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A Patchwork Method to improve the performance of the current ECGI methods for sinus rythm

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1. Introduction

Noninvasive electrocardiographic imaging (ECGI) provides real-time panoramic images of epicardial electrical activity from potential measurements on the torso surface. This non-invasive imaging modality can become a powerful clinical tool to help understand the mechanisms underlying many cardiac diseases, and to define the appropriate treatment. ECGI is mathematically represented by a Cauchy problem for the Laplace equation

$$\begin{cases} \text{div}(\sigma \nabla u) = 0 \text{ in the torso volume,} \\ u = u_T \text{ and } \sigma \nabla u \cdot n = 0 \text{ on the torso surface,} \end{cases} \quad (1)$$

where u is the electric potential and σ the conductivity. This problem being ill-posed, regularization is needed to numerically solve u in the heart from the given u_T. Several numerical methods are commonly used for ECGI: the finite-element method (FEM), the boundary-element method (BEM) and the method of fundamental solutions (MFS). Each of them can be used with various regularization terms, leading to a wide range of possible algorithms. While the accuracy of these methods have been compared using different types of data [5], there is still no consensus that one method globally outperforms the others.

Validation studies have shown that ECGI provides accurate activation maps in healthy hearts to localize ectopic sources of ventricular activity [6] and characterize ventricular dyssynchrony [1]. However, current implementations are inaccurate in reconstructing electrical activity during sinus rhythm in the presence of conduction abnormalities such as LBBB [1, 3] and in structurally heterogeneous hearts [7]. Epicardial breakthrough sites can be missed or inaccurately localized, and artificial lines of block can appear. To prevent such artefacts we propose a method that locally selects, from several numerical solutions, the one that minimizes the estimated reconstruction error.

2. Patchwork method

2.1 Algorithm

We propose a patchwork method (PM) that locally selects the best solution among several methods. The linear relationship between the cardiac sources and the torso surface potentials after the discretization can be written in matrix form:

$$Au_h = u_T,$$

where A is the transfer matrix, obtained from multiple resolutions of the forward problem, u_h represents the unknown cardiac sources, and u_T the torso measurements. We denote by A_F, A_B and A_M the transfer matrices with the FEM, BEM and MFS. The residuals $R_\gamma(u_h) = A_\gamma u_h - u_T$, with $\gamma = F, B, M$ represent the difference between the numerical solution on the torso obtained with u_h and the measurements u_T.

Let us denote u^{ex} the array representing the exact solution of the inverse problem discretized on an epicardial mesh. For all methods, the residual of u^{ex} tends to zero when the mesh size tends to zero:

$$\lim_{h \to 0} R_\gamma(u^{ex}) = 0, \ \gamma = F, B, M,$$

We propose to use this property as a criterion to select locally, among several numerical solutions obtained with different algorithms, the one that is closest to the exact solution, without knowing what the exact solution is. As a first example, we compared the results obtained with the FEM and the MFS and a zeroth-order Tikhonov regularization.

Our algorithm is the following:

- For each time step n:
  - Compute the approximate solutions $u^n_{h,F}$ and $u^n_{h,M}$ with the FEM and the MFS,
  - Use these solutions to compute the forward solution and the associated residuals $R_B(u^n_{h,F})$ and $R_B(u^n_{h,M})$ on the torso surface using the BEM formulation,
  - For each epicardial point, select the method whose residual is the smallest on the nearest torso point, and define a coefficient α^n = 0 if the MFS has the smallest residual, and 1 otherwise,
- Perform a temporal regularization of the coefficient α to avoid sudden variations between successive time steps,
- For each time step n, compute the new approximate solution as

$$u^n_h = \alpha^n u^n_{h,F} + (1 - \alpha^n) u^n_{h,M}.$$

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2.2 Data

The method was tested using data generated with a detailed heart-torso model that was previously tailored to a patient. We used a set of 8 simulations, including 7 with tissue damage. Activation was simulated with a monodomain reaction-diffusion equation using the TNNP membrane model, at 0.2-mm resolution. Extracellular potentials were computed by solving the elliptic bidomain equation in a whole-torso model at 1-mm resolution. Damage patterns consisted of sheets of connective tissue aligned with the 3 coordinate axes [4]. The sheets were 0.4 mm thick and were placed at 1-mm intervals. 20 % of the surface of the sheets consisted of holes. The sheets extended through the entire myocardium but not through the thin layer that represents the Purkinje system in the model.

2.3 Evaluation test

Activation times were determined from ECGI electrograms using a spatio-temporal algorithm [2]. Correlation coefficients (CC) and relative errors (RE) were computed between ECGI-detected and true activation times. Epicardial breakthrough sites were identified from activation maps as sites with a local minimum in activation time. The centers of the early activation areas were taken as the breakthrough sites. We also calculated the localization error of the breakthrough sites (LE1-LE3) using the geodesic distance and the time difference between the ECGI-detected and the nearest actual breakthroughs. Statistical analyses were performed using GraphPad Prism 8.3. For each metric, the significance of the differences was tested using paired t-tests with $p < 0.05$ defined as significant. Data are expressed as mean $\pm$ SD.

3. Results and discussion

Figure 1 shows the correlation and relative error between activation maps of different methods. Activation maps reconstructed by PM were more correlated to the simulated maps than those recontructed by MFS and FEM (p = 0.0049). PM also reduced the RE for activation maps (p = 0.0009).

Table 1 presents numerical comparisons of ECGI-detected and the nearest true breakthroughs sites. MFS captured only 2 breakthrough sites and FEM sometimes missed one breakthrough. However PM always succeeded in detecting all the breakthrough sites. The localization error obtained by PM and MFS was smaller than that obtained by FEM. Time differences between ECGI-detected breakthroughs and the nearest actual breakthrough was similar for the three methods.

4. Conclusion

We presented a novel ECGI approach to reconstruct electrical activity in sinus rhythm in structurally abnormal hearts. This new approach, called the patchwork method, is an efficient tool to help overcome some of the limitations of current numerical methods, improving the accuracy of activation maps and localization of epicardial breakthroughs.

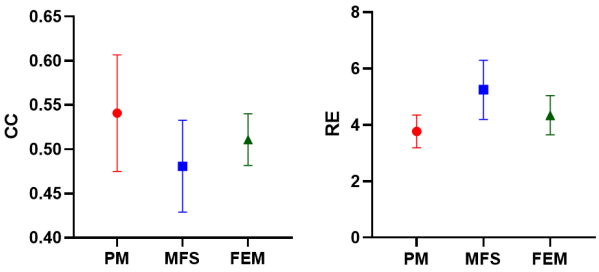

Figure 1: Correlation coefficients (CC) and relative errors (RE) for activation time for new method (PM), MFS and FEM.

		MFS	FEM	PM
N_{BT}	actual	3	3	3
	detected	2	2–3	3
LE (mm)	LE1	10.5±5.4	22.2±4.7	10.7±3.6
	LE2	5.0±1.2	7.9±2.6	5.0±1.2
	LE3			3.3±0.3
time offset (ms)	1	5.9±0.0	5.9±0.0	5.9±0.0
	2	5.9±0.0	5.9±0.0	5.9±0.0
	3			8.3±0.0

Table 1: Numerical comparisons of ECGI-detected and genuine epicardial breakthrough sites. N_{BT} = number of breakthroughs.

5. Acknowledgements

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