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Simultaneous mapping of endocardium and epicardium from multielectrode intrachamber and intravenous catheters: a computer simulation-based validation

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Abstract A multielectrode basket-shaped contact catheter (MBC) provides simultaneous recordings of unipolar or bipolar electrograms from within the heart chambers. Another catheter-based mapping approach uses the multielectrode intravenous catheters (MIVCs), which are widely used to diagnose and treat supraventricular arrhythmias. It is also known that mapping techniques are usually limited to one surface at a time. Therefore, an approach that can be used for simultaneous mapping of left and right endocardial surfaces and epicardial surface will be beneficial to characterize and discriminate the endocardial and epicardial sources of the arrhythmias more accurately. In this study, we used statistical estimation method to map the endocardial and epicardial surfaces simultaneously based on combined usage of the MBC and MIVC. The statistical estimation method is based on high-resolution training data set to hypothesize the relationship between catheter measurements and inaccessible sites. To test this approach, we created a high-resolution map database consisting of computer simulation results of Aliev-Panfilov model of cardiac electrical activity on 3-dimensional Auckland canine heart geometry. The simulation database included 2590 maps each paced from a unique endocardial or epicardial site. Fifty or five percent of the database was used as the training data set and the remaining as test data set in the statistical estimation procedure. We selected 64 sites on the left and 64 on the right endocardial surfaces of the model heart geometry and used them as the surrogate MBC measurement sites. Ninety-one sites on the epicardium corresponding to the major coronary veins served as the surrogate MIVC leads. Finally, we tested the success of the method to determine the source of the arrhythmias using the correlation coefficient between the original and estimated activation maps and linear distance between their earliest activated sites. The performance of this approach was promising, such as when MBC on the left endocardium and MIVC were used together, the average linear distance was ~2.4 mm and mean correlation coefficient was 0.995. It was possible to locate 95% of epicardial arrhythmia cases correctly on the epicardium. Ninety-nine percent of left endocardially originating arrhythmias were correctly located on the left endocardium. The results of this study showed that this approach is feasible and requires further effort.
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Introduction

Because of their minimal invasiveness, catheter-based approaches have become a common practice among cardiac electrophysiologists for the characterization of cardiac arrhythmias. Currently available catheter-based mapping techniques usually use standard electrophysiologic catheters with a limited number of electrodes, which are sequentially steered to selected sites in the coronary vessels and on the endocardium and epicardium to record local electrical activity or to perform cardiac pacing. Activation sequence mapping with current techniques is time-consuming, technically difficult, not reproducible, and not suitable for hemodynamically unstable patients or short-lived generated arrhythmias.[1]

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To overcome these setbacks in mapping methodology, the systems that enable mapping by means of localizable catheters[2,3] and, noncontact multielectrode catheters,[4] and balloon and expandable, multielectrode, basket-shaped contact catheters[5] have emerged in the last 20 years. A multielectrode basket-shaped contact catheter (MBC) can be delivered to the endocardial surface by a standard percutaneous catheterization technique.[5-10] The MBC represents a basket-shaped array of electrodes distributed evenly on linear support structures called splines. Experimental[6-8] and clinical data[5,9,10] provide information on the advantages of using basket catheters for mapping and ablation of atrial and ventricular arrhythmias. Clinical use of MBCs in humans is still very limited except for a series of recent studies on the usage of MBCs in curative treatment of atrial fibrillation.[11]

Another catheter-based mapping approach uses the multielectrode intravenous catheters (MIVCs). Venous catheter-based approach is widely used to diagnose and treat supraventricular arrhythmias. Their application to the epicardium is highly limited because much of the heart does not lie close to a major vessel segment. Although epicardial mapping using multielectrode catheters can be performed by a direct approach after percutaneous puncture of the pericardial space using a subxyphoid approach, it still has a problem of sparse spatial sampling of the epicardial surface. Several studies have investigated the usage of MIVCs in epicardial mapping[12,13] because 5% to 15% of the ventricular arrhythmias are believed to originate from the epicardial or subepicardial regions of the heart.[14] It has been shown that endocardial mapping and subsequent ablation fails in patients with epi/subepicardial arrhythmias.[15] It is also known that mapping techniques are usually limited to one surface at a time. Therefore, an approach that can be used for simultaneously mapping both endocardial and epicardial surfaces will be benefical to characterize and discriminate the epicardial and endocardial sources of the arrhythmias more accurately.

Previously, Yilmaz et al have investigated a method called statistical estimation, by which epicardial mapping can be achieved using MIVC measurements and have reported its success in localizing focal arrhythmias in dogs.[16-18] The statistical estimation method is based on high-resolution training data set to hypothesize the relationship between catheter measurements and unmeasured sites. In those studies, training data set was composed of high-resolution epicardial maps acquired from a series of experiments performed on dog hearts. In a recent study,[19] we performed whole-heart simulations of focal arrhythmias originating from the epicardium using a computer model developed by Aliev and Panfilov[20,21] to study electrical activity of the heart. The simulations were performed within the ventricles of the realistic Auckland canine heart model.

In this current study, we hypothesize that the usage of statistical estimation approach for simultaneous mapping of endocardial and epicardial surfaces from multielectrode intravenous and intrachamber basket catheter measurements may be an alternative as a minimally invasive diagnostic technique with which it would be also possible to discriminate epicardial sources from endocardial counterparts. The realistic whole-heart computer simulation results served as our testbed.

Methods

Simulation database

To create the high-resolution simulation database, we performed cardiac simulations using Aliev-Panfilov model, which is a modified FitzHugh-Nagumo model.[22-24] Aliev-Panfilov model is composed of a pair of differential equations defining fast and slow processes.[21] The computer simulation geometry was composed of the ventricles of the Auckland canine heart model for which the coordinate and fiber orientation information have been obtained by Nielsen et al.[25] In our work we used an interpolated version of these data containing 532 552 heart points. To work on a reasonable number of points, we selected a subset that included 2590 points on the epicardial and endocardial surfaces. 562, 488, and 1540 points, which were regularly distributed on the simulation heart geometry, were selected on the left (LE) and right (RE) endocardial surfaces, and on the epicardial (Epi) surface, respectively. We started the simulations from these 2590 unique sites (by activating each site and the neighboring 14 other points) one by one, and thus, for each simulation, we obtained 532 552 activation-time values on all heart points. Each simulation result corresponded to a focal arrhythmic activity on the ventricles. We then extracted the activation-time values from 2590 points for each computer simulation. We finally constructed the simulation database as a matrix of 2590 by 2590 (2590 maps and 2590 sites).

Statistical estimation method

As the catheter measurement sites, we selected 64 points on the left endocardial surface of 562 preselected points and 64 points of preselected 488 points on the right endocardium of the model heart and used them as the surrogate MBCs. Each 64 points corresponded to the sites on the model heart distributed evenly on 8 splines of MBC (8 sites on each spline were selected manually). Ninety-one sites on the epicardial surface corresponding to the major coronary veins served as the surrogate MIVC. In the statistical estimation approach,[16] first, the training data set was reordered in such a way that the activation-time data obtained from each beat were set as column vector so various beats resulted in a matrix called **A**, in which surrogate catheter measurements (accessible values) were at the upper rows and the remaining inaccessible values were at the lower part. Then, using matrix **A**, covariance matrix, **C**, was computed.

$$C = \left(\frac{\left(A - \overline{A}\right)\left(A - \overline{A}\right)^T}{N} \right) \tag{1}$$

C matrix contains auto-covariance, $\mathbf{C_{aa}}$ and $\mathbf{C_{ii}}$, and cross-covariance, $\mathbf{C_{ia}}$ and $\mathbf{C_{ai}}$, of accessible and inaccessible activation time values. N is the total number of accessible and inaccessible sites. The estimation matrix, **T**, was formed by $T = (C_{\mathrm{ia}})^{\mathrm{T}}(C_{\mathrm{aa}})^{-1}$. Finally, for each map, the multiplication of

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