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Selection of the Number and Location of Leads for Catheter Based Epicardial Mapping

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***Abstract*— We have developed a statistical estimation approach by which to estimate high-resolution maps of epicardial activation from very low resolution multielectrode venous catheter measurements. With this system, we have overcome the limitation that catheter based electrophysiologic studies of the epicardium are limited to regions near the coronary vessels or require transthoracic access. The goal of this study was to improve our understanding of the statistical estimation approach by investigating and optimizing one of its key components: the placement and number of catheter leads. We sought to determine the role of leadset selection in the accuracy of catheter based estimation, specifically the effect of lead location and number on solution accuracy. The results from the leadset analysis showed that regularly spaced leadset perform similarly to the leadsets selected using other, more sophisticated methods and suggested that rather than using irregularly distributed leads on each venous branch, regularly spaced leads with a 1 cm interelectrode distance would be more practical. The results of this study provide further evidence that such an approach is feasible for locating the source of epicardial ectopic foci. Moreover, the electrode technology required is available and would be quite straightforward to deploy.**

***Keywords*— Epicardial activation mapping, catheter mapping, statistical estimation, leadset selection**

I. Introduction

Even though the majority of the sources of ventricular tachycardias are believed to be endocardial, several studies suggest that approximately 15% of clinical cases have an epicardial/subepicardial component [1]. In this subgroup of patients, mapping techniques that are limited to the endocardium result in localization errors and failure in subsequent ablation procedures. In 1996, Sosa, Scanavacca, d'Avila and Pilleggi introduced a new technique that requires the insertion of an ablation catheter directly through the thorax and into the pericardial space [2]. More recently, several clinical investigators have shown the effectiveness of this technique in patients with various types of VT [3]. This transthoracic approach is relatively invasive and carries some risk; its deployment should be reserved for patients in whom the indications of epicardial involvement exceed the risk. Thus there is a need to evaluate the ectopic electrical activity on epicardial surface using minimally invasive techniques.

Coronary venous catheters provide such an alternative means of access to the epicardial surface and are already in widespread use [4]. The major limitation of these catheters however is their restricted epicardial access via the coronary veins, which leaves most of the epicardium inaccessible to direct measurement.

In order to compensate for this limited spatial coverage, we have developed a statistical estimation technique by which it is possible to reconstruct the activation pattern over the epicardial surface using only the values measured from multielectrode venous catheters. This technique uses a linear estimation model that hypothesizes the relationship between venous catheter measurements and unmeasured epicardial sites based on a training data set of previously recorded, high-resolution epicardial activation maps. Two key components of this approach are the content of the training set and the location and number of catheter electrodes. The topic of this study is the selection of venous catheter leadsets that can provide accurate estimation of activation maps.

Previously, we have shown that signals from venous catheters were highly correlated with those from nearby epicardial sites in terms of signal morphology and activation times [5]. These results provided the justification for a testing paradigm we have used in all subsequent studies; from a high-resolution epicardial electrode array we selected a subset of electrodes (limited-lead subset) that lay near the coronary veins and treated these electrodes as surrogates for true catheter measurements.

Throughout the history of electrocardiography, selection of the best electrode locations has been either an explicit or an implicit component of investigation. Although most studies focused on body-surface electrode locations, the same basic ideas apply to selecting leads in and on the heart. The goal remains to place electrodes and measured leads (potential differences) in a way that is maximally sensitive to important electrophysiologic or diagnostic features of cardiac electrical activity. There have been a number of studies attempting to determine optimized leadsets based on statistical approaches [6], [7]. Lux, Smith, Wyatt and Abildskov developed an algorithm for the selection of limited numbers of leads that resulted in practical lead systems used in the body-surface potential mapping [8]. This algorithm used the spatial covariance of the body surface signals to select leads that possess the highest average correlated power with all other sites.

In this study, we compared strategies for lead selection with the overall goal of developing a tractable and clinically relevant strategy for limited lead mapping of epicardial activation.

II. Methods

In all the experiments we acquired the epicardial signals using a 490-electrode sock array with an average interelectrode distance of approximately 4.3 mm. Digitization of

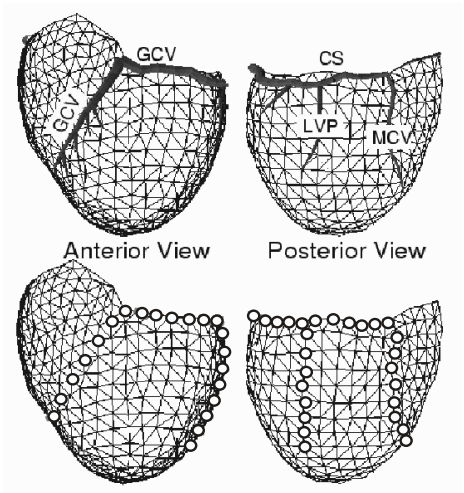

Fig. 1. A diagram representing the 490-lead epicardial sock. The 490 electrodes are located at the nodes of the mesh; larger dots indicate the 42 leads used as a surrogate catheter subset. The vessels include great cardiac vein (GCV), the coronary sinus (CS), the left ventricular posterior vein (LVP), and the middle cardiac vein (MCV).

the electrode locations yielded a three-dimensional geometric model of the recording sites and the coronary vessel anatomy. We then identified 42 electrodes that lay along the major, superficial coronary veins thus establishing a set of surrogate catheter leads, as shown in Fig. 1. The vessels included in the model were the great cardiac vein (GCV), the coronary sinus (CS), the left ventricular posterior vein (LVP), and the middle cardiac vein (MCV). The resulting set of electrode sites had a mean spacing of 6 mm and served as the full, control electrode set from which we then subsampled according to the strategies listed below.

We performed 14 dog experiments, which were approved by our institution's animal care and use committee, to create the epicardial activation map database. The two canine preparations used were an *in situ* intact animal with exposed heart and an isolated heart suspended in a torso-shaped tank. We created a database for this study that included 592 epicardial activation maps which we divided into training and test data sets. The training data set included beats from 12 normal, healthy hearts paced at a total of 470 different ventricular sites (239 right ventricular and 231 left ventricular pacing sites). The purpose of using single site stimulation in both of the training and the test sets was to simulate the early activation that occurs in reentrant and focal tachycardias due to ectopic activity. The test set included beats paced from both both ventricles (53 right ventricular and 69 left ventricular pacing sites) and the following intervention groups: (1) 75 beats from two different experiments in healthy animals and (2) 47 beats from animals following interventions such as 5-day old infarctions from coronary ligation or after injecting ethanol into the coronary arteries to create acute infarction.

We recorded time signals (electrograms) from the high-resolution sock array using our custom-built data acquisition system simultaneously with 1 kHz sampling rate and 12-bit resolution. Postprocessing of the signals consisted of the selection of one relatively high-quality beat from a three-second recording for subsequent activation-time determination. For each lead we computed the activation time using the minimum-time-derivative method and then carried out manual quality control using our custom-built visualization software.

A. Estimation method

We first selected L catheter leads as known and the remaining leads (490-L) comprised the unknown leads, *i.e.*, leads that are not accessible from the coronary veins. The known leads were a subset of the full set of 42 surrogate catheter leads. We reordered the training set in such a way that the known values comprised the first L rows then calculated the covariance matrix. The covariance matrix consisted of auto-covariance, $\mathbf{C_{kk}}$ and $\mathbf{C_{uu}}$, and cross-covariance diagonal blocks, $\mathbf{C_{ku}}$ and $\mathbf{C_{uk}}$. The minimum least-squares estimator was then computed by solving the simple matrix equation $\mathbf{T} = \mathbf{C_{ku}^T C_{kk}^{-1}}$. The multiplication of the estimator with the vector of the selected known values gave the estimated values on the unknown sites. In the computation of the inverse of $\mathbf{C_{kk}}$, we used the truncated singular-value decomposition technique. The subset singular values used in the truncation were those whose summation equaled 99.1% of the sum of all of them.

B. Testing paradigms

To evaluate the performance of the estimation, we used two testing paradigms; "Leave-one-map-out" (LMap) and "Separate-test-set" (STest). The first paradigm, LMap, consisted of using the 470-map training set both as training and test data. In LMap, we kept the map to be estimated (test map) out of the training data set and trained the transformation matrix, $\mathbf{T}$, with the remaining maps. Repeating this process for each of the maps in the database and then comparing each test map to the associated estimate provided a means of computing overall statistics that included beats from a range of pacing sites. In the second paradigm, STest, training data did not include any maps from the hearts used for the test data. This latter protocol most closely represents the anticipated clinical application of the estimation method because the training and test data came from totally different animals.

We compared estimate and actual maps for all cases by means of two error metrics: 1) the Euclidean distance between the actual and the estimated site of earliest activation, LDist and 2) the percentage of cases in which LDist was larger than 12.9 mm (three times the mean inter-electrode distance).

C. Leadset analysis

The leadset analysis has two components: (1) investigation of different catheter lead selection methods, (2) determination of optimal number of leads to be used in the estimation approach.

1) Location of leads: Result from a previous study with a smaller database indicated that leadset selection had at least some bearing on the accuracy of the resulting estimation [9] and set out here to examine this behavior in more detail. For this, we investigated four different leadset selection approaches; 1) regularly spaced leads, 2) average-power-based sequentially selected leads, 3) best-mean-Euclidean-distance based sequentially added leads, and (4) best-mean-Euclidean-distance based sequentially removed (or eliminated) leads, which we referred to as "regular leads," "SSS leads," "minLDist-add leads," and "minLDist-remove leads," respectively. The subsampled vascular leadsets consisted of 21, 14, and 10 sites in all four approaches.

In the first method, the regular leads were approximately evenly spaced along the associated veins with mean inter-electrode distances of 11.5, 17, and 24 mm. The criterion for the subsampling was to maintain the uniformity in spacing and similar coverage of the veins as in the 42-lead full set.

The second method used a slightly modified version of the selection algorithm that was developed in [8] for body surface potential mapping in determining the SSS leads. Each individual selection was an optimal selection (at least in a least-squares sense). Our modification was to select the leads to be used from the surrogate catheter locations instead of all sites on the epicardium. Thus, we chose the sites corresponding to the coronary veins which had the highest average correlated power with all the sites on the sock geometry.

The third approach that we developed was based on the estimation approach itself. Starting from six SSS leads, we added one lead from the remaining possible surrogate catheter sites and applied estimation using these seven leads, thus determining the lead resulting in the best mean LDist over all test maps (STest testing paradigm). We continued adding leads using the same criterion, thereby obtaining leadsets which gave the minimum mean LDist results (minLDist-add).

The fourth approach consisted of the successive elimination of single leads starting from 42-lead set (full set) such that the remaining leads performed with the highest accuracy (best mean LDist) among all possible combinations. Thus, we were able to remove successively the lead that least degraded the performance of the estimation technique. Successive removal continued in this manner until the desired number of leads remained.

2) Number of leads: To evaluate the effect of the number of leads on estimation accuracy, we applied each of the SSS leads, minLDist-add leads, and minLDist-remove leads selection methods to generate the best leadset for each possible number of leads from the original 42 surrogate catheter leads down to a single lead. For each leadset we computed LDist.

III. Results

A. Location of leads

Table I summarizes the results of the selection method comparison for different numbers of leads and test beats paced from the left ventricle (LV) and right ventricle (RV), using the LMap testing paradigm. The table shows the consistently diminishing performance with fewer leads except for the case of regularly spaced leads going from 21 to 14 for LV paced beats; in this case, performance was better with 14 leads than with 21.

Maps with LV pacing site		
Leadset	LDist	$> 12.9\ mm$ %
21 Regular leads	8.42 ± 5.5	23
21 SSS leads	8.36 ± 5.4	19
21 MinLDist-add leads	8.50 ± 5.2	18
21 MinLDist-remove leads	8.10 ± 5.4	17
14 Regular leads	8.18 ± 5.0	15
14 SSS leads	8.90 ± 5.5	23
14 MinLDist-add leads	9.00 ± 5.3	22
14 MinLDist-remove leads	9.58 ± 5.8	27
10 Regular leads	9.24 ± 5.8	23
10 SSS leads	10.95 ± 6.2	34
10 MinLDist-add leads	9.46 ± 5.2	24
10 MinLDist-remove leads	11.34 ± 6.5	36
Maps with RV pacing site		
21 Regular leads	12.98 ± 8.0	44
21 SSS leads	12.67 ± 8.1	43
21 MinLDist-add leads	13.42 ± 8.4	46
21 MinLDist-remove leads	12.91 ± 7.9	49
14 Regular leads	13.39 ± 8.4	44
14 SSS leads	12.92 ± 8.0	43
14 MinLDist-add leads	13.78 ± 9.2	47
14 MinLDist-remove leads	13.50 ± 7.8	49
10 Regular leads	16.46 ± 10.5	55
10 SSS leads	13.62 ± 8.4	46
10 MinLDist-add leads	13.83 ± 9.0	49
10 MinLDist-remove leads	14.14 ± 8.8	49

TABLE I

SUMMARY OF ESTIMATION ERROR FOR DIFFERENT NUMBER OF LEADS AND SELECTION METHODS ON THE LEFT AND RIGHT VENTRICULARLY PACED BEATS USING THE LMAP TESTING PARADIGM.

Fig. 2 illustrates sets of estimation results for one case with a pacing site on the mid-anterior LV using the four methods of leadset selection investigated in this study. The topography of the maps supports the statistical summary results. All four methods yielded similar accuracy levels and similar estimated activation patterns.

B. Number of leads

Fig. 3 contains a comparison of the three selection methods (SSS, minLDist-add, and minLDist-remove) for each number of selected leads. For the minLDist-add method, the estimation performance improved until approximately 15 leads were included in the leadset and stayed at the same level for the rest of the lead additions. With the other two methods, SSS and minLDist-remove, the mean LDist decreased with increasing number of leads in the set; however, again after 15 leads the improvement was relatively small.

IV. Discussion

The goal of this study was to improve our understanding of the statistical estimation approach by investigating and optimizing one of its key components. We addressed the specific aim of determining the role of leadset selection in the

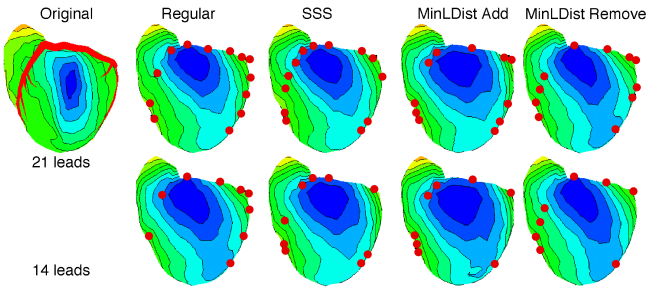

Fig. 2. Estimation results of different leadset selection methods using 21 and 14 leads for a map paced from the mid-anterior LV using LMap testing paradigm. Blue indicates the early activation. To most clearly reveal the earliest site of activation and the details of the activation sequence, we used local scaling for each of the activation maps, *i.e.*, the mapping of value to color is specific to each case. In all maps, blue and red indicate early and late activation, respectively, and the spacing between isocontours was approximately 7 to 10 ms throughout. Red tubes in the first panel of the figure represent the coronary veins which we used to select the best matching surrogate catheter leads. The red squares on each estimated map locate the selected catheter leads with the different methods.

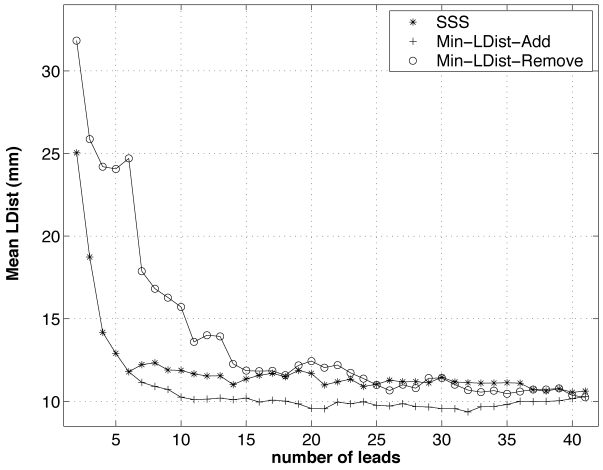

Fig. 3. Comparison of estimation performance for different number of leads obtained from three different selection methods.

accuracy of catheter based estimation, specifically the effect of lead location and number.

The comparison of selection methods showed that regularly spaced leadsets performed similarly to leadsets selected using the other methods we tested; the statistical sequential selection and the best-mean-Euclidean-distance based sequential addition and removal methods. This result suggests that instead of using specifically distributed leads on each venous branch, regularly spaced leads will not only be much more practical but will maintain the same performance. Hence the same catheter design could be used for each branch. Furthermore, we found that an inter-electrode distance of approximately 1 cm would be adequate for the estimation technique.

In these studies, we did not address the problem of determining the closest sock leads corresponding to the catheter leads during the catheterization procedure. Instead we used surrogate leads which lay along the coronary veins. Our goal was to evaluate the potential for the technique rather than solve all associated engineering challenges.

Although we have shown that this approach to epicardial mapping is quite feasible and accurate, its application to clinical practice will require overcoming additional technical hurdles. Perhaps the first is the need to acquire high-resolution epicardial maps with which to build the necessary database. Obtaining such data does require direct access to the heart. However, open-chest surgery is still a relatively frequent occurrence for such procedures as valve repair and replacement and coronary artery bypass grafts. The time required during such procedures to obtain epicardial maps is just minutes, so that it might not present substantial additional burden to the patient.

The results of this study encourage further effort and provide evidence that an epicardial mapping approach based on venous catheter measurements is feasible and also provides adequate accuracy for clinical applications. With the advances in transthoracic access to the pericardial space, catheter ablation of cardiac arrhythmias is very feasible [3], such an estimation approach will complement epicardial ablation treatment as a minimally invasive diagnostic technique.

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