

Comparison of Electric- and Magnetic- Cardiograms produced by Myocardial Ischemia in Models of the Human Ventricle and Torso

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Abstract

Myocardial ventricular ischemia arises from the lack of blood supply to the heart, which may cause abnormal excitation wave conduction and repolarization patterns in the tissue, leading to cardiac arrhythmias and even sudden death. Current diagnosis of cardiac ischemia by the 12-lead electrocardiogram (ECG) has limitations as they are insensitive in many cases and may show unnoticeable differences compared to normal patterns. As the magnetic field provides extra information of cardiac excitation and is more sensitive to tangential currents to the surface of the chest, whereas the electric field is more sensitive to radial currents, it has been hypothesized that the magnetocardiogram (MCG) may provide a complementary method to the ECG in ischemic diagnosis. However, it is unclear yet about the differences in the sensitivity of the ECG and MCG signals to ischemic conditions. The aim of this study was to investigate such differences by using multi-scale biophysically detailed computational models of the human ventricles and torso model, to simulate normal and ischemic conditions.

1. Introduction

Ischemic heart disease is one of the principal causes of death in developed countries and worldwide [1–3]. Coronary artery occlusion can cause, within hours, cell death in ischemic myocardium [1]. This results from a lack of blood flow to the heart which decreases partially or completely the oxygen supply to the cell, damaging the muscle [1]. Significant ischemic regions within the heart can promote abnormal excitation wave conduction and repolarization patterns, leading to ventricular arrhythmias and even sudden cardiac death [4,5]. Therefore, being able to detect, quantify and locate the site of acute transient ischemic regions in the heart by non-invasive techniques is a clinically important challenge [3,6].

The 12-lead electrocardiogram (ECG) has been implemented as a standard bedside evaluation procedure for cardiac condition diagnosis for multiple decades. Unfortunately, the standard 12-lead ECG has been shown to be insensitive to cardiac ischemia; the ECG waveforms of patients with ischemia may only differ by 70-85% compared to normal patients [3,4,6,7]. This therefore suggests that the 12-lead ECG provides insufficient information for satisfactory ischemia diagnosis. Other non-invasive techniques, including radionuclide methods, magnetic resonance imaging and positron computed tomography, are far more sensitive to the detection of ischemia. However, they are highly expensive and time consuming, and therefore not practical for day-to-day, bedside monitoring and detection of asymptomatic ischemia (i.e. which does not present as an arrhythmia) [8,9].

Previous studies have shown that spatially extended recordings of ECG configurations on the torso provide more information for the diagnosis of irregular cardiac conduction and repolarization patterns than the standard 12-lead ECG [7,9,10]. Moreover, the magnetic field produced by the electrical activity of the heart may provide a greater level of detail of cardiac excitation compared to the body surface potential, because magnetocardiograms (MCG) are more sensitive to currents tangential to the surface of the chest than ECGs. Combined with its high independent tissue inhomogeneities in electrical resistivity inside the body and on the skin [9,11,12], the MCG therefore provides a potential practical alternative to the ECG for monitoring the cardiac conditions. However, detailed correlation between the presence of ischemia and the characteristics of the MCG has yet to be established.

In this study, we compare and quantify the effect of the presence of ventricular ischemia on the 36-lead ECG and MCG using multi-scale computational models of the human heart and torso.

2. Methods

Biophysically detailed computational models of the

human ventricles in 1D, 2D and 3D were incorporated into a heart-torso model to simulate normal and ischemic conditions (Figure 1). The 1D ventricular model comprises of a strand 1.5 cm in length composed of 100 cells connected through gap junctions (Figure 1A). The 2D ventricular model comprises of a slice through the right and left ventricles, segmented from the female visible human dataset [13] (Figure 1A). The 3D ventricular anatomical model was previously developed and is also segmented into the major distinctive regions in the heart [14] (Figure 1A). All of the models incorporated anatomical structures and detailed electrophysiological heterogeneity with cellular electrophysiology being modelled by the Ten Tusscher et al. single cell model [15].

In simulations, four different electrophysiological conditions for acute ischemia-induced changes in cardiac electrophysiology were considered: (i) an increase in extracellular potassium concentration; (ii) both extracellular and intracellular acidosis; (iii) anoxia; and (iv) integrated action of (i)-(iii), following the work of Shaw and Rudy for implementing ischemic parameters in the models [16].

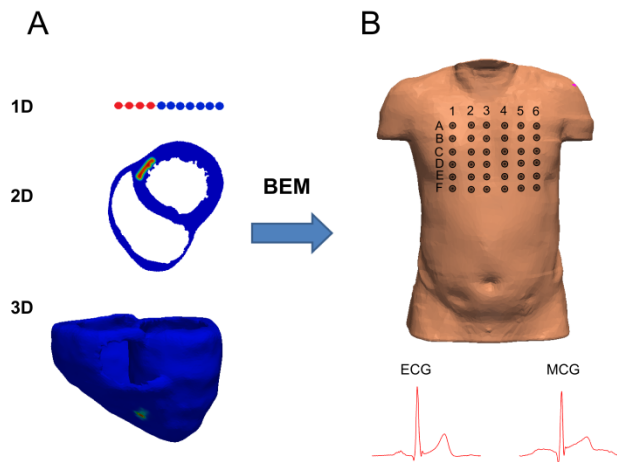


Figure 1. Multi-scale computer models of the human ventricles and torso. (A) 1D, 2D and 3D ventricular models used to simulate the normal and ischemic conditions. (B) Torso model and positions of the electrodes/sensors in the surface of the body, used to measure the MCG and ECG signals through the BEM

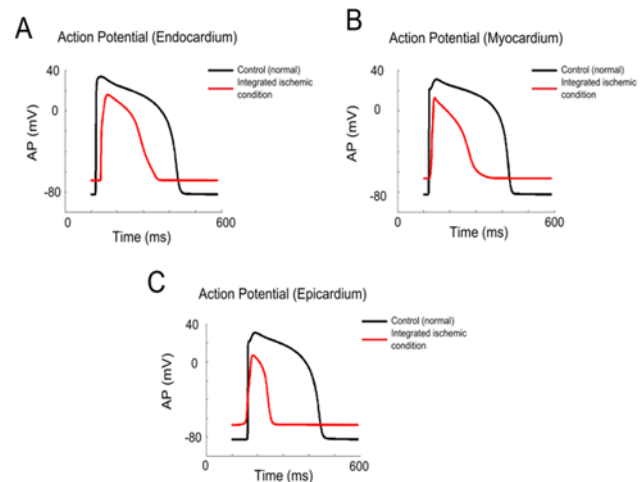


Figure 2. Simulated action potentials (APs) of the normal (Control) and integrated ischemic conditions. (A) Endocardium. (B) Myocardium cell. (C) Epicardium.

Figure 2 shows the action of ischemia on the action potential of three different ventricular cells: Endocardium (Figure 2A), Mid-myocardium (Figure 2B) and Epicardium (Figure 2C). It was shown that ischemia caused an elevation in the resting potential, reduced amplitude of AP and shorter action potential durations (APDs) at the cellular level.

To simulate ECG and MCG, the ventricle models were placed within a previously developed torso model which considers the presence of lungs, liver, blood masses and spinal cord, each of them with different electrical conductivity [17]. A boundary element method was used to compute the magnetic field and the electric potentials on the surface of the body, resulting from the electrical activity on the surface of the ventricular tissue-models (Figure 3). Elements of the torso mesh corresponding to the locations of the electrodes and magnetic sensors were selected to simulate 12- and 36- lead ECGs and 36-lead MCG (Figure 1B).

The body surface potentials and multi-lead ECG configurations were validated in previous studies [17]. The polarity patterns of the MCG signals was compared to experimental data.

At the tissue level, we considered three different extents and locations of ischemia, covering (i) the whole epicardial region; (ii) the whole midcardial region; and (iii) the whole endocardial region.

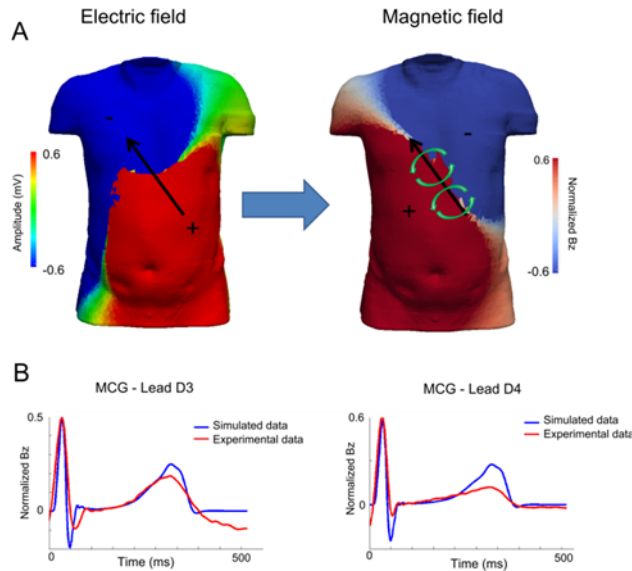


Figure 3. Validation of the simulated ECG and MCG. (A) Electric and magnetic fields produced by the 3D ventricular model. The black arrows show the direction of the electric potential, while the green arrows show the direction of the magnetic field, consistent with the right hand rule and the calculation of BZ. (B) Comparison of the magnetic experimental data [18] (red line) and the simulated data (blue line) of two different lead position D3 and D4.

4. Results

During normal conditions, the simulated QRS complex and T-waves of the ECG and MCG showed strong agreement to experimental data (Figure 3B), which validated the multi-scale models of the ventricle.

Figure 4 shows the effects of the ischemic conditions on the ECG and MCGs. The presence of ischemia resulted in only minor alterations to the 12-lead ECG compared to control (normal conditions). The 36-lead ECG and MCG provided more information compared to the 12-lead ECG; more significant alterations to the waveforms of the ECG and MCG maps were observed in specific regions. Primarily, the ST segment was more affected by the presence of ischemia in both ECG and MCG (Figure 4), consistent with previous studies [8,11].

In the 1D model, small differences between ECG and MCG ischemic conditions were observed. In most of the ischemic conditions, the relative differences compared with normal conditions were on the same order of magnitude for both ECG and MCG data, where a delay of 40 ms of QRS complex was seen. However, marked changes were seen in the T-wave, which was dependent on associated ischemic regions (i.e., celltype), which could even lead to a change in the polarity of the T-wave (Figure 4A).

In the 2D model, both ECG and MCG showed marked alterations to the ST-segment due to the presence of the ischemic conditions. The precise alterations were highly dependent on the anatomical region (and associated celltype) in ischemia (Figure 4 B); the T-wave was more affected by the presence of ischemia in the Epicardium compared with the Endocardium and Mid-Myocardium, which showed changes up to 40% of the amplitude. Unlike the 1D case, the MCG in this case was more sensitive to certain ischemic conditions than the ECG.

Also, in the specific ischemic condition with an elevated extracellular potassium concentration ($K_o=10\text{mM}$) in the 2D model (Figure 4B), marked changes in the ST-segment in both of calculated ECG and MCG were observed. However, whereas the T-wave of the ECG was almost unaffected by the ischemic condition, marked changes in the T-wave of MCG were observed in some ischemic cases (depending on ischemic location, i.e. celltype), especially when ischemia was in the Epicardium.

Results from the 3D model simulations are still under development and analysis, but preliminary results showed greater sensitivity of the MCG than the ECG to ischemia, in accordance with results from 2D simulations.

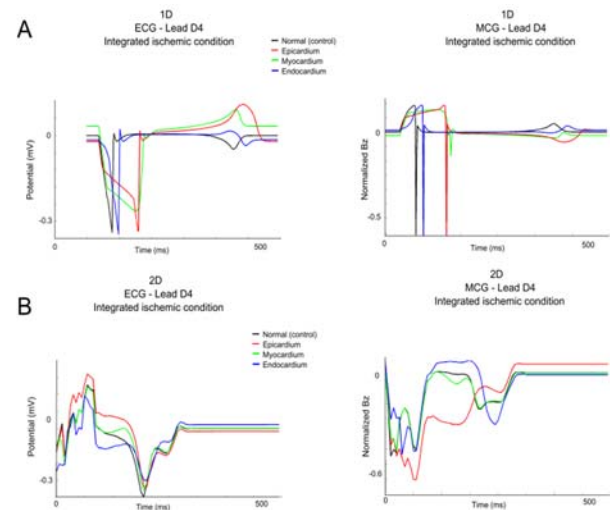


Figure 4. QRS complex and T-wave of lead D4 of ECG and MCG under control and ischemic condition in one of the three different regions models: Normal (black line), Epicardium (red line), Myocardium (green line) and Endocardium (blue line). (A) 1D model with the integrated ischemic condition. (B) 2D model with the integrated ischemic condition.

5. Conclusion

Computer modelling provides a useful tool to compare the electric and magnetic field produced by the electrical activity of the heart during normal and ischemic conditions, which is a challenging task in clinical settings. Using biophysically detailed models of 1D, 2D and 3D human ventricle and torso, we have compared the sensitivity of the ECG and MCG in response to ischemic conditions, to identify the advantages that the MCG may offer.

Our simulation results show that the 12-lead ECG is insufficient to provide effective diagnosis of the ischemia, whereas the 36-lead ECG and in particular MCG offer advantages in the identification of ischemic conditions. The T-wave and ST segment present the most significant alterations under ischemic conditions, indicating a primary effect on ventricular repolarisation. These repolarisation heterogeneities may play an important role in the development of arrhythmias and thus identification of these alterations may prove valuable in early diagnosis and treatment.

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