Proceedings of the 28th IEEE
EMBS Annual International Conference
New York City, USA, Aug 30-Sept 3, 2006

Arrhythmia Source Localization from Intravenous and Transthoracic Catheter Measurements

Bülent Yılmaz[1], Uğur Cunedioğlu[1] and Oğuzhan Cakır[2]
[1]Biomedical Engineering Department, Baskent University
[2]Electrical and Electronics Engineering Department, Baskent University
Baglica Kampusu Eskisehir Yolu 20. km, 06530, Ankara, Turkey

Abstract— **Catheter-based epicardial mapping is possible with two access methods: Transthoracic access and transvenous access. Transthoracic access requires lengthy sequential mapping procedures and stable arrhythmias. Transvenous access uses the multielectrode (4-to-20 electrodes) catheters placed in the coronary veins, however, leaves most of the epicardium inaccessible to direct measurement. The aim of this present study is to demonstrate that the reconstruction of the high-resolution maps using sparse measurements from different sites on the epicardium and on the multielectrode catheters is possible with a reasonably high accuracy in terms of locating the origin of the ventricular arrhythmia. In this study we investigated strategies for recordings of transvenous and transthoracic epicardial mapping catheters, alone and in combination. For this purpose, we first examined the problem of best sampling resolution using transthoracic mapping catheters and secondly studied the feasibility of the combined usage of both mapping approaches. We evaluated two prediction methods; the Laplacian interpolation and statistical estimation. We performed 14 dog experiments to create a high-resolution epicardial potential map database. We found that 2 cm sampling resolution is quite feasible. The combined usage of transvenous and transthoracic mapping approaches improved the accuracy significantly. The results of this study encourage further investigation and provide adequate evidence for the clinical applicability of such an epicardial mapping method based on catheters.**

Index Terms— **ventricular arrhythmias, catheter mapping, Laplacian interpolation, statistical estimation**

I. INTRODUCTION

Cardiac electrophysiological (EP) studies are used to capture the complete or partial picture of the electrical activity on the heart by acquiring spatiotemporal information from the heart. EP studies that are limited to the endocardium fail to localize the source of arrhythmias when arrhythmic substrates are located deep in the subendocardium or in the subepicardium [2]. A recent extensive study [7] has shown that in 80% of the patients with failed radiofrequency (RF) ablation for ventricular tachycardia the source of the arrhythmia is epicardial/subepicardial.

Epicardial mapping in which conventional [8] or specialized electroanatomical catheters [7] introduced into the pericardial space through a puncture on the thorax (transthoracic access) have been found to be highly efficient in this subgroup of patients. The disadvantage of this approach is that it requires lengthy sequential mapping procedures and stable arrhythmias. Inducing and maintaining an arrhythmia in an EP laboratory for a long duration may be a dangerous situation for patients whose hearts are hemodynamically unstable. Another epicardial mapping approach uses the multielectrode (4-to-20 electrodes) catheters placed in the coronary veins (transvenous access) [1]. Their design (outer diameter is around 0.8 mm) permits insertion of multiple catheters using one guide-wire, therefore, simultaneous mapping of different regions of the heart is possible. This approach increases the speed of the mapping procedure. The major limitation of these catheters, however, is their restricted access via coronary veins, which leaves most of the epicardium inaccessible to direct measurement.

In addition to these techniques, a novel mapping approach targeting the epicardium which is based on combining the sparse epicardial transthoracic catheter measurements and intravenous multielectrode catheter measurements has a potential. Decreasing the number of transthoracic measurements and compensating this by the intravenous catheter measurements can improve the efficiency of the procedure and result in fast mapping during an induced arrhythmia.

There are two straight-forward approaches to predicting surrogate measurements at inaccessible sites from the measurements localized to the cardiac veins and sparse epicardial sites: (1) interpolation, which assumes some a priori knowledge of the relationship between measured and predicted values, *eg.,* a polynomial function that fits the measured values, and (2) "statistical estimation," which creates such a relationship by means of analyzing a previously acquired "training data set."

Previously, Kuenzler *et al.* showed that signals acquired from venous catheters were highly correlated with those from nearby epicardial sites in terms of signal morphology [3]. 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.

The aim of this present study is to demonstrate that the reconstruction of the high-resolution maps using sparse measurements from different sites on the epicardium and on the multielectrode catheters is possible with a reasonably high accuracy in terms of locating the origin of the ventricular arrhythmia. This study addresses a critical engineering aspect of a potential approach based on the combined usage of the transthoracic and intravenous catheters by examining the effect of degree of resolution (or sparsity) of the electrical

1-4244-0033-3/06/$20.00 ©2006 IEEE.

activity recording sites on the epicardium and the sites on the multielectrode catheters and their combination on solution accuracy. Here we evaluated several resolution levels and prediction methods.

Our evaluation of these hypothesis and the resulting prediction methods was based on a database of 592 beats recorded from 14 different animals. We sampled the epicardial potentials using a flexible sock electrode array containing 490 unipolar electrodes and stimulated the activations via unipolar pacing from all over the epicardium. Thus, we simulated focal ventricular tachyarrhythmias originating from different sites on the epicardium. The results from this study showed that combining the transvenous and transthoracic access methods for the mapping of the epicardium is indeed feasible and improves the high-resolution map reconstruction accuracy.

II. METHODS

A. Experimental Setup

This study includes 14 dog experiments, which were approved by the University Utah's animal care and use committee, to create a high-resolution epicardial potential distribution database (a total of 592 beats). We recorded epicardial electrograms by using a 490-electrode sock array (average distance between electrodes was 4.3 mm). We defined the 21-lead surrogate venous catheter subset on the locations of the selected large coronary vessels. We also assumed that all the measurements from the electrodes on the sock could be used as surrogates for transthoracic mapping recordings. This allowed us considerable flexibility in the selection and evaluation of the number and placement of such surrogate electrodes while still creating realistic conditions for potential clinical applications of the technique. The maps in our database were separated into two sets; training and test data sets. The training data set was obtained by electrically stimulating (pacing) a total of 470 different ventricular sites (beats with 239 right ventricular (RV) and 231 left ventricular (LV) pacing sites) in 12 dogs. The test set included a total of 122 beats from two experiments (53 maps with RV and 69 with LV pacing sites). We used a custom-built data acquisition system that was capable of sampling and saving continuously to magnetic disk up to 1024 channels with 1 kHz sampling rate. Processing of the resulting signals consisted of selecting one representative and relatively high-quality beat from each 3-second recording.

In this study we created our database first by extracting the QRS complexes from each electrogram and then by concatenating them to form a matrix of 490-by-N, where N is the total number of frames (QRS duration of each beat multiplied by the number of total beats included in the database). N was 48347 for the training set and 9777 for the test set.

B. Statistical estimation algorithm

Details of the linear minimum mean-squared Bayesian estimation algorithm applied to this problem have been reported elsewhere [10]. Briefly, we first defined the training database and selected the surrogate catheter leadset (L leads). We assumed that those L leads contained "known" values (surrogates for the venous catheter leads) and the remaining 490-L leads (for which we wished to estimate values) contained "unknown" activation values. We reordered the training set in such a way that the known values comprised the first L rows and then calculated the covariance matrix. The estimation matrix, $\mathbf{E}$, is formed by solving the simple matrix equation, $\mathbf{E} = \mathbf{K_{ku}}^T \mathbf{K_{kk}}^{-1}$, where $\mathbf{K_{kk}}$ is the auto-covariance of the known leads and $\mathbf{K_{uk}}$ is the cross-covariance of known and unknown leads.

Left multiplication by $\mathbf{E}$ of any measurement vector of the known leads yields an estimate of the values at all remaining sites and thus a complete, high-resolution map. In the computation of the inverse of $\mathbf{K_{kk}}$, we used the truncated-singular value decomposition (SVD) technique. In the computation of the inverse of $\mathbf{K_{kk}}$, we used the truncated singular-value decomposition technique [6]. The number of singular values used in the truncation was set equal to the number of largest singular values whose summation comprised 99.9% of the cumulative sum of all of them.

C. Laplacian interpolation

Van Oosterom *et al.* developed the Laplacian interpolation scheme for body surface potential mapping [9]. MacLeod *et al.* have tested the method on experiments with an electrolytic torso tank and extended its use to epicardial surface potentials [4]. This method has two conceptual steps. First, a local approximation of the second order spatial gradient (the surface Laplacian) is defined over all the points in the geometry. In the second step, the values at unmeasured points in the geometry are adjusted so as to globally minimize the Laplacian [5].

$$\Delta^2 f(x_0) \approx \frac{4}{\bar{h}}\left(\frac{1}{n}\sum_{i=1}^{N}\frac{f_i}{h_i} - \overline{1/h} f(x_0)\right) \tag{1}$$

h_i is the distance between the node at which the potentials are interpolated and i^{th} neighbor with value f_i. $\bar{h}$ is the mean distance to all n neighbors, and $\overline{1/h}$ is the mean inverse distance to all n neighbors. The minimization step can be expressed as a matrix equation that requires the solution of a well-behaved overdetermined system, which can be solved using a standard least-squares method.

D. Spatial sampling resolution of transthoracic mapping

In this study we investigated strategies for the reconstruction of epicardial potential distribution from recordings of transvenous and transthoracic epicardial mapping catheters, alone and in combination. For this purpose, we first examined the problem of best number of epicardial measurement sites (or best sampling resolution) using transthoracic mapping catheters and secondly studied the feasibility of the combined usage of both mapping approaches. In order to determine the best spatial sampling resolution of transthoracic catheter-based mapping we tested three different resolution levels (average distance between measurement sites); 1 cm, 2 cm, and 4 cm. An average of 1 cm resolution sampling was

possible using 121 leads out of a 490-lead set. Similarly, for a 2 cm resolution 30 leads and for 4 cm resolution only 8 leads were used. These leads were selected manually in order to maintain a regular distribution on the epicardium. We assumed that the measurements from these leads were available (known values) and the remaining leads (out of 490 leads 369, 460, and 482 leads were assumed to be unknown, respectively) were predicted using the statistical estimation and Laplacian interpolation methods.

E. Combination of mapping approaches

The feasibility study of the combination of the two above-mentioned mapping approaches was based on the usage of only the venous catheter electrode measurements as the starting point ("Cath21") and then adding 8 and 30 surrogate transthoracic measurements ("Cath21+Carto8" and "Cath21+Carto30", respectively). For the sake of consistent comparison the added leads were the same with the ones that were used in the previous step of this study.

F. Testing paradigms and error metrics

To evaluate the performance of the statistical estimator, we used a "separate-test-set" protocol (STest), in which training data did not include any beats from the hearts that were used to obtain test data. In the evaluation of the Laplacian interpolator, we only used the test data so that a good comparison of the results between two prediction methods was possible. Comparing the test data to the associated reconstruction for each of the frames in the test data set provided a means of computing overall statistics that included beats from a range of pacing sites. The error criteria used was the correlation coefficient(CC) and root-mean squared error (RMSE):

$$CC = \frac{\sum_{i=1}^{N}\left(V_i^m - \overline{V^m}\right)\left(V_i^e - \overline{V^e}\right)}{\sqrt{\sum_{i=1}^{N}\left(V_i^m - \overline{V^m}\right)^2}\sqrt{\sum_{i=1}^{N}\left(V_i^e - \overline{V^e}\right)^2}} \quad (2)$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}\left(V_i^e - V_i^m\right)^2}{N}} \quad (3)$$

where V_i^m represents the measured values and V_i^m represents the estimated values, $\overline{V^m}$ is the mean of the V_i^m's and $\overline{V^e}$ is the mean of the V_i^e's, N is the number of samples compared. CC shows more sensitivity to differences in pattern than amplitude of the signals. The RMSE represents the average squared error between signals in absolute terms.

III. RESULTS

A. Spatial sampling resolution of transthoracic mapping

Table I contains the summary of reconstruction error statistics for the Laplacian interpolation and the statistical estimation using different number of leads (*i.e.,* spatial resolution levels). In the context of transthoracic sampling (Carto# of leads rows on the table), the table shows the trend of consistent improvement in reconstruction accuracy with the increase in the number of leads used in prediction methods.

Method	# of leads	CC (mean±std)	RMSE(mean±std)
Laplacian	Carto121	0.90 ± 0.11	3.71 ± 1.75
	Carto30	0.77 ± 0.21	5.41 ± 2.59
	Carto8	0.56 ± 0.27	8.18 ± 4.46
	Cath21	0.05 ± 0.34	14.23 ± 9.24
	Cath21+Carto8	0.69 ± 0.25	6.70 ± 3.54
	Cath21+Carto30	0.81 ± 0.19	4.94 ± 2.43
StatEst	Carto121	0.91 ± 0.10	3.77 ± 1.74
	Carto30	0.78 ± 0.20	5.37 ± 2.58
	Carto8	0.57 ± 0.28	7.51 ± 3.96
	Cath21	0.57 ± 0.28	7.75 ± 4.18
	Cath21+Carto8	0.70 ± 0.23	6.32 ± 3.28
	Cath21+Carto30	0.82 ± 0.18	4.90 ± 2.39

TABLE I

SUMMARY OF RECONSTRUCTION ERROR STATISTICS FOR THE LAPLACIAN INTERPOLATION AND THE STATISTICAL ESTIMATION USING DIFFERENT NUMBER OF LEADS (SPATIAL RESOLUTION LEVELS). CORRELATION COEFFICIENT (CC) AND ROOT-MEAN SQUARED ERROR (RMSE) ARE GIVEN IN TERMS OF THEIR MEANS ± STANDARD DEVIATIONS.

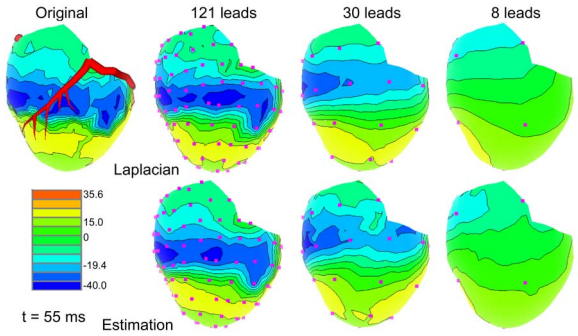

Fig. 1. An example of epicardial potential distribution reconstruction for the Laplacian interpolation and the statistical estimation using different number of surrogate transthoracic measurement sites. This figure shows the original (left most column) and reconstructed potential maps paced from the left ventricle using the Laplacian interpolation (upper row) and statistical estimation (lower row). The maps indicate the original and reconstructed epicardial potential distributions "55 ms" after the pacing. See text for the details.

Figure 1 shows examples of epicardial potential distribution reconstructions for the Laplacian interpolation and the statistical estimation using different number of surrogate transthoracic catheter leads on a case in which the heart was paced from a anterobasal left ventricular site. The maps are the original and predicted epicardial potential distributions "55 ms" after the pacing. The surrogate measurement locations on which the potential values were assumed to be known are represented with pink dots on the predicted maps. Predictions obtained from the highest resolution sampling most faithfully replicated the original high-resolution map. We note that both prediction methods performed similarly.

B. Combination of mapping approaches

Table I also contains the summary of reconstruction error statistics for the investigated two methods for different number of combined transthoracic and intravenous surrogate

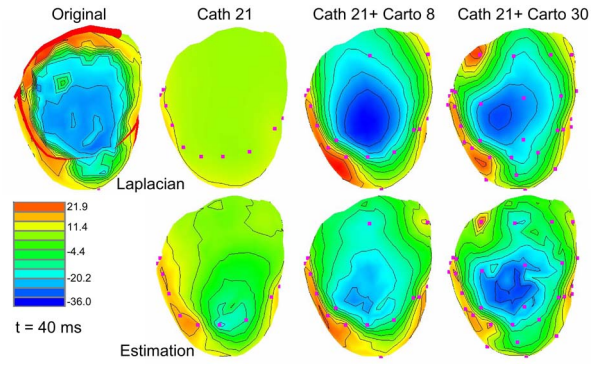

Fig. 2. An example of the results for the combination of transthoracic surrogate leads with the intravenous catheter measurements in order to reconstruct the potential distribution on the epicardium from 21 to 51 leads using the Laplacian interpolation and the statistical estimation. This figure has the same configuration with the previous figures. The maps indicate the original and reconstructed epicardial potential distributions "40 ms" after a pacing on a posterolateral right ventricular site.

measurement sites. The table shows the consistent improvement in the performance of the prediction methods with the increase in the number of measurement sites.

Figure 2 shows examples of epicardial potential distribution reconstructions for the two prediction methods with only 21 intravenous catheter recordings and after the addition of 8 and 30 leads which are assumed to be the surrogate transthoracic catheter measurement sites. We note that both Laplacian interpolation and statistical estimation methods performed similarly except the case in which the reconstruction was based on only 21 intravenous catheter leads. The sparsity of the sampling was too high.

IV. DISCUSSION

The aim of this study was to develop strategies for the reconstruction of epicardial potential distribution from recordings of intravenous and transthoracic epicardial mapping catheters, alone and in combination. Specifically, we tested three different resolution levels for the transthoracic catheter-based epicardial mapping; 1 cm, 2 cm, and 4 cm and found that 2 cm sampling resolution is quite feasible. The study of the combination of the two approaches was based on the usage of the intravenous catheter electrode measurements as the starting point and then adding 8 and 30 transthoracic surrogate catheter measurements. The addition of epicardial leads to the intravenous catheter leads improved the reconstruction accuracy both in terms of activation propagation pattern and potential values.

Clinicians already make use of the information from these catheters to reveal local electrical activity in arrhythmia cases but are unable to identify and localize events that occur more than a few millimeters from the veins. Once there is adequate evidence to suggest epicardial involvement, there are also methods by which to bring radio-frequency ablation catheters to the critical sites and carry out treatment. Therefore, there exists both a need to develop techniques for mapping epicardial arrhythmias and an emerging diagnostic technology that could lead to a treatment paradigm. We concentrated in this study on epicardial mapping even though the approaches we describe also apply to endocardial mapping.

The results of this study encourage further investigation and provides adequate evidence that an epicardial mapping approach based on intravenous and transthoracic catheter measurements is feasible and can provide adequate accuracy for clinical applications. With the advances in transthoracic access to the pericardial space in order to apply catheter ablation of cardiac arrhythmias, this approach will complement this type of treatment.

V. ACKNOWLEDGMENT

We gratefully acknowledge Dr, Robert S. MacLeod, Dr. Bruno Taccardi, Dr. Bonnie B. Punske, Jayne Davis, Matt Allison, Dr. Phil Ershler, and Bruce Steadman at the CVRTI, for their assistance in the experiments. We thank Dr. Jeroen Stinstra and Dr. Dana H. Brooks for their thoughtful suggestions.

REFERENCES

[1] A.A. de Paola, W.D. Melo, M.Z. Tavora, and E.E. Martinez. Angiographic and electrophysiological substrates for ventricular tachycardia mapping through the coronary veins. *Heart (CEN)*, 79(1):59–63, 1998.

[2] W. Kaltenbrunner, R. Cardinal, M. Dubuc, M. Shenasa, R. Nadeau, G. Tremblay, M. Vermeulen, P. Savard, and P.L. Page. Epicardial and endocardial mapping of ventricular tachyarrhythmia in patients with myocardial infarction. Is the origin of the tachycardia always subendocardially localized? *Circ.*, 84:1058–1071, 1991.

[3] R.O. Kuenzler, R.S. MacLeod, B. Taccardi, Q. Ni, and R.L Lux. Estimation of epicardial activation maps from intravascular recordings. *J. Electrocardiol.*, 32(2):77–92, April 1999.

[4] R.S. MacLeod and C.R. Johnson. Map3d: Interactive scientific visualization for bioengineering data. In *Proceedings of the IEEE Engineering in Medicine and Biology Society 15th Annual International Conference*, pages 30–31. IEEE Press, 1993.

[5] Quan Ni. *Assessment of Spatial and Temporal Information in Electric Activity of the Heart*. PhD thesis, University of Utah, 2000.

[6] W.H. Press, B.P. Flannery, S.A. Teukolsky, and W.T. Vetterling. *Numerical Recipes: The Art of Scientific Computing*. Cambridge University Press, Cambridge, New York, Melbourne, 1986.

[7] R.A. Schweikert, W.I. Saliba, G. Tomassoni, N.F. Marrouche, C.R. Cole, T.J. Dresing, P.J. Chou, D. Bash, S. Beheiry, C. Lam, L. Kanagaratnam, and A. Natale. Percutaneous pericardial instrumentation for endo-epicardial mapping of previously failed ablations. *Circ.*, 108:1329–1335, 2003.

[8] E. Sosa, M. Scanavacca, A. d'Avila, and F. Pilleggi. A new technique to perform epicardial mapping in the electrophysiology laboratory. *J. Cardiovasc. Electrophysiol.*, 7:531–536, 1996.

[9] A. van Oosterom T.F. Oostendorp and G.J. Huiskamp. Interpolation on a triangulated 3d surface. *J Comp Physics*, 80:331–343, 1989.

[10] B. Yılmaz, R.S. MacLeod, B.B. Punske, B. Taccardi, and D.H. Brooks. Venous catheter based mapping of epicardial ectopic activation: Training set selection for statistical estimaiton. *IEEE Trans. Biomed. Eng.*, 52(11):1823–1831, 2005.