FEM Based Forward Simulations of ECG with Varying Tissue Conductivity

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Abstract- Computer simulations using the CIBC ECG forward/inverse toolkit were used to investigate the effect of tissue conductivity inhomogeneity using FEM-based electrocardiographic potentials. The considered tissue conductivities are for fat, muscle, lungs, myocardium, air, skin, heart blood, fatpad, bone, blood and heart. The simulated BSPM results back up the values reported in the literature, indicating that the algorithm for potential-based FEM in the CIBC forward/inverse toolkit is accurate.

Keywords- FEM, BSPM, Tissue conductivity, Sensitivity analysis.

I. INTRODUCTION

The effects of torso inhomogeneities have been investigated by many groups [1]-[13] in the past. These studies can be placed into one of three categories: (1) Theoretical using simplified spherical and planar geometries for the heart, lungs and thorax (2) experimental using a current dipole to represent the heart and electrolytic tank models to represent the thorax and its inhomogeneities and (3) experimental using the in-vivo animal heart and altering the conductivity of the thoracic inhomogeneities usually the intracardiac blood [14]. A vast literature is available for reference on each of these classes. We attempt to make use of experimental class using the simplified Utah-torso model to address the alterations in computed body surface potentials arising from conductivity value uncertainties used in the forward problem solved using finite element methods. To the best of our knowledge the first time simulation of forward problem of electrocardiography including air, skin, fat, muscle, lungs, myocardium, heart blood, fatpad, bone, blood and heart conducting regions altogether to show the effects on BSPM is being carried by us. The particular interest in examining the body surface potentials' sensitivity to conductance is due to the difficulty faced in the experimental measurements of accurate tissue conductivity that vary physiologically and experimentally with factors like temperature, hydration level and frequency etc.[15]-[16]. However textbooks have cited values of conductivity for certain in-vivo tissues that differ by more than 50% [17]-[19], [21].

II. POBLEMS OF ELECTROCARDIOGRAPHY

The problems of electrocardiography are grouped into two categories i.e. forward problem and inverse problem. The goal of solutions to the forward problem is to obtain the body surface potentials with predetermined cardiac electrical sources and the torso's geometry and conductivities were involved. whereas the aim of the inverse problem is to obtain the cardiac sources with given body surface potentials and the same geometry and conductivity information. However, solution to the inverse problem presupposes that a solution to the forward problem is also available. The source model treated in this work is the potential-based source model assumes that cardiac sources can be described by a time-varying electrical potential on a surface enclosing all electrical sources. According to the rules of Gauss every such set of potentials is special, and the model is more useful the closer the surface is to the myocardial surface. As a result, the surface is often referred to as the epicardium, which is closed off at the base of the core by a fictional top surface [22].

III. FEM BASED SOLUTIONS TO THE FORWARD PROBLEM OF ECG

A. *Difference in FEM and BEM methods*

The solutions to the forward problem of ECG presented in this section are taken from [22]. The wavelengths are several orders of magnitude greater than the dimensions of the human body, and the temporal frequencies that are important to electrocardiographic bioelectricity are comparatively low. As a result, the governing partial deferential equation (PDE) in bioelectricity is Laplace's equation:

$$\nabla . (\sigma \nabla \Phi) = 0 \quad (1)$$

where σ are the conductivities and Φ the electrical potentials. The boundary conditions are given by:

$$\Phi (x, y, z) |\Omega_k = V_k \quad (2)$$

$$\partial \Phi / \partial n |_{\Omega} = 0 \quad (3)$$

where Ω_k is the surface containing the sources.

In complex geometries such as realistic torso models, equation (1) can be solved using numerical solutions. There is a lot of literature on computational methods like this. The Finite Element Method (FEM) and the Boundary Element Method (BEM) have dominated the literature for forward electrocardiography (BEM). The major difference, from the practical application point of view, between FEM and BEM is:

TABLE 1: Difference between FEM and BEM

FEM	BEM
1. Handles anisotropic regions	1. Handles electrically homogeneous regions only
2. A full domain mesh is required	2. Only boundary solutions are generated
3. Entire domain solution is generated	3. Gives more precise results for potentials and gradients for a given mesh discretisation.
4. Symmetric sparse matrices are produced	4. Smaller non symmetric and dense matrices are produced
5. Element integrals are easily evaluated numerically	5. Requires accurate evaluation of integrals with singular integrands

IV. RESULTS AND DISSCUSIONS

Forward-problem network of potential-based-fem from CIBC ECG forward/inverse toolkit is simulated to visualize the effects of varying conductivity of air, skin, fat, muscle, lungs, myocardium, heart blood, fatpad, bone, blood and heart tissues on body surface potential maps. The conductivity values are changed as per the literature cited values. The default values stored in the network for different tissues are:

TABLE 2: Default values of different tissue conductivities stored in CIBC ECG forward/inverse toolkit**.**

Sr.Number	Tissue	Conductivity Value (S/m)
1.	Air	0.0
2.	Skin	0.00005
3.	Fat	0.0000375
4.	Muscle	0.000125
5.	Lungs	0.000054
6.	Myocardium	0.000238
7.	Heart Blood	0.00068
8.	Fatpad	0.00005
9.	Bone	0.00068
10.	Blood	0.00068
11.	Heart	0.000238

When the network is simulated with its default values for all tissue conductivities the resulting body surface potential maps is as shown in figure 1. The horizontal scale ranging from -0.44mm to 0.83mm shows epicardial potentials and vertical scale with range -0.37mm to 0.71mm shows the body surface potentials in all figures.

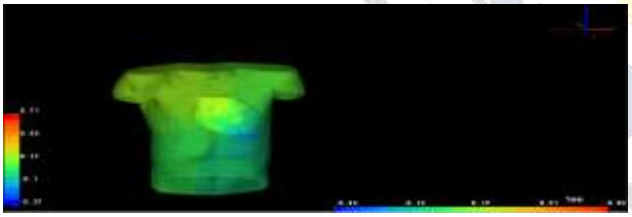

FIG. 1: BSPM with default values stored in the network of tissue conductivity (Table 2).

TABLE 3: Change in the Lungs Conductivity from 0.000054 S/m to o.050 S/m.

Sr.Number	Tissue	Conductivity Value (S/m)
1.	Air	0.0
2.	Skin	0.00005
3.	Fat	0.0000375
4.	Muscle	0.000125
5.	**Lungs**	**0.050**
6.	Myocardium	0.000238
7.	Heart Blood	0.00068
8.	Fatpad	0.00005
9.	Bone	0.00068
10.	Blood	0.00068
11.	Heart	0.000238

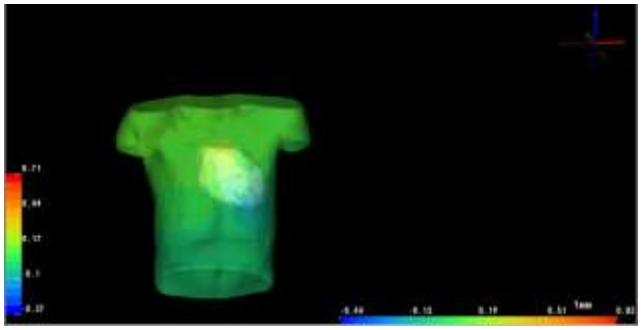

FIG. 2: BSPM with tissue conductivities as shown in Table3.

TABLE 4: Change in the Muscle Conductivity from 0.000125 S/m to o.520 S/m.

Sr.Number	Tissue	Conductivity Value (S/m)
1.	Air	0.0
2.	Skin	0.00005
3.	Fat	0.0000375
4.	**Muscle**	**0.520**
5.	Lungs	0.000054
6.	Myocardium	0.000238
7.	Heart Blood	0.00068
8.	Fatpad	0.00005
9.	Bone	0.00068
10.	Blood	0.00068
11.	Heart	0.000238

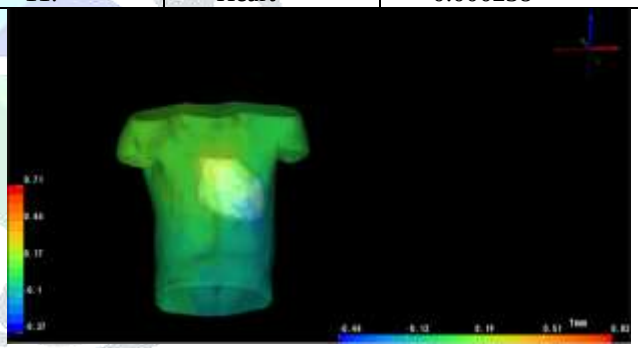

FIG. 3: BSPM with tissue conductivities as shown in Table4.

TABLE 5: Change in the Fat Conductivity from 0.0000375 S/m to o.040 S/m.

Sr.Number	Tissue	Conductivity Value (S/m)
1.	Air	0.0
2.	Skin	0.00005
3.	**Fat**	**0.040**
4.	Muscle	0.000125
5.	Lungs	0.000054
6.	Myocardium	0.000238
7.	Heart Blood	0.00068
8.	Fatpad	0.00005
9.	Bone	0.00068
10.	Blood	0.00068
11.	Heart	0.000238

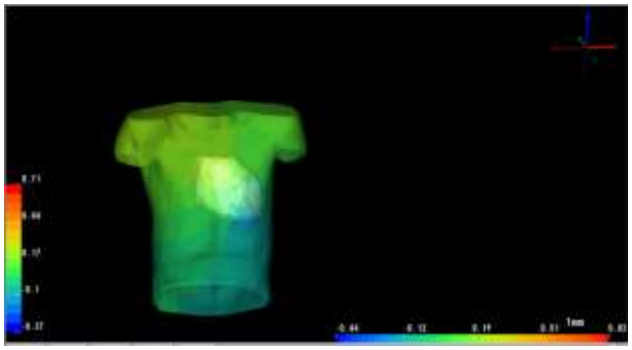

FIG. 4: BSPM with tissue conductivities as shown in Table5.

TABLE 6: Change in the Heart Conductivity from 0.000238 S/m to o.500 S/m.

Sr.Number	Tissue	Conductivity Value (S/m)
1.	Air	0.0
2.	Skin	0.00005
3.	Fat	0.0000375
4.	Muscle	0.000125
5.	Lungs	0.000054
6.	Myocardium	0.000238
7.	Heart Blood	0.00068
8.	Fatpad	0.00005
9.	Bone	0.00068
10.	Blood	0.00068
11.	**Heart**	**0.500**

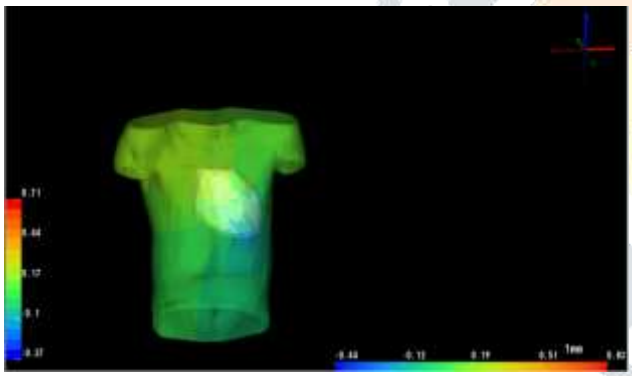

FIG. 5: BSPM with tissue conductivities as shown in Table6.

TABLE 7: Change in the Fat, Muscle, Lungs and Heart Conductivities altogether.

Sr.Number	Tissue	Conductivity Value (S/m)
1.	Air	0.0
2.	Skin	0.00005
3.	**Fat**	**0.040**
4.	**Muscle**	**0.520**
5.	**Lungs**	**0.050**
6.	Myocardium	0.000238
7.	Heart Blood	0.00068
8.	Fatpad	0.00005
9.	Bone	0.00068
10.	Blood	0.00068
11.	**Heart**	**0.500**

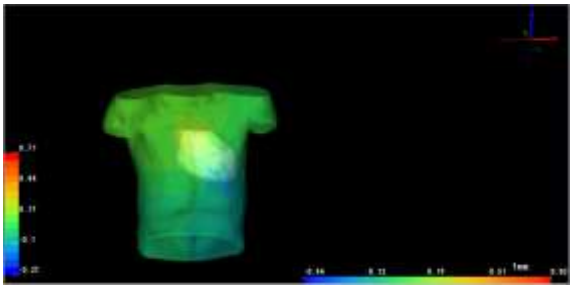

FIG. 6: BSPM with tissue conductivities as shown in Table7.

As seen in the figures from 2-6, with the corresponding change in the mentioned tissue conductivity, changed in the heart surface potentials is clearly visible which reflects the changes in surface potentials. The changes to these tissue conductivities and their corresponding results are as per the literature [20]-[21], [23]-[25]. However, we also have confirmed that the other tissues (for which conductivity values have not been changed) do not have significant effect on BSPM. The numerical values compilation of the results and relative tissue conductivity effects on BSPM with a comparison with BEM based forward solutions includes the future work.

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