Inverse problem of electrocardiography • Premature ventricular complexes Ectopic activity • Noninvasive localization

1 Introduction

Premature ventricular complexes (PVCs) in patients with underlying chronic structural disease increase the risk of sudden cardiac death and total cardiac death. The PVC focus can be located anywhere in the ventricles and adjacent structures. Usually, anti-arrhythmic therapy is used in these patients. However, when the patient does not respond to the pharmacological treatment, a catheter radiofrequency ablation (RFA) is performed during the invasive electrophysiological (EP) study. Accurate localization of the PVC focus is highly important for successful RFA [1]. Therefore, a preoperative noninvasive estimation of the PVC focus location using a novel method of electrocardiographic imaging [2, 3] can decrease the time of the invasive EP procedure and improve the ablation success rate.

This novel method requires solution of the inverse problem of electrocardiography, which uses multiple ECG leads signals to compute BSP maps representing the electrical activity of the heart, realistic 3D torso model and a model representing the cardiac electrical generator. Because the inverse problem is ill-posed slight inaccuracies or disturbances of the input data might lead to significant changes in the obtained inverse results [4]. Therefore, we can suspect that noisy ECG signals can lead to faulty results of the inverse solution. In this study we will evaluate whether exclusion of the noisy leads can improve the accuracy of the inverse solution.

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2　Materials and Methods

The study population consisted of two male (Pat004—77Y, Pat006—51Y) and three female (Pat005—43Y, Pat007—54Y, Pat009—74Y) patients with frequent PVCs. The study complied with the Ethical Principles for Medical Research Involving Human Subjects as stated in the Declaration of Helsinki and received approval from the Ethic Committee of the University Hospital Kralovske Vinohrady, where the data were collected after obtaining written informed consent from the study participants.

All patients underwent BSP mapping, full torso computed tomography (CT) scanning and intracardiac EP study.

2.1　Body Surface Potential Mapping

High-resolution multichannel ECG system ProCardio-8 [5] was used to record ECGs and compute integral BSP maps. Disposable pre-gelled Ag/AgCl electrodes with active adapters were applied to record limb leads and 96 chest leads. Chest electrodes were evenly distributed over the torso and organized in 12 strips of 8 electrodes. The sampling frequency was 1 kHz, data resolution was 16 bit. The ECG recording time was up to 10 min.

Processing of the multichannel ECGs to obtain BSP maps included baseline correction by applying the Lynn's high-pass filter [6]. In each patient five PVCs were chosen for further analysis.

In order to study the effect of the noisy leads removal on the inverse solution, assessment of the present noise had to be performed. For each PVC, the noise in the signal was evaluated as follows: (1) time interval with no physiological signal (amplitude close to zero), usually during the compensatory pause, was selected; (2) linear two-point baseline correction was applied to this interval to correct baseline wandering and shift the signal closer to zero; (3) root mean square of the signal was calculated as a noise estimator (RMS_{noise}) for each of the 96 chest leads.

Then, the PVC signal was processed using two-point baseline correction with points before and after the whole PVC beat. Time interval of 20 ms duration was selected at the beginning of the PVC to represent the pathological activity of the ectopic focus [7]. Root mean square of the signal (RMS_{signal}) was evaluated for each of the 96 leads. Signal to noise ratio (SNR) was assessed using the equation:

$$SNR = 20log\left(RMS_{signal}/RMS_{noise}\right), \quad (1)$$

where

SNR—signal to noise ratio in dB for each lead;
RMS_{signal}—root mean square of the 20 ms PVC signal in each lead;
RMS_{noise}—root mean square of the noise signal in each lead.

Four levels of the SNR were studied: 10, 20, 30, 40 dB. If the SNR on the lead was less than the studied SNR level, the electrode was excluded. Therefore, amount and configuration of the leads varied between the beats and between studied levels of the SNR (see Fig. 1). If the position of the lead was missing in the CT, the lead was excluded as well. From the used leads the integral BSP map was computed for each SNR and each PVC as:

$$ibspm = \int_I \phi(t)dt, \quad (2)$$

where

ibspm—integral BSP map,
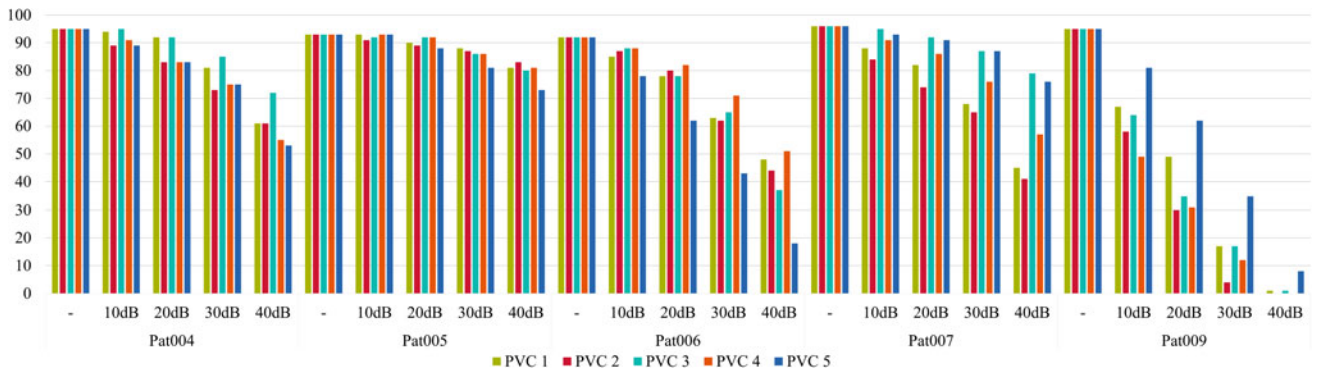$\phi(t)$—BSP map in time instant t,
I—examined time interval.

Fig. 1 Number of ECG leads for all patients, for each of 5 selected PVCs and 5 lead sets: full set, leads with SNR > 10 dB, with SNR > 20 dB, with SNR > 30 dB and with SNR > 40 dB

2.2 Computed Tomography

Computed tomography scanning was performed for the whole torso using Siemens Somatom Definition system immediately after the BSP mapping. ECG electrodes were still attached to the torso in order to determine their precise positions. CT scanning had 0.3 mm slice thickness and was used to obtain inhomogeneous patient-specific 3D torso model using TomoCon PACS® software. The torso model included geometries of torso, lungs, heart atria and ventricles (epi- and endocardial surfaces), aorta and pulmonary artery. Conductivities of its compartments were assigned so that the lungs conductivity was assumed to be four times lower than the torso conductivity, and the conductivity of the heart cavities (right and left atria, right and left ventricles), aorta and pulmonary artery was assumed three times higher than the torso conductivity [8].

2.3 Electrophysiological Study

On the same day of the BSP mapping and CT scanning procedures or the next day, an invasive intracardiac EP study was performed using the cardiac mapping and navigation system (CARTO 3® Biosense Webster Inc.) to reveal the position of the premature ectopic activity and navigate the ablation catheter. All patients underwent the EP study under mild conscious sedation with fentanyl. Intracardiac electrograms were recorded using the electrophysiological recording system (LabSystem PRO, Boston Scientific).

Invasive localization of the PVC focus was determined by activation mapping and confirmed by pace mapping. After localization of the pathological ectopic focus RFA was performed using an open irrigated ablation catheter (Thermocool Navistar, Biosense Webster Inc.) in the power-control mode (25–40 W, flow 15–20 ml/min, max. temperature 43 °C). In order to ensure the complete destruction of the ventricular ectopic focus, after the last energy application and 15 min monitoring the patients were challenged with isoproterenol.

2.4 Inverse Solution

Inverse solution based on single dipole model of the cardiac electrical generator was used for noninvasive localization of the PVC focus. Integral BSP maps computed from the measured multichannel ECGs and patient-specific inhomogeneous torso geometry were used as input data for the inverse solution. It was assumed that the area of the ectopic focus can be represented by a single dipole and its electrical activity is defined by the integral BSP map computed from the initial 20 ms time interval of the PVC. All possible positions of the equivalent dipole generator G' were supposed in a regular 3 mm cubic grid throughout the whole volume of the ventricular myocardium model. For each of these positions, parameters of the dipole were computed by the inverse solution using the equation:

$$G' = B^+ ibspm, \tag{3}$$

where

G'—equivalent integral dipole generator,
B^+—pseudo-inverse of the transfer matrix **B** representing the relation between the equivalent dipole generator and potentials on the torso.

The location of the PVC focus was determined as the position of the equivalent dipole generator best representing the measured electrical field according to the criterion of minimal relative residual error (RRE) between the input integral BSP map (ibspm) and map (gm) computed from the equivalent dipole generator G':

$$RRE = \frac{\sqrt{\sum_{i=1}^{n}(ibspm_i - gm_i)^2}}{\sqrt{\sum_{i=1}^{n} ibspm_i^2}}, \tag{4}$$

where n is the number of points in the maps.

In each patient the inverse solution was calculated for 5 PVCs from selected ECG leads (based on the SNR). For each PVC 5 lead configurations were used: all available leads, and leads having SNR > 10, SNR > 20, SNR > 30, and SNR > 40 dB.

2.5 Evaluation of the Inverse Solution

The locations of the equivalent dipoles obtained from the inverse solution were compared with the positions of the ablation points obtained during the intracardiac EP study. In order to make the comparison unbiased, the positions obtained from the EP study were evaluated by the physician and technician who performed the study, and the locations of the inverse solution were evaluated by the technicians who performed the non-invasive localization. The locations of the equivalent dipoles and ablation points were characterized depending on their position in the heart chambers and assigned to appropriate segments. The LV was divided into 17 segments according to the American Heart Association recommendations [9]. The right ventricular outflow tract (RVOT) was displayed in the superior view and divided into 12 segments. If the segments of the equivalent dipole and the ablation point were the same, the result of the inverse solution was marked as correct.
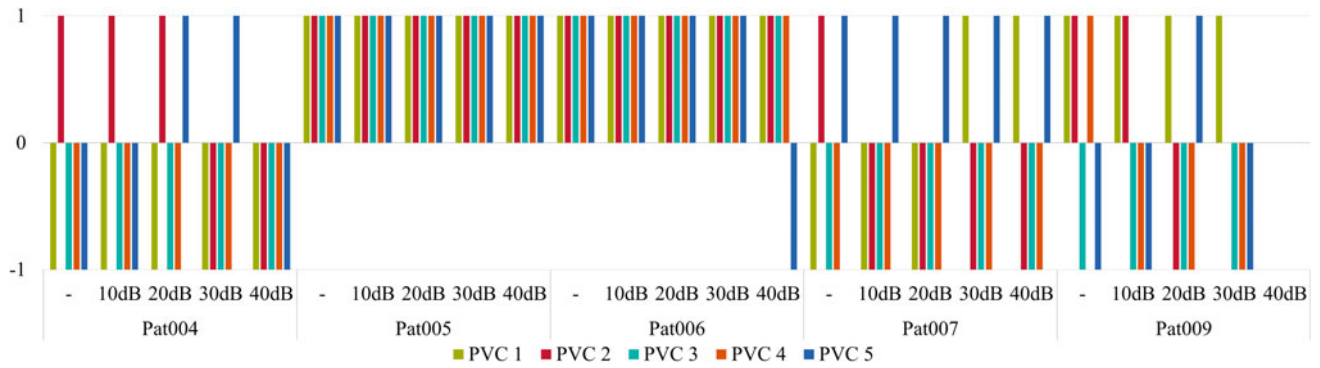
Fig. 2 Correctness (correct +1, incorrect −1) of the inverse solution for all patients and each of 5 PVCs for 5 lead sets: full set; leads where SNR > 10, SNR > 20, SNR > 30, SNR > 40 dB
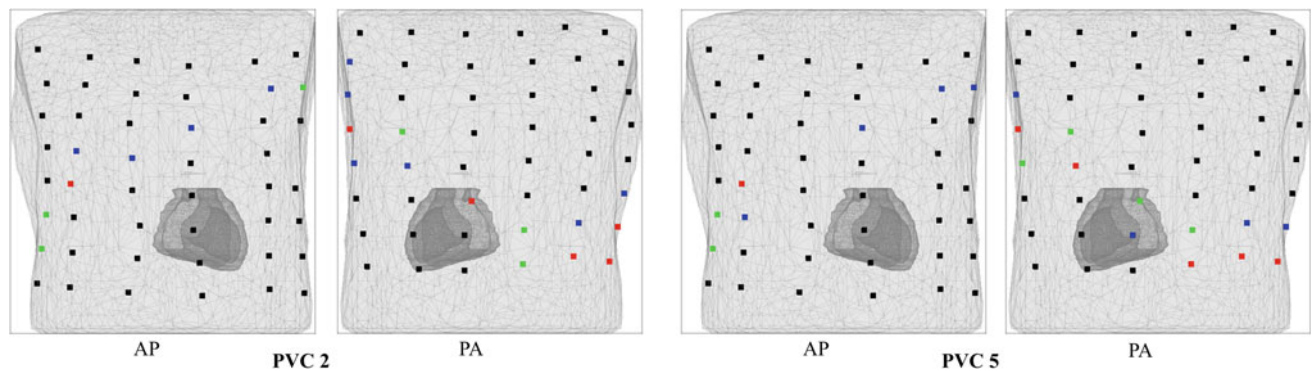

Fig. 3 Torso model of the patient Pat004 in anterior-posterior (AP) and posterior-anterior view (PA) with leads used in evaluation of PVC 2 and PVC 5 with different SNR levels. Black: SNR > 30 dB, Blue: SNR > 20 dB, Green: SNR > 10 dB, Red: SNR < 10 dB
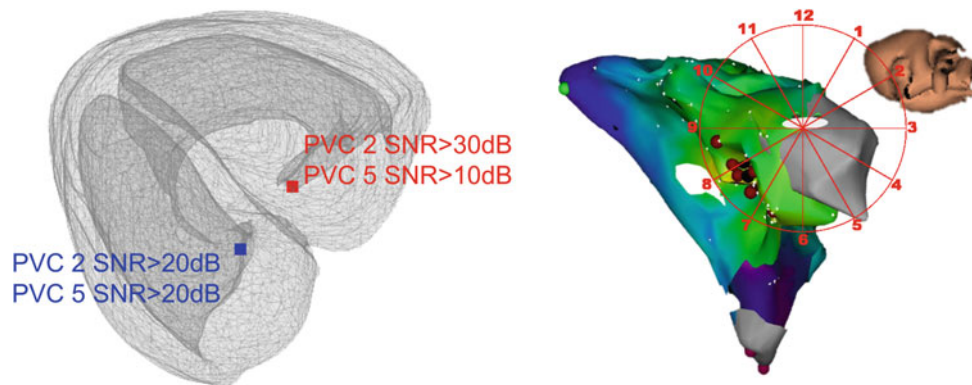

Fig. 4 Results for Pat004. Superior view. Left: Model of the heart ventricles with positions of the inverse solutions obtained for PVC 2 and PVC 5 using different SNR levels. Blue: correct results, Red: incorrect results. Right: Endocardial model of the right ventricle. Ablation points are marked by red markers

3 Results

Number of ECG leads for each of 5 lead sets (full set, and leads having SNR > 10, SNR > 20, SNR > 30, and SNR > 40 dB) is given in Fig. 1. The correctness of the inverse solution for all patients, for each of the five analyzed PVCs and each lead set (full set and 4 sets with leads above selected SNR) is presented in Fig. 2.

Patient Pat005 had correct inverse solutions in all cases (5 PVCs, for all analyzed SNRs), patient Pat006 had correct

inverse solutions in all cases, except PVC 5 with SNR > 40 dB, when most leads were removed (78 out of 96).

Removal of the noisy ECG leads not located in the left anterior torso region (heart region) improved the PVCs localization whereas the elimination of the noisy ECG leads in the heart region caused up to 2 cm shift of the inverse PVC focus localization. One example is presented in Pat004 showing that elimination of the electrodes located precordially near the heart region (see Fig. 3, PVC 2) worsened the inverse localization (Fig. 4, PVC 2). In contrast, removal of the noisy leads from the back (see Fig. 3, PVC 5) improved the results of the inverse solution (see Fig. 4, PVC 5).

4 Conclusion

Small disturbances in the input data can lead to faulty results of the inverse solution due to the ill-posedness of the problem. Measurements in real patients are usually impaired by noise. Assessment of the noisy ECG leads elimination effect on the inverse solution was performed for the following SNR for each of five selected beats: 10, 20, 30, 40 dB.

When considering individual BSP maps, exclusion of noisy ECG leads did not improve the PVC focus localization if the noisy leads were located in the heart region—on left anterior torso surface. The inverse solution obtained using also noisy ECG leads in this region provided more accurate results when compared with the inverse solution computed from the input BSP map obtained only from ECG leads with high SNR level. Limitation of the study is the small number of evaluated patients. Validity of the results could be verified after more patient records will be available.

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