A Comparison of Methods for Estimating Endocardial Potentials from a Noncontact Probe

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Abstract

In this paper we compare zero and first order Tikhonov and Generalized Eigensystem (GES) regularization for estimating the endocardial potentials from measured potentials on a noncontact probe. In all cases, the Composite Residual Error and Smoothing Operator (CRESO) was used to estimate the regularization parameter. In this limited study the use of higher order regularization produced larger average correlation coefficients between the estimated and measured endocardial electrograms.

1. Introduction

In this paper, we compare zero and first order Tikhonov and Generalized Eigensystem (GES) methods for estimating the endocardial potentials from potentials measured on a noncontact probe inserted into one of the chambers of the heart. There have been numerous investigations into this type of inverse problem [1, 2, 3, 4, 5] and some new inverse techniques, such as spatial regularization, have been developed as unique approaches to solving this type of problem. However, this is the first attempt to apply the GES method to this problem and compare the effects of various regularization orders on the endocardial estimates.

2. Experimental data and model

An Ensite 3000^{TM} noncontact probe (Endocardial Solutions Inc.) was inserted into the left ventricle of a patient undergoing endocardial mapping. The Ensite system measured the location of the probe and the ablation catheter as the catheter was moved to twenty different locations in the left ventricle. At each location a sinus rhythm depolarization was recorded. These asynchronous recordings were then synchronized in time by aligning body surface ECG signals. A finite element model of the volume between the probe surface and the endocardial surface was generated using the volume model generated by the Ensite system.

3. Algorithms

Inverse Algorithms. Both Tikhonov regularization and the Generalized Eigensystem (GES) regularization methods can be formulated as solutions to the following minimization problem

$$\min_{\underline{\hat{e}}} \quad \Pi = ||\underline{\hat{p}} - \underline{p}||^2 + \lambda||\mathbf{R}\underline{\hat{e}}||^2 \tag{1}$$

where $\underline{p}$ is a vector of known (measured) probe surface potentials, $\underline{\hat{e}}$ and $\underline{\hat{p}}$ are estimates of the potentials on the endocardial surface and probe surface, respectively, $\mathbf{R}$ is the regularization operator, and λ is the regularization parameter. $\underline{\hat{p}}$ and $\underline{\hat{e}}$ are related through the modelling constraint $\underline{\hat{p}} = \mathbf{Z}\underline{\hat{e}}$ where $\mathbf{Z}$ is the transfer matrix. For zero order regularization, $\mathbf{R}$ is an identity matrix, and endocardial potential estimates with large amplitudes are penalized. For first order regularization, $\mathbf{R}$ is a surface gradient operator, and endocardial potential estimates with large spatial slopes are penalized. In general, we attempt to match the estimated probe surface potentials with the measured probe surface potentials, while penalizing endocardial estimates with large magnitudes or slopes. The regularization parameter λ indicates the relative weight given to the two terms, and needs to be estimated based on measurable data.

For Tikhonov regularization, we use the modelling constraint directly, and have the estimate

$$\underline{\hat{e}} \quad = \quad \left(\mathbf{Z}^T\mathbf{Z} + \lambda\mathbf{R}^T\mathbf{R}\right)^{-1}\mathbf{Z}^T\underline{p} \tag{2}$$

For the Generalized eigensystem methods [6, 7], we assume

$$\underline{\hat{p}} \quad = \quad \mathbf{\Phi}_P\underline{\alpha} \tag{3}$$

$$\underline{\hat{e}} \quad = \quad \mathbf{\Phi}_E\underline{\alpha} \tag{4}$$

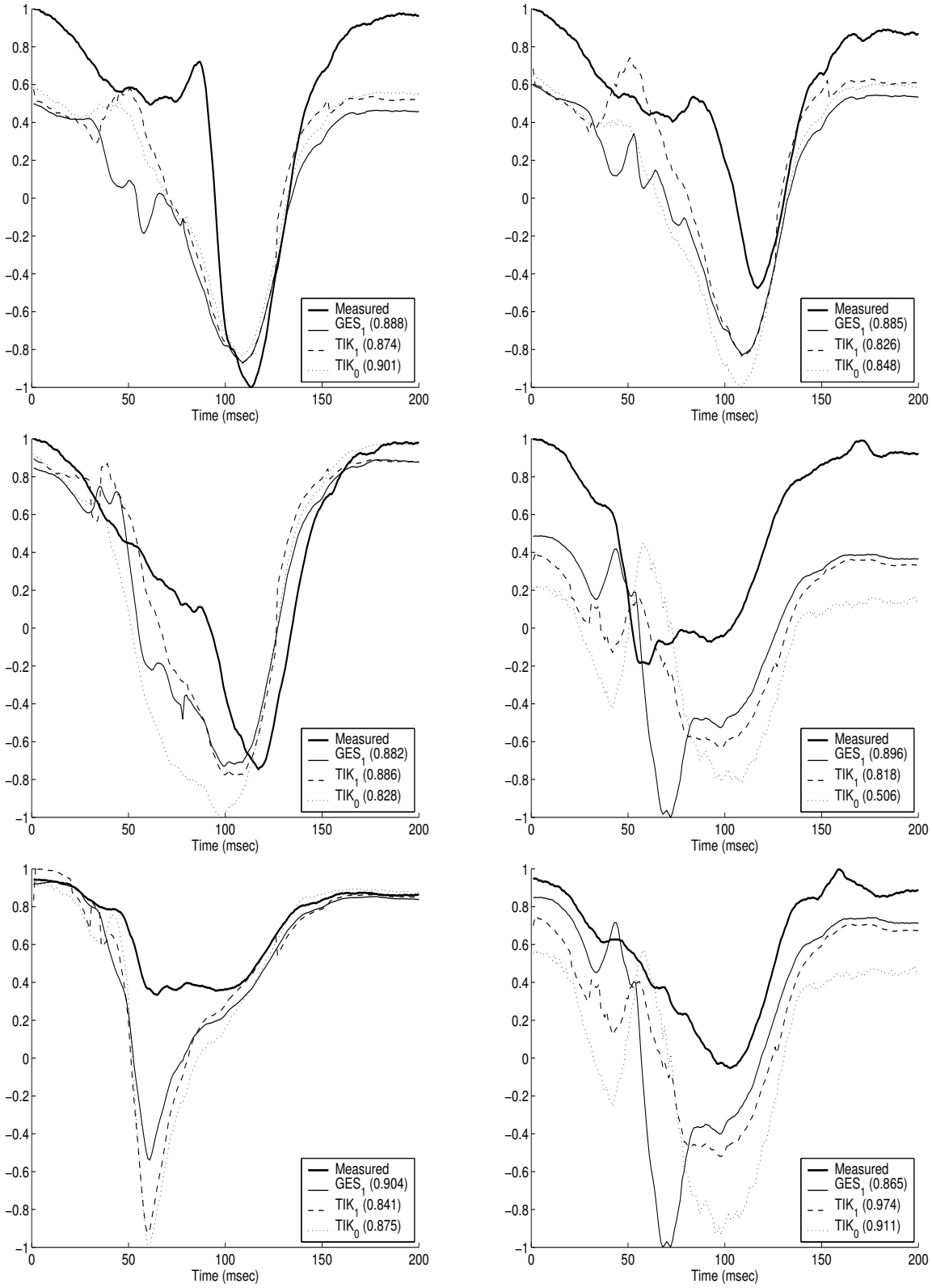

Figure 1. Measured and estimated endocardial potentials at six endocardial sites for zero order Tikhonov regularization (TIK_0), first order Tikhonov regularization (TIK_1), and first order GES regularization (GES_1). The ordinate is arbitrarily scaled from -1 to 1, while the abscissa indicates the time in milliseconds. The correlation coefficients between the estimated and true electrograms are displayed in the legend.

where $\mathbf{\Phi}_P$ and $\mathbf{\Phi}_E$ are suitably chosen matrices whose columns contain the expansion vectors, and $\underline{\alpha}$ is a vector of expansion coefficients. Note that the expansion vectors on the endocardium and probe surface are related through the transfer matrix $\mathbf{Z}$,

$$\mathbf{\Phi}_P \quad = \quad \mathbf{Z}\mathbf{\Phi}_E \tag{5}$$

Minimizing Π leads to the expression for $\underline{\alpha}$

$$\left(\mathbf{\Phi}_P^T\mathbf{\Phi}_P + \lambda\mathbf{\Phi}_E^T\mathbf{R}^T\mathbf{R}\mathbf{\Phi}_E\right)\underline{\alpha} = \mathbf{\Phi}_P^T\underline{p} \tag{6}$$

Since there were 64 sensors on the endocardial probe, we limited both methods to 64 modes.

Composite Residual Error and Smoothing Operator. Originally proposed by Colli-Franzone [8], CRESO is a commonly used method for determining the regularization parameter for Tikhonov regularization in inverse electrocardiography [9, 10]. CRESO finds the value of λ that maximizes the difference between the derivative of the smoothing term $\lambda||\mathbf{R}\underline{\hat{e}}||^2$ and the fit to the probe surface data $||\underline{\hat{p}} - \underline{p}||^2$. That is, we want to find the smallest value of λ which maximizes the function

$$B(\lambda) \quad = \quad \lambda||\mathbf{R}\underline{\hat{e}}||^2 - ||\underline{\hat{p}} - \underline{p}||^2 \tag{7}$$

CRESO was used for finding the regularization parameter for both Tikhonov and GES regularization.

4. Results and discussion

The average correlation coefficients between the estimated and measured endocardial electrograms were 0.667 and 0.754 for zero order GES and Tikhonov, and 0.871 and 0.849 for first order GES and Tikhonov, respectively. Figure 1 displays selected estimated and true (measured) endocardial potentials for zero order Tikhonov (TIK_0), first order Tikhonov (TIK_1), and first order GES (GES_1) for six of the twenty measured endocardial sites. The ordinate is arbitrarily scaled from -1 to 1, while the abscissa displays the time in milliseconds. The figure also includes the correlation coefficients between the estimated and measured endocardial electrograms for each method analyzed. These results are fairly typical of what we obtained for the twenty endocardial sites in that some estimates were very good, but other estimates appeared to be quite poor.

In this initial study, which included data from only one patient, the use of higher order regularization produced a significant increase in the average correlation coefficient between the estimated and measured endocardial electrograms for both of the regularization methods examined.

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