A Fast Greedy Sparse Method of Current Sources Reconstruction for Ventricular Torsion Detection

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Abstract. A fast greedy sparse (FGS) method of cardiac equivalent current sources reconstruction is developed for non-invasive detection and quantitative analysis of individual left ventricular torsion. The cardiac magnetic field inverse problem is solved based on a distributed source model. The analysis of real 61-channel magnetocardiogram (MCG) data demonstrates that one or two dominant current source with larger strength can be identified efficiently by the FGS algorithm. Then, the left ventricle torsion during systole is examined on the basis of x, y and z coordination curves and angle change of reconstructed dominant current sources. The advantages of this method are non-invasive, visible, with higher sensitivity and resolution. It may enable the clinical detection of cardiac systolic and ejection dysfunction.

1. Introduction

Left ventricular torsion can be derived from the twisting of the heart along its long axis [1, 2]. It has been investigated by several measurement and imaging techniques, such as magnetic resonance imaging (MRI), tissue Doppler imaging by echocardiography, two-dimensional ultrasound speckle tracking imaging, speckle tracking imaging, and velocity vector imaging. There has been much interest in the analysis and description the function of the left ventricular torsion, torsion assessment of systolic and diastolic dysfunction regarding various cardiac diseases, and the knowledge for clinical diagnosis.

It is very important to evaluate the accuracy of left ventricular torsion detection. However, detection and quantitative analysis of left ventricular torsion are difficult, because of the physiological variability of ventricular torsion, e.g. the size and diameter of the left ventricular vary in a cardiac cycle, and the limitations of various measurement approaches that may show some conflicting results [2]. In previous research, most of the approaches focused on the angle and direction of left ventricular torsion [1]. At present, no gold standard of quantitative analysis has been established for the ventricular torsion detection.

In this paper, we propose a magnetic imaging approach to detect the left ventricular torsion. It is divided into three processes: acquisition of magnetocardiography (MCG) data using a multichannel superconducting quantum interference device (SQUID) system, reconstruction and imaging cardiac moving current sources through solving the cardiac magnetic field inverse problem, and detection of

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the left ventricular torsion by means of the position coordination and angle change curves of reconstructed dominant current sources.

In general, current source reconstruction needs to solve a highly ill-posed inverse problem, in which the distributed source number is more than that of measurement points, so that an optimization method needs to be used. Since MCG maps were mainly dipolar, we assume the unknown sources are sparse. Thus, the underlying inverse problem can be expressed as finding a minimal numbers of basis vectors that represent the solution of interest, i.e., to find the l^0-based sparsest solution [3].

We developed a sparse solution of the cardiac source reconstruction based on the distributed current source model [4]. In addition, we investigated a fast greedy sparse (FGS) algorithm for solving the highly ill-posed problem of source reconstruction. Thereby, the sparse sources with larger strength can be identified efficiently. This has been demonstrated by a series of simulation experiments and the results of real MCG data.

We try to detect a twisting movement of the ventricle by means of the continuity analysis of the dominant current sources trajectories of x, y and z direction, i.e., the number of times of the position and the angle change of the dominant current sources occurring in the QRS complex of a cardiac cycle, based on a fixed coordinate system corresponding the measurement plane on the body surface.

2. Methods

The MCG inverse problem is expressed by the linear distributed source model as

$$\boldsymbol{b} = \boldsymbol{A}\boldsymbol{x} + \boldsymbol{v} \tag{1}$$

where $\boldsymbol{b}$ is a $M \times 1$ measurement signal vector, which acquired by M SQUID sensors on a measurement plane over the human thoracic surface. $\boldsymbol{x}$ is a $N \times 1$ source moment vector of $\mathbf{Q}$ distributed current sources. $\boldsymbol{A}$ is a $M \times N$ lead field matrix. $\boldsymbol{v}$ represents the measurement noise. Due to $M \ll N$, $\boldsymbol{A}$ is highly underdetermined, so that equation (1) has no unique solution. It is common to search for an optimal $\boldsymbol{x}$ by reducing the number of unknowns or constraining dipole orientations.

We developed a fast greedy sparse method of current source reconstruction and achieved a sparse solution on the basis of the sparse decomposition theory [5]:

$$\boldsymbol{x}^n_{\Gamma^n} = \boldsymbol{A}^\dagger_{\Gamma^n}\boldsymbol{b} \tag{2}$$

where x_{Γ^n} is a sub-vector of $\boldsymbol{x}, \boldsymbol{\Gamma}^n = \{i : \boldsymbol{x}_i \neq 0\}$. n is the iteration number. $\boldsymbol{A}_{\boldsymbol{\Gamma}^n}$ is a sub-matrix of $\boldsymbol{A}$. $\boldsymbol{A}^\dagger_{\boldsymbol{\Gamma}^n}$ is the Moore-Penrose inverse. The directional optimization of the source moment vector can be obtained [6]:

$$\boldsymbol{x}^n = \boldsymbol{x}^{n-1} + a^n \boldsymbol{d}_{\Gamma^n} \tag{3}$$

where a^n is the step-size that can be determined explicitly. $\boldsymbol{d}_{\boldsymbol{\Gamma}^n}$ denotes an approximate conjugate gradient pursuit to optimize the source direction.

We adopted the strategy of selecting several elements per iteration, calculating the depth of distributed sources based on a hierarchical source space and simultaneously improving the time-consuming and accuracy of sparse source reconstruction based on a priori knowledge of the MCG map [5, 6], thereby significantly decreasing the computational complexity. In addition, we chose the reconstructed sparse sources whose strength ≥ 90% of the maximum at any instant as dominant equivalent current sources with the aim of reducing the number of sources under consideration, which may be caused by the measurement noise or the cases that can be neglected here.

3. Current source reconstruction

The fast greedy sparse (FGS) algorithm is tested by real MCG data for equivalent current source reconstruction. As shown in figure 1, MCG data were recorded by a 61 channel biomagnetometer (Magnes1300C, 4D Neuroimaging, San Diego, USA) inside a standard 3-layered magnetically shielded room (AK3b, Vacuumschmelze, Hanau, Germany). Over a circular area of 824 cm^2 with a sensor spacing of ca. 38 mm, the signals were measured for 3 minutes in each subject, at a sampling rate of 1 kHz with a 200 Hz low pass filter.

The sparse current sources were reconstructed by the FGS algorithm using MCG data during QRS complex. The x, y and z coordination and angle change curves of reconstructed dominant current sources from a healthy subject and a CAD patient are shown in figure 2, where the time interval of (t2-t1) and (t2-Qon) are shown by red and blue broken lines, respectively. The reconstructed source trajectories start at Q-wave onset and end at the Jpoint.

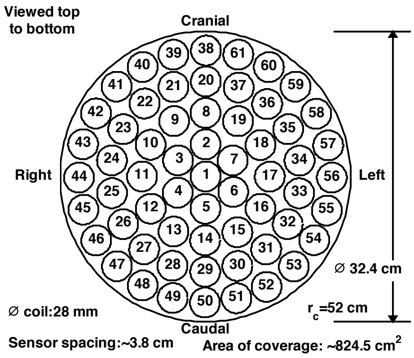
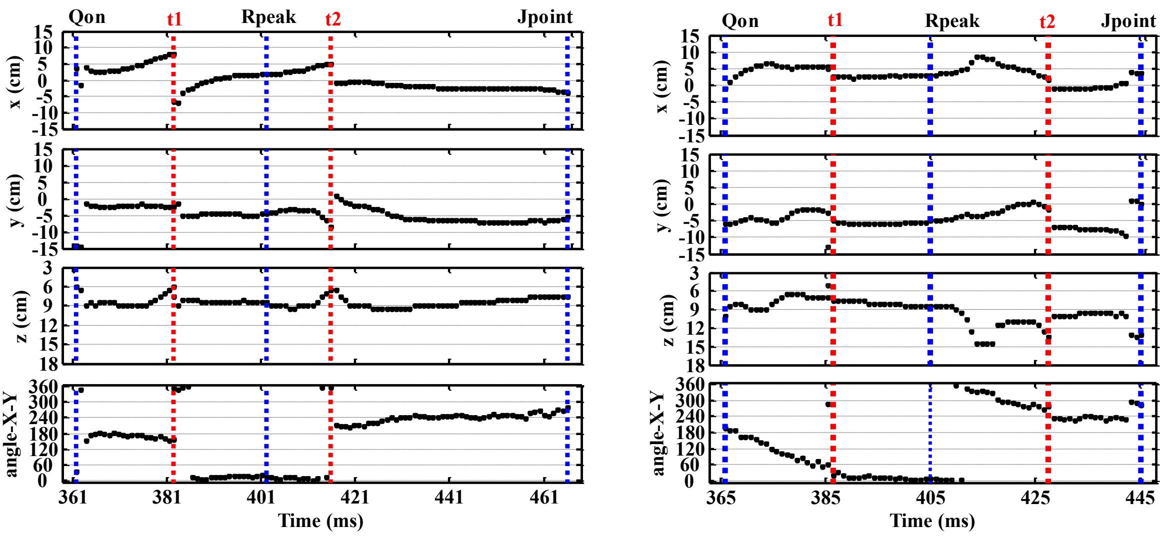


Figure 1. A circular measurement area with 61 sensors



(a) the healthy subject (b) the CAD patient

Figure 2. The reconstructed spatial source trajectories during QRS complex from the healthy subject (a) and the CAD patient (b) The time interval of (t2-t1) and (t2-Qon) are shown by red and blue broken lines, respectively.

4. Detection of the left ventricular torsion

The trajectories permit the calculation of the time interval between two obvious position changes occurring before and after the R peak in a cardiac cycle indicated by (t2-t1), and a second time interval starting at Q-wave onset and the second position change (t2-Qon), which is the time, about 40-60 ms, that the mechanical motion falls behind electrical activities of the atrium and the ventricle of the heart.

Figure 2 shows the time intervals of t2-t1 and t2-Qon of the CAD patient are a little longer than that of the healthy subject. The results of detection the left ventricular torsion from 39 healthy subjects and 15 coronary artery disease (CAD) patients showed that source trajectories of 35 healthy subjects and 14 CAD patients displayed at least two position changes in x (or y) direction during the QRS complex, where the time interval between the two obvious position changes of the 33 healthy subjects was 12 to 35ms, and 10 CAD patients was 16 to 46ms. 26 healthy subjects had position changes between 41 and 61ms after the beginning of the QRS complex, and 10 CAD patients were 48 to 64ms.

Because of the given source space resolution in z-axis different from that in x and y-axes, the trajectory change in z direction also has a little different. We chose two better examples of reconstructed source trajectories to show in figure 2. Namely, in some results with poor reconstructions may be difficult to accurately detect and determine the time of twisting of the heart.

5. Conclusion

We developed a fast greedy sparse (FGS) method and it has been tested for non-invasive cardiac equivalent current source reconstruction. The left ventricle torsion during systole is detected and quantitatively analyzed on the basis of position curves and angle change of reconstructed dominant current sources. The advantages of this method are noninvasive, visible, with higher sensitivity and resolution. It may enable the clinical detection of cardiac systolic and ejection dysfunction. The statistical analysis with a number of real MCG data is needed to fully validate the effectiveness of this technique.

Acknowledgments

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