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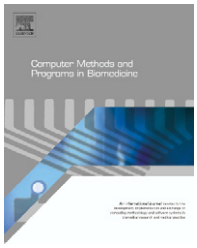

Estimating the measuring sensitivity of unipolar and bipolar ECG with lead field method and FDM models

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ABSTRACT

New portable electrocardiogram (ECG) measurement systems are emerging into market. Some use nonstandard bipolar electrode montage and sometimes very small interelectrode distances to improve the usability of the system. Modeling could provide a straightforward method to test new electrode systems. The aim of this study was to assess whether modeling the electrodes' measuring sensitivity with lead field method can provide a simple tool for testing a number of new electrode locations. We evaluated whether the actual ECG signal strength can be estimated by lead fields with two realistic 3D finite difference method (FDM) thorax models. We compared the modeling results to clinical body surface potential map (BSPM) data from 236 normal patients and studied 117 unipolar and 42 bipolar leads. In the case of unipolar electrodes the modeled measuring sensitivities correlated well with the clinical data ($r = 0.86$, $N = 117$, $p < 0.05$). In the case of bipolar electrodes the correlation was moderate ($r = 0.62$ between Model 1 and clinical data, $r = 0.71$ between Model 2 and clinical data, $N = 42$ and $p < 0.05$ for both). Based on this we can conclude that lead field analysis based on realistic thorax models provides a good initial prediction for designing new electrode montages and measurement systems.

1. Introduction

New wearable or implantable electrocardiogram (ECG) measuring devices enable using smaller measurement electrode configurations. Since investigation of the performance of new electrode systems may be tedious if numerous clinical trials are needed, modeling tools can provide new means of predicting signal behavior. Models have been utilized in a number of applications. Computer models have been used for implantable defibrillator electrode comparison [1], and for evaluation and optimization of defibrillation fields [2,3] as well as inverse problems. Computer modeling and lead field theory have been utilized in developing implantable ECG monitor [4] and impedance cardiography [5]. Studies with both modeling and clinical data have also been conducted. Takano described cross-approach evaluations of ECG lead selection and body surface map lead reconstruction with a thorax model and actual ECG data in [6]. However, no studies have been conducted on the capability of 3D thorax modeling to estimate the actual clinical ECG signal strength.

The main aim in the present work was to assess how well the measuring sensitivity values obtained from 3D finite difference method (FDM) model predict the actual signal strength given by real body surface potential map (BSPM) ECG data. We also sought to establish how well the modeling results correlate with real ECG data in different cases such as unipolar and bipolar measurement. For this, we modeled the measuring sensitivity of unipolar and bipolar ECG with two realistic 3D thorax models and compared the results to the signal strength obtained from real BSPM ECG data. Our modeling

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study was based on FDM models, and lead field and reciprocity theories.

2. Material and methods

We used two methods: (a) modeling the thorax as a volume conductor with two 3D FDM models and (b) analyzing clinical BSPM ECG data. These approaches were used for studying the measuring sensitivity and the signal strength in two electrode sets: 117 unipolar BSPM leads, and 42 bipolar electrode pairs located in the area of the standard 12-lead ECG precordial electrodes V1–V6.

2.1. *Thorax models*

We utilized two realistic but passive (the activation of the heart was not modeled) FDM thorax models: a 3D model based on the visible human man (VHM) project [7] and a 3D model based on magnetic resonance images presenting the anatomy during the diastole [8]. We hereafter refer to these models as Models 1 and 2, respectively.

In FDM, the modeled domain is subdivided or discretized into a grid of rectangular blocks or cells. The model is thus composed of cubic elements, each representing e.g. a pixel of the original MR or CT image. These cubic elements form a resistor network, where the resistivity of a voxel is defined as the corresponding tissue resistivity [9,10].

The anatomy of Model 1 was based on VHM data and extracted from a full thorax model by Kauppinen and associates [7,11]. This model represented segmented transverse slice images of an adult male cadaver thorax and included all visible details and 36 tissue types.

The anatomy of Model 2 was derived from a set of MR images studied and supplied by Wang and Patterson [8]. The image data comprised 70 transverse slices presenting the anatomy during the diastole. This model represented an adult male thorax, including altogether 26 distinct tissue types, such as intracavitary blood, pericardium, major vessels, lungs, subcutaneous muscles and fat, bony structures, and some internal organs (liver, spleen). The main inhomogeneities included in the models and their resistivity values are listed in Table 1 [12–14]. Models 1 and 2 are both illustrated in Fig. 1 with the appearance of heart masses and main cardiac vessels.

Table 1 – The main inhomogeneities included in the models and their resistivity values.

Inhomogeneity	Resistivity (Ω cm)
Bone	2000
Lungs	1325
Subcutaneous fat	2000
Skeletal muscle	400
Liver	600
Stomach	400
Heart fat	2000
Heart muscle	450
Blood masses	150
Including intracardiac blood masses, great arteries and veins	
Other tissues and organs	460

The resolution of both models had been adapted so as to provide a more accurate presentation of the anatomy in the heart area. In this area the element size was 3 mm × 3 mm × 4 mm in Model 1 and 3 mm × 3 mm × 5 mm in Model 2, increasing towards the back of the thorax and to the right side. Model 1 included a total of 258,442 nodes and Model 2 a total of 253,468 nodes.

2.2. *Clinical BSPM data*

To evaluate and validate the modeling results, we analyzed clinical BSPM data provided by Professor Fred Kornreich, Vrije Universiteit Brussel, Belgium. These BSPM data consisted of 120-lead ECGs acquired from 236 normal patients. The electrode system comprises three unipolar limb leads (RA: right arm; LA: left arm; LF: left foot) and 117 body surface unipolar leads. The 117 body surface electrode positions are defined with a grid of 9 rows and 18 columns. This electrode system

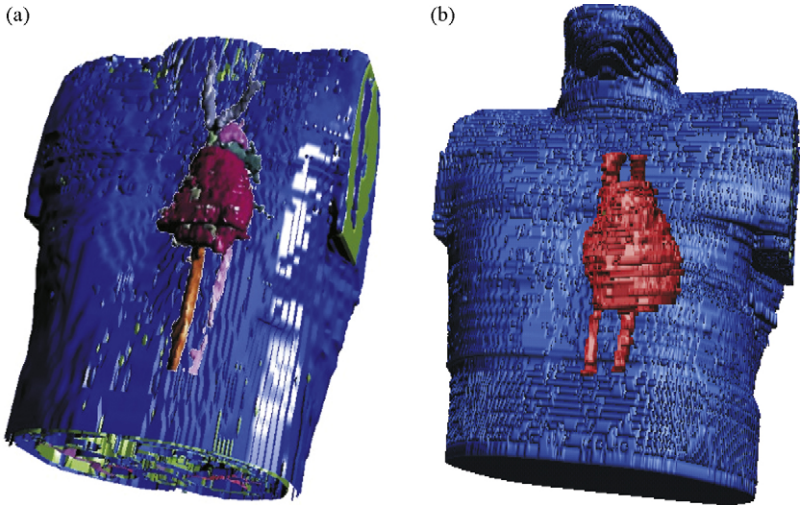

Fig. 1 – Visualization of the realistic 3D thorax models: (a) Model 1 based on VHM data and (b) Model 2 based on MR images. The appearance of heart masses and main cardiac vessels is also visualized.