The Theoretical Basis Of Electrocardiology

Solving the Electrocardiography Inverse Problem by Using an Optimal Algorithm Based on the Total Least Squares Theory

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Abstract

The inverse problem of electrocardiography (ECG) is to estimate the activity of the heart from the measured body surface potentials (BSPs) using the numerical methods. Since it is ill-posed, it needs the dedicated numerical regularization process. The common regularization methods used in the ECG inverse problem, like Tikhonov regularization and Truncated Singular Decomposition (TSVD), are based on the linear least square, in which only the measurement noise in the right hand side BSP data is considered. In the paper, we attempt to investigate the ECG inverse problem with a full consideration of noises/errors appearing on both sides of the linear system equation Ax=b. Here, we solve the ECG inverse problem that reconstructs epicardial potentials (EPs) from BSPs by using an optimal algorithm based on the Total Least Squares (TLS) theory – Regularized TLS (RTLS), which has not been investigated in the bioelectromagnetic inverse problems. The algorithm is tested by using a realistic shaped heart-lung-torso model with inhomogeneous conductivities. The performance of the RTLS is compared with other conventional approaches like Tikhonov and TSVD. In the numerical experiments, the EPs are reconstructed with a combination of measurement noise and/or geometry errors. The simulation results demonstrate that, in most cases, RTLS performs better than Tikhonov and TSVD. With proper physiological constraints, RTLS is able to robustly reconstruct EPs from BSPs, and therefore is a promising, feasible alternative for the ECG inverse problem.

1. Introduction

The objective of the ECG inverse problem is to estimate the activity of the heart from the measured body surface potentials (BSPs) [1-3]. And the reconstructed objects mainly divided into equivalent sources [2] and cardiac potential distributions [3]. Although the equivalent sources can successfully represent cardiac activity, they are difficult to interpret and diagnose by physicians. In contrast, the heart-surface potentials are easy to interpret and can be readily inferred, and has been the goal of most recent work on inverse solutions [3, 4].

In the paper, we investigate the ECG inverse problem with the target of reconstruction of EPs from BSPs, which is to solve the Laplace equation with the Cauchy boundary conditions [3]:

$$\begin{cases} \nabla \cdot \sigma \nabla \Phi = 0 & in\ \Omega \\ \sigma \nabla \Phi \cdot n = 0 & on\ \Gamma_T \\ \Phi = \Phi_T & on\ \Gamma_T \end{cases} \quad \text{Find } \Phi_E \text{ on } \Gamma_E \qquad (1)$$

where Φ is the quasi-static potential, Φ_E and Φ_T are the potentials on the epicardial surface Γ_E and body surface Γ_T, which encloses the volume conductor Ω, σ is the tissue-dependent conductivity tensor. The final numerical formulation for Φ_E and Φ_T is a linear system equation as

$$A\Phi_E = \Phi_T \qquad (2)$$

where A is the transfer-matrix, which can be solved by boundary element method (BEM). However, the transfer matrix is ill-conditioned or even rank-deficient with the singular values decreasing to zero without significant gap, the ECG inverse problem is a typical 'discrete ill-posed problem' [5], in which small measurement errors in the BSPs, or geometry errors in the volume conductor model, lead to large perturbations in the EPs. In this case, the conventional least-squares (LS) or total least squares (TLS) error solutions can be physically meaningless, and the regularization is essential for stabilizing the solution.

The most common regularization methods used in the ECG inverse problem are the Tikhonov regularization [4, 6] and Truncate singular-value decomposition (TSVD) [1]. The former is imposing constraints on the magnitude or derivatives of the EPs, while the latter using the truncation technique (by ignoring small singular values). Some other approaches like level-set method [7], GMRes method [4] and Genetic algorithm [8], are also applied before.

The effectiveness of the above mentioned inverse solvers were tested with the involvement of measurement errors. However, they are all based on the LS and have a

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