Temporal Sparse Promoting Three Dimensional Imaging of Cardiac Activation

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Abstract

We propose a new Cardiac Electrical Sparse Imaging (CESI) technique to image cardiac activation throughout the three-dimensional (3D) ventricular myocardium from body surface electrocardiogram (ECG) with the aid of heart-torso geometry. Sparse property of cardiac electrical activity along time is utilized in the temporal sparse inverse problem. Computer simulations were carried out to evaluate the performance of this imaging method under various circumstances. A total of 12 single site pacing simulations with various noise/disturbance were employed to evaluate the accuracy, stability and robustness of the technique. The imaged activation sequence is compared with the simulated ones and those from the conventional weighted minimum norm method. The results show that CESI outperformed the conventional method. In summary, we have proposed a novel method for cardiac activation imaging, and our results suggest that CESI has enhanced performance and has the potential to image ventricular activation and assist in clinical management of ventricular arrhythmias.

1. Introduction

Cardiovascular disease is a significant challenge to public health and a leading killer world widely. Each year, about 400,000 sudden cardiac deaths are reported in the U.S. alone [1]. In clinical practice, anti-arrhythmic medications are administered to suppress the life-threatening syndromes. For those medically refractory cases, catheter ablation becomes a standard procedure to eliminate the arrhythmic activities, whose success relies on identifying the arrhythmogenesis [2]. Contact or non-contact mapping techniques have been used to guide catheter ablative procedures [3]. However, due to their invasive nature, an excessive amount of time and medical expertise have to be consumed while only mapping a single ventricular chamber. The non-invasive approaches, as an alternative, have been pursued by solving the inverse problem of electrocardiography (ECG) [4-10]. In the present study, we propose a weighted group sparse promoting strategy based on a physical model to exploit sparse properties of cardiac electrical activity and therefore improve the spatial-temporal resolution and the robustness in imaging 3D cardiac electrical activity. We conduct computer simulation studies to evaluate the performance of the proposed Cardiac Electrical Sparse Imaging (CESI) technique.

2. Method

2.1. Forward transfer function

When a myocardial cell is activated, the Trans-Membrane Potential (TMP) has a transient rise from the -90 mV polarized state to the plateau potential at around 0 mV. Regardless of individual variations in resting or plateau potential, the impulsive current flow can indicate the cell activation time with sharp peaks, where it is almost electrically silent during the remainder of the cardiac cycle. This Electrophysiological (EP) dynamic indicates that a temporal sparse property can be exploited for enhanced imaging performance.

Based on bidomain theory and distributed ECD model, the electrical activity in myocardium can be represented with the following governing equation [11]:

$$\nabla \cdot [(G_i(r) + G_e(r))\nabla\Phi_e(r,t)] = \nabla \cdot J_{eq}(r,t) \quad (1)$$

Where $G_e(r)$ and $G_i(r)$ are the intracellular and extracellular effective conductivity tensors and $\Phi_e(r,t)$ and $J_{eq}(r,t)$ represents the extracellular potential and the equivalent current density at location r and time instant t. With boundary element model approximation, e.q. (1) can be discretized into matrix-vector transfer function as [10,12]:

$$\vec{\Phi} = L\vec{J} \quad (2)$$

With L serving as the transfer matrix between body surface potential $\vec{\Phi}$ and current density $\vec{J}$. L can be expanded for the whole time course into L_T and formulate:

$$\vec{\Phi}_T = L_T \vec{J}_T \quad (3)$$

Where the relation between the body surface potential and the myocardial current density can be depicted over the entire time course.

2.2. Inverse problem

By nature, the inverse problem solving the equivalent current density suffers from serious ill-posedness and is unable to be solved directly. Minimum energy based reconstructing strategies have been investigated for cardiac electrical imaging [10]. However, simple physical constraints fail to incorporate any physiological knowledge or account for temporal dynamic in the reconstruction. Based on general electrophysiology of myocardial tissue, the depolarization occurs with the ionic flow across the cell membrane which introduces a rapid shift in extracellular potential from the resting potential to the depolarized potential plateau. This rapid shift in potential results in a spike in current flow at the depolarizing instant whereas during the rest of the cardiac cycle the myocardial tissue remains nearly electrically silent. The electrical dynamic suggests that temporal sparsity can be assumed for each site as additional electrophysiological knowledge for improved performance. In our proposed CESI method, a novel dipole-wise temporal weighted sparse reconstruction strategy is applied. For each myocardial location, weighted sparse constraints are independently imposed in the temporal domain. With the novel problem formulation, the electrical spike that is generated by depolarization can be directly reconstructed and in this way, accuracy, robustness, and temporal resolution can be improved.

2.3. Computer simulation

A human heart-torso model with 4096 body surface vertex and 30085 myocardial automatons were used. Two hundred electrodes were evenly placed on both chest and back in the computer simulation. Single site pacing simulation was carried out on 12 sites, including basal anterior (BA), basal left wall (BLW), basal right wall (BRW), basal anterior (BA), basal posterior (BP), basal Septum (BS), middle left wall (MLW), middle right wall (MRW), middle anterior (MA), middle posterior (MP), apical anterior (AA) and Apical posterior(AP). Artificial Gaussian white noise on various levels (0, 5 10, 20, 40, 60, 80 μV) and hospital recorded sensor noise were employed in the simulations to evaluate the stability of CESI.

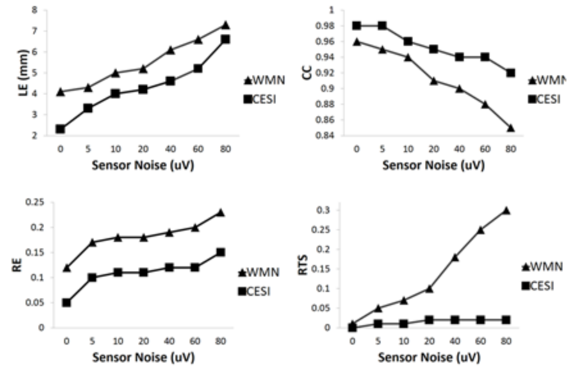

Figure 1. Summarized statistics of artificial sensor noise simulation.

2.4. Data analysis

Correlation Coefficient (CC), Relative Error (RE), Localization Error (LE) and Relative Temporal Shrinkage (RTS) were computed. CC, RE and LE have been defined previously [10] and RTS is defined as:

$$RTS = \frac{T_s - T_I}{T_s}$$

where T_s is the simulated or measured total activation length and T_I stands for that in the imaging results.

All CESI results are compared with those of the conventional weighted minimum norm method, previously demonstrated to have generally good performance among the minimum energy methods [10].

3. Results

Artificial noise on various level were used in single pace simulation. The statistics of the simulations are summarized in figure 1 and Table 1. Statistics of CESI decay slower than those of WMN as noise level increased and CESI was barely affected by noise in terms RTS, remaining in a minimum level. Figure 2 shows some examples of pacing computer simulation and the comparison with WMN results. BSPMs generated through simulations were contaminated with realistic noise recorded from hospital and filtered with 1-30 Hz band pass FIR filter. CESI results demonstrate higher concordance to the simulated results and suffer less smoothing and distortion compared with WMN results. The smoothing effect shown in WMN solutions in the figures are most significant at the earliest and the latest period of activation, indicating a non-linear distortion on imaged activation. On the other hand, CESI results are in good agreement with simulated activation sequences uniformly along the time course with only minimal loss of the temporal resolution and minor differences in activation.

4. Discussion & conclusion

A novel cardiac electrical imaging technique, Cardiac Electrical Sparse Imaging (CESI), has been proposed and evaluated with computational simulations that employ various disturbances. The proposed technique employs a novel 4D inverse problem formulation to incorporate sparse property of cardiac electrical activity to preserve the temporal resolution and detailed activation information to improve imaging accuracy and robustness. The results show that CESI in general outperformed the conventional WMN method and is able to image with good accuracy, robustness against various disturbance and has the potential to function in realistic and complicated circumstances.

Table 1. Summarized statistics of simulation with hospital recorded noise.

	WMN	CESI
CC	0.83±0.05	0.91±0.03
RE	0.26±0.05	0.15±0.02
LE	7±1.4 mm	4±1.4 mm
RTS	0.21±0.08	0.02±0.004

Efforts have been made in pursuit for high resolution noninvasive imaging of cardiac electrical activity [4-10]. The proposed 4D inverse problem formulation in the CESI technique can image the whole cardiac electrical process and the weighted sparse constraints incorporate the temporal sparse property of cardiac electrical dynamics into reconstruction. The temporal sparse property of cardiac electrical dynamics is derived directly from general electrophysiological knowledge of myocardial cellular depolarization. The property is based on a universal phenomenon that is not only observed in healthy but also in many pathological conditions. Moreover, this property is different from an electrophysiological model that requires certain individualized physiological knowledge which can vary as the condition changes. The inverse reconstruction of CESI still employs a physical-model based strategy but incorporates general physiological knowledge. The cardiac electrical inverse problem, by its nature, is often heavily ill-posed and thus not all the information can be directly reconstructed from the measurements. By incorporating the whole BSPM time course as input and temporal sparse constraints to pinpoint the activation time, CESI is able to greatly decrease the severity of ill-posedness and allow for a better representation of the information reflected in BSPM. The resolution of 1.5 mm spatially and 1ms temporal can be achieved.

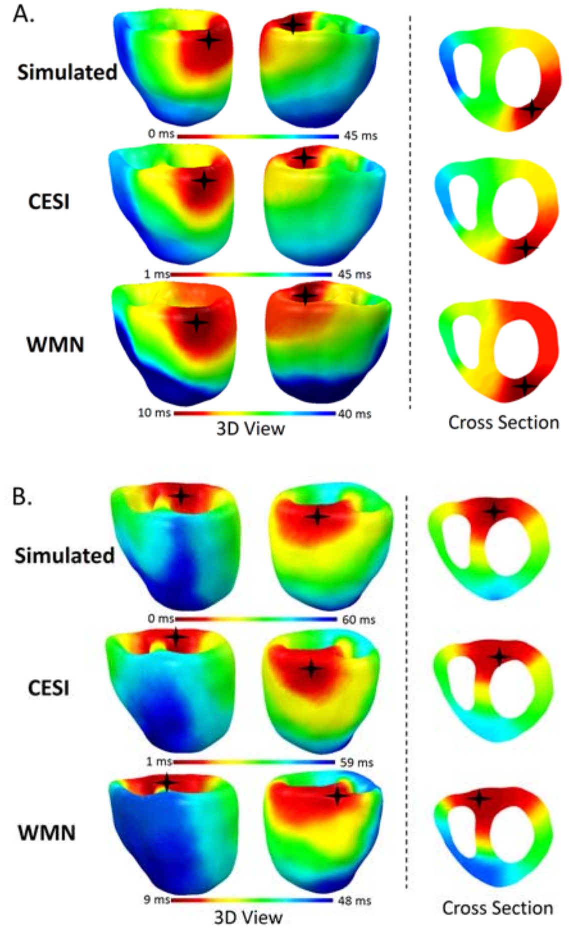

Figure 2. Comparisons between CESI and WMN results in single site pacing simulations. Black star represents the initiation of activation.

Unlike the energy based physical constraints such as minimum norm and singular value truncation, sparse constrained solution attempts to not omit the detailed information in the solutions but to utilize the sparse property of the cardiac electrical activity for its reconstruction. With these constraints, the reconstruction algorithm will search for the solution that can fit the measurements well and has an electrophysiologically based sparse property that will help reduce the loss of detailed information. Also, as can be found in the problem formulation, the CESI defines a convex problem and has a unique solution which can be obtained with different optimization methods. The reconstruction strategy in CESI seeks for a balance between the physical model based techniques and their physiological model based counterparts. The results shown in Section III demonstrate that CESI is capable of imaging the electrical activation in the myocardium more accurately and robustly while at the same time works without any individual based physiological information.

CESI incorporates raw data from various modalities to image the electrical activation in the myocardial volume. In practice, the quality of the raw data is limited. Simulations conducted in the study tried to evaluate the accuracy, stability and robustness in various conditions. In the simulations utilizing the hospital recorded noise, CESI also achieved good accuracy. The results demonstrate that CESI is capable of producing stable and accurate imaging results in relatively extreme and realistic conditions.

In clinical management of focal arrhythmias, such as premature ventricular complex and automatic ventricular tachycardia, catheter ablation is usually performed on suspected initiation site of the ectopic beats to terminate the arrhythmias. Therefore, the capability in identifying the activation pattern in the initiation of the ectopic beat becomes crucial. Shown in figure 2, CESI has the capability in correctly imaging the early activation patterns, identifying a clear focal initiation pattern by evading the smearing effect that the minimum energy methods usually impose on the results. This demonstrates a good potential of CESI in localizing the ablation target within a smaller area and shortening the time of invasive mapping and ablation.

In conclusion, we have proposed a novel Cardiac Electrical Sparse Imaging (CESI) approach and evaluated it with a series of computer simulations. The results have shown that CESI can image the cardiac electrical activation accurately and better than conventional linear inverse methods in various conditions. The promising performance of CESI suggests its potential application to map cardiac electrical activity and aid catheter ablation of arrhythmia in a clinical setting.

Acknowledgements

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