Towards the Cardiac Equivalent Source Models in Electrocardiography and Magnetocardiography: A Simulation Study

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Abstract

The cardiac equivalent source model is very crucial in the electrocardiogram (ECG) and magnetocardiography (MCG) problems. In this study, we presented a thoroughly investigation of the three models: the dipole, equivalent double layer (EDL) and epicardial potential (EP) models in terms of the ECG/MCG forward problem within a unified framework. The cardiac electromagnetic field is calculated using boundary element method (BEM). The numerical performance and the properties of the three source models are studied in detail. Three different resolutions of dipole and two of EP and EDL models are studied. Besides, the effect of the volume conductor model is studied. The simulation results demonstrated that the resolution of the source models shouldn't be too small, otherwise some information about the cardiac activities will be lost as shown in the single dipole model situation. The effect of the resolution on the MCG is larger than that on BSP. The higher resolutions of the source, the larger effect of the volume conductor happened for each source. While for the EDL source, the lung has little effect on the MCG. The EDL source can generate the similar performance compared to the dipole source, and the largest difference happened at the time when the ventricle start or finish the activation. The presented study suggests that the EDL source is a good choice as source model for ECG/MCG problem

1. Introduction

Since the advent of electrocardiogram (ECG) one hundred years ago, the biophysical models were proposed and developed along with the development of ECG's clinical application. As the model based study of the cardiac electrical activities and ECG forward and inverse problem, the biophysical model was used to quantitatively relate the electrical sources confined to the heart to the ECG or magnetocardiography (MCG).

In general, the biophysical model in cardiac study can be separated into the source model and the volume conductor model. Compared to the volume conductor model, the source model is more important since it is used to macroscopically describe the cardiac activities. In this study, the source model will be thoroughly investigated. Many cardiac source models are proposed and used in the ECG/MCG problems, in which the dipole, epicardial potential (EP) and equivalent double layer (EDL) models are often used nowadays [1]. The purpose of this study is to comprehensively compare the three cardiac source models in terms of the calculated ECG and MCG based on the virtual heart model, and to demonstrate the different performances of the three source models for the volume conductor model. Boundary element method (BEM) with linear collocation is used to calculate the forward problem [2]. And the effects of the different properties of source and volume conductor models are summarized. Through the comparison of the performance of the three source models in this study, it helps to choose the appropriate source model in cardiac study.

2. Theory and method

2.1. Cardiac equivalent source model

The cardiac equivalent source models can be classified as point-like and distributed source models according to the locations. The former is the equivalent current dipole, which has been extended from a fixed dipole at the beginning to a moving dipole, multipole and multiple dipoles etc. The distributed source models mainly include uniform double layer (UDL), EDL and EP source. In these distributed source models, the UDL is used to describe the activity of ventricle during depolarization, and can be equivalent as the EDL based on the solid angle theory [3]. Therefore, in this study, only the dipole, EDL and EP source models are compared. A brief overview of these three source models is presented here, and for more details please refer to publications [1, 3-4] or textbooks [5-6].

The dipole source is the firstly proposed model, represented by six parameters, three with the coordinates and three with the magnitude and direction. Though the dipole model can't be directly linked with the electrophysiological activity of the heart, it is excellent to describe the ECG waveform from the biophysical point of

view. The EDL source model is also called as equivalent surface source model, including the endo- and epicardial surface of ventricle. The strength of the EDL source is equivalent described by the TMP. It is firstly described by Geslowitz [7]. Later, the EDL source model has been used to calculated EP [8] and ECG [9] for forward problem. And based on the EDL source model, the inverse solution of TMP and activation time on ventricular surface from body surface potentials (BSP) are commonly studied [10-12].The EP source model was defined as the potentials on a closed surface encompassing the myocardium [13]. The closed surface always refers to the epicardium or pericardium. The EP source model provides a 'closer look' at the cardiac activity compared to the 'farther look' of ECG, and has been often used in the inverse problem [2, 11, 13].

In the quasi-static approximation, the electric potentials Φ can be calculated based on Poisson or Laplace equations from the three cardiac source models [2, 14], and the magnetic field $\vec{B}(\vec{r})$ based on Biot-Savart law [15].

The relationship of the three source models is sketched in Fig.1, which shows that BSP can be calculated from dipole, EP and EDL source models. The dipole and EDL source can be obtained directly from the virtual heart, while the EP can be calculated from the virtual heart by solving mon- or bi-domain models, or from dipole[2] or EDL[8] source models. In this study, the EP is only calculated from dipole or EDL source, with the consideration of the computational demand.
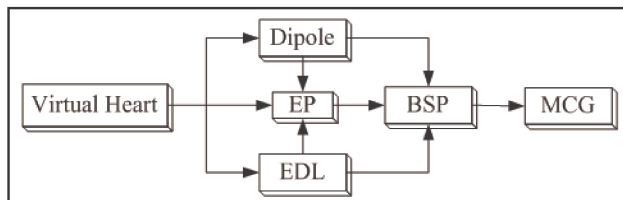

Figure 1. The sketch of the forward problem with three source models: dipole, EP and EDL.

2.2. Simulation protocol

The ECG and MCG forward problem was performed within a geometrically realistic thorax model [16]. In the thorax model, the electric and magnetic fields are calculated from a virtual heart model[16]. The MCG is calculated on the locations which is 1.2 times larger than that of the thorax mesh, and the normal direction's values of the MCG are compared.

The three source models are shown in Fig.2. One(DIP_I), 53(DIP_II) and 36767(DIP_III) dipoles are applied for the dipole source model. The EP and EDL sources are modeled as the ventricular surface including endocardial and epicardial surfaces. The geometrical locations of EP and EDL source models are same with two resolutions: the sparse ventricular surface (larger spheres, EP_I and EDL_I) and the whole ventricular surface (smaller spheres, EP_II and EDL_II). For these various source models, the BSP and MCG are calculated and compared with the solutions of DIP_III as the reference values. Meanwhile, the effect of lung is investigated.

The calculated BSP and MCG from different source models are evaluated by relative error (RE) and correlation coefficient (CC) estimate.
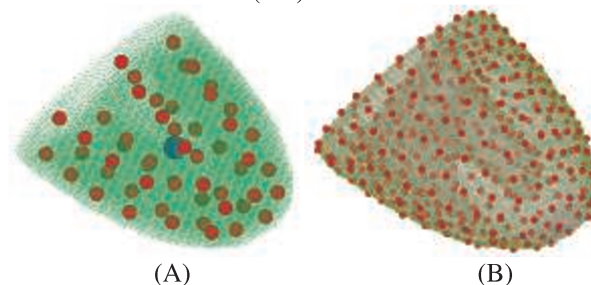

Figure 2. The three source models: (A) the dipole source models: the largest blue sphere is the single dipole, the middle red spheres are the 53 dipoles and the green smallest spheres are the 36767 dipoles; (B) the EDL and EP source models with two different resolutions: larger spheres are the sparse mesh with 478 nodes, while the smaller spheres are the whole heart surface mesh with 7082 nodes.

3. Results

Based on the virtual heart model, the ECG and MCG are calculated from the three various source models and the magnitudes are normalized. At first, the effect of the resolution is investigated, meanwhile, the inhomogeneous and homogeneous cases are considered. Fig.3 display the CC of BSP and MCG for each time instants. The reference values (the former one) and the test values (the latter one) for CC calculation are marked in the legend. Fig. 3 (A) show that the DIP_II and DIP_III's results have no much difference, while the DIP_I is very different from DIP_II, which is also exist in the homogeneous situation. If the heart is expressed by the DIP_I, then some details are missed and the BSP/ECG is much smoothed. The difference in homogeneous situation is larger than that in inhomogeneous one for the dipole source. For the EDL source as shown in Fig.3(B), the difference of EDL_I and EDL_II is small in both homogeneous and inhomogeneous situations, and the largest one is happened at the times when the excitation starts and finishes. The performance of the EP source is shown in Fig.3(C). From these curves, it can be found that the BSP/ECG calculated from EP source is closely related to the dipole source which used to calculated EP, which means once the dipole source is chosen, then the

BSP/MCG are similar regardless of the different resolutions of EP. And the difference of the BSP for EP source is larger in homogeneous situation than that in inhomogeneous one, which is similar as that in dipole source. The performance of MCG is generally similar as that in BSP, however, the CC in inhomogeneous situation is larger than that in homogeneous one for MCG, which is opposite with BSP.

In order to check the effect of volume conductor, the BSP/MCG without lung is compared to that with lung. The CC of BSP and MCG between inhomogeneous and homogeneous situations are shown in Fig. 4. The CC curves of BSP for DIP_I, EP_II_DIP_I and EP_I_DIP_I are much similar, while the other six ones are similar. And the higher resolutions of the source, the larger of the effect of the volume conductor for each source. An interesting thing can be found in Fig.4 (B) that the CC of MCG for EDL source are close to 1, which means the lung has little effect to the MCG's shape. While if the magnitudes of the ECG are compared between inhomogeneous and homogeneous situations, it can be found that the including of lung improve the magnitudes of values for both source models.
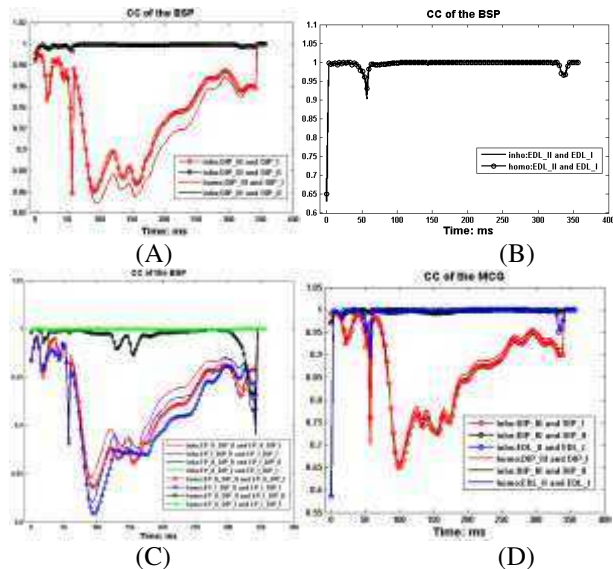

(A)   (B)   (C)   (D)

Figure 3.The CC of the BSP for the three source models: (A) the dipole, (B) the EDL and (C) the EP. And (D)the CC of the MCG for the dipole and EDL source models The 'inho' means the inhomogeneous volume conductor and 'homo' the homogeneous one. The former source data is the reference value and the latter one is the test one as shown in the legend.

The different performances of various resolutions' source models and different volume conductors have been compared above for each source model. Now, the difference between the three source models are investigated only for inhomogeneous situation, in which
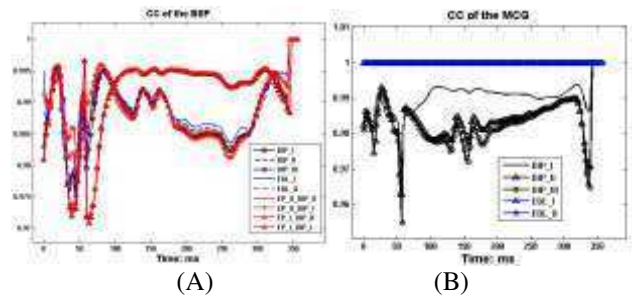

(A)   (B)

Figure 4. The CC of BSP and MCG between inhomogeneous and homogeneous situations for the different source models. The sources are marked in the legend.

the result of the DIP_III is set as the 'golden reference' and the other two source models' results are compared. The RE and CC of BSP and MCG for EDL_II and EP_II are shown in Fig.5, in which the EP is calculated from DIP_II. As can be seen in Fig.5 that the three source models can generate very similar BSP/MCG and the BSP is more similar than the MCG. However, it should be noted that in several time instants like 3, 60 and 354 ms, the CC is small. In order to give a visual comparison, the BSP and MCG at 60ms are shown in Fig.6. which shows that no large difference even at the largest RE's time.
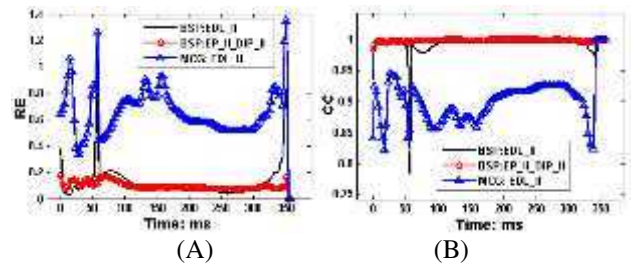

(A)   (B)

Figure 5. The RE and CC of BSP and MCG for the EDL_II and EP_II sources compared to that of DIP_III. The sources are marked in the legend.
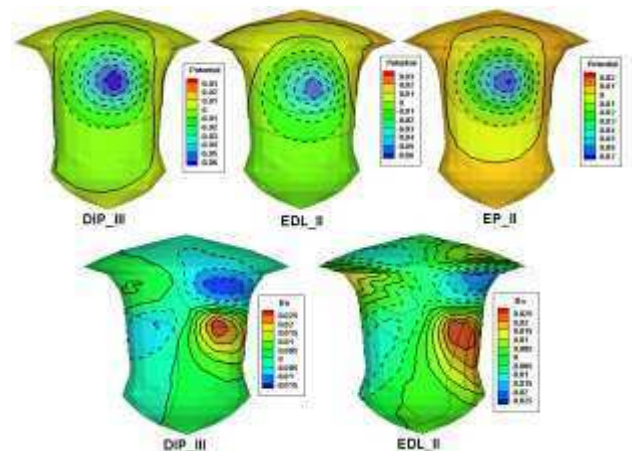

Figure 6. The BSP (top row) and MCG (low row) calculated from the different source models at 60 ms, in which the largest difference happened.

4. Discussion and conclusion

In the ECG/MCG forward and inverse problem, the choice of an appropriate source model is very crucial. The dipole, EDL and EP source models are currently often used in the ECG/MCG forward or inverse problem. The current study thoroughly investigated these three source models in terms of the forward problem with ECG and MCG. Using the BEM method, the ECG/MCG was calculated using the three source models with the concentric sphere models with assumed sources, and with realistic lung-torso model with the virtual heart, respectively. Theoretically, the dipole source is calculated from all myocardium cells and includes more information than the EDL source, which only considers the surface myocardial cells. Therefore, in the realistic geometrical model, the results of dipole source are used as the standard to compare the EP and EDL source models. The different factors in source and volume conductor model were studied for the three source models.

The results demonstrated that the three source models can generate the similar BSP and MCG, though the different performance happened for the various affect factors. In the use of the EDL source in the forward or inverse problem, several time instants corresponding to the start and finish of activation should be paid attention. The number of dipole source shouldn't be too less since some information of the cardiac activities might loss. The presented comparison suggests that the EDL source is a good choice for source model for ECG/MCG problem and the single dipole source will lose some detail information about the heart. To sum up, this investigation provided a comprehensive comparison of the three source models and can be used to the optimal choice of the source model in inverse problem.

Acknowledgements

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