Analysing Effects of Implant Dimensions on Electrocardiograph: A Modeling Approach

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Abstract

Modeling offers effective means of studying the effects of implant dimensions on the measured electrocardiograph (ECG) prior to any in vivo tests, and thus provides the designer with valuable information. Finite difference (FDM) and lead field approaches combined with cardiac activation models offer straightforward and effective methods for analyzing different ECG measurement configurations. In the present study such methods are applied in studying the effects of implant dimensions on the simulated ECG which describes an ectopic beat originating from the apex. The results indicated that the change in interelectrode distance has the largest effects on the ECG. Other parameters related implant dimensions have minor effect on the ECG.

1. Introduction

The research and development of wireless and/or implantable measurement devices for ECG measurements has been continuously increasing during the 21st century [1-3]. These modern measurement devices offer stable and long-term monitoring possibilities. The implantable ECG monitors have been noticed to be efficient and useful in detecting various cardiac arrhythmias and ECG patterns and thus their use is continuously increasing [4-7].

Implantation of measurement device into the human body is time-consuming and expensive. The effects of different implant designs on the measurement cannot thus be tested and reviewed by actually implanting the device into humans during the design process. There is thus a need for methods providing information about the effects without actual implantation of a device in test subjects. Modeling affords an effective means of investigating the effects of implant characteristics such as implant dimensions on the ECG signal. This information would be available without expensive and time-consuming in vivo trials. Most of the modeling studies related to implantable cardiac devices have concentrated on modeling the current distributions generated by stimulation devices such as implantable cardiac defibrillators [8-13] but the effects of implantation and implant dimensions on the sensitivity distributions have been also studied [17].

In the present study computational modeling methods were applied to provide information on the effects of implantable ECG monitor designs on measured ECG. The methods applied were lead field and finite difference modeling approaches together with state-machine based cardiac activation model. The lead field and reciprocity approach [14] with the finite difference method (FDM) [15, 16] has been efficiently applied in studies where body surface measurements have been analyzed. The objectives of the study were to analyze the effects of implant dimensions on the measured ECG by applying simulated activation sequence together with lead fields and evaluate how the results differ from the previously published results [17] when only properties of lead fields were analyzed.

2. Methods

2.1. Model data

The present study applies the finite difference method (FDM) in modeling the electric fields in the volume conductor. In the FDM the segmented volume data, e.g. from an MRI dataset, are divided into cubic elements forming a resistive network. The FDM is based on the Poisson's equation which describes the bioelectric quasistatic source-field problems. Poisson's equations use the information of the conductivities and shape of the volume conductor acquired from the image data. Continuous Poisson's functions are discretized to form linear equations which describe the model. A potential distribution within the model for a specific source configuration is solved with these linear equations with iterative methods. The resulting potential distribution is applied when sensitivity distribution, i.e. lead field, is solved. [18]

The FDM allows the implementation of complex anatomic geometries from the image data, and the resulting potentials and currents can be calculated within

the whole volume conductor model [18]. In the present study we applied a FDM model of the 3D male thorax based on the Visible Human Man dataset (VHM) [19]. The applied dataset represents data on 95 segmented slices containing altogether 2.7 million nodes with 2.6 million elements. The model applied contains over 20 different organ and tissue types with corresponding resistivities which are listed in [20].

The implant model in the present study has electrodes attached to the ends. The implant was inserted into the model to demonstrate the use of these methods in studying the effects of implant dimensions on simulated ECG. Here the implant was located vertically on the left side of the thorax and tilted to go along the figure of body surface. The location of the implant is in the region between precordial leads V3 and V4 from the standard 12-lead ECG system. The electrodes are approximately 5 mm under the body surface. Figure 1 illustrates the model of the thorax with the implant
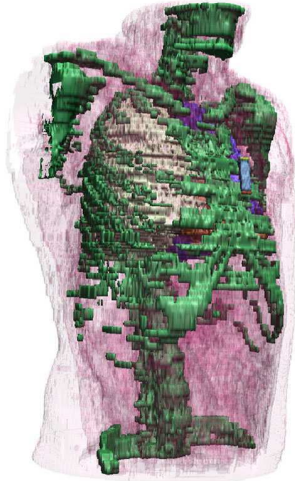

Figure 1. The 3D thorax model and implant

2.2. Lead Field and Reciprocity

Here lead fields were applied to describe sensitivity of measurement lead on the sources simulated by cardiac activation model. The lead current density vectors define the relationship between the measured potential in the lead and the current sources in the volume conductor following Equation 1.

$$z[n] = \sum_V \frac{1}{\sigma} \frac{1}{I_r} \overline{J}_L \bullet \overline{J}^i[n] \tag{1}$$

Where $z[n]$ is the lead voltage as a function of time $[n]$, $\overline{J}_L$ is the lead current density vector [A/cm^2], I_r is the applied reciprocal current [A], $\overline{J}^i[n]$ is the current

source density vector [A/cm^2] as a function of time, σ is the conductivity [1/Ωcm] of the source location in the volume conductor and V is the source volume.

The lead field in the volume conductor can be established by applying the principle of reciprocity. In [14] it is stated that the current field in the volume conductor raised by the reciprocal unit current (I_r=1 A) applied to the measurement electrodes corresponds to the lead current density and hence to the lead field.

2.3. Cardiac Activation Model

A state machine approach was adopted as a cardiac activation model [21]. This model of activation reproduces electric restitution of action potential duration (APD) and conduction velocity (CV), as well as curvature effects. Cardiac tissue is modeled as a grid of discrete elements characterized by three discrete states, namely, *Rest*, *Refractory*1 and *Refractory*2, and transitions among them. The excitation of an element is interpreted as a probabilistic event, depending on the amount of excitation in its neighborhood, and the excitability of the element, that can be accessed through the restitution curve of CV. Transitions from *Refractory*1 to *Rest* through *Refractory*2 depend on the current of APD. Additionally, a membrane voltage is assigned at every time instant, by temporarily scaling a standard ventricular one. Finally, non-conservative sources, $\overline{J}^i[n]$, at each time n and location within ventricular myocardium i are solved based on the voltage differences and conductivities between neighboring elements. The activation pattern, $\overline{J}^i[n]$, simulated here starts from the apex and conducts through both ventricles over 0.5 seconds.

2.4. Calculations

The effects of implant dimensions on the ECG were studied by applying 6 different dimensional settings presented in Table 1. The dimensions of the reference implant correlate with those of the commercial implantable Holter loop recorder (www.medtronic.com), although in our model the electrode positioning is different.

Lead fields, $\overline{J}_L$, for all dimensional settings were calculated in a realistic model of the male thorax by applying the principle of reciprocity. The calculations were executed with bioelectric field software which applies the Incomplete Cholesky Preconditioner and Conjugate Gradient in solving linear equations [22].

The measured ECG, $z[n]$, for each dimensional case was solved by applying corresponding lead field and activation pattern in Equation 1.

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Table 1. Dimensional settings for implant

| Dimensional Combinations (mm) | | | | | |
	Reference	Thick (x)	Width (y)		Length (z)	
X	6.7	**3.3**	6.7	6.7	6.7	6.7
Y	23.4	23.4	**10**	**3.3**	23.4	23.4
Z	60	60	60	60	**40**	**20**

2.5.   Analysis

The effects of dimensions on the ECG were analyzed by calculating the mean square difference (MSD) between the reference signal and signal of each dimensional case. From (1), we can express that the ECG measured with implant having change in dimension is $z[n]$ and $z_{ref}[n]$ is the ECG measured with reference implant. If we measure the similarity between $z[n]$ and $z_o[n]$ based on MSD, we obtain:

$$MSD = \frac{E[(z[n] - z_{ref}[n])^2]}{E[z_{ref}[n]^2]} \quad (2)$$

The MSD describes only the mean difference in signal amplitudes but in order to analyze similarity between signals more deeply the correlation coefficients between $z[n]$ and $z_{ref}[n]$ were also calculated.

3.   Results

The simulated ECG signals for all 6 dimensional combinations are presented in Figure 2. Table 2 presents total signal power, MSD and correlation values for all dimensional settings. It can be noticed that electrode distance has largest effects on signal amplitudes and correlations are high for all dimensional settings.

Table 2. Total signal power for all 6 dimensional combinations. Mean square difference and correlation between corresponding dimensional setting and reference

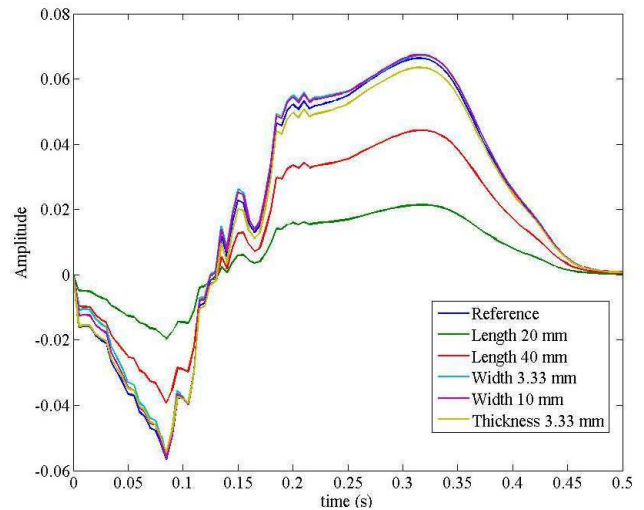|	Total Signal Power	MSD	Correlation
Reference	0.166	-	-
Length 20 mm	0.017	0.460	0.999
Length 40 mm	0.074	0.112	0.999
Width 3.3 mm	0.170	0.003	0.999
Width 10 mm	0.171	0.001	1.000
Thick 3.33 mm	0.153	0.002	1.000

Figure 2. Simulated ECG signals for all dimensional combinations.

4.   Discussion and conclusions

The present study introduces a modeling based approach to analyze effects of implant dimensions on the ECG. Present study applies reciprocal lead field analysis together with state-machine based cardiac automata applying fast and effective method to analyze different implant designs and electrode setups. Reciprocal lead field approach is effective because the sensitivity of measurement lead to all locations in the volume conductor can be achieved with one calculation.

The limitations of the study are in the model of volume conductor. The applied model is based on the anatomy of a single human subject and the segmentation of the tissues might also have some shortcomings. Furthermore, the model is isotropic. Anisotropic conductivities, especially of the cardiac muscle might improve the accuracy simulations. The model also lacks of conduction pathways such as Purkinje fibers. It would be valuable to study how these shortcomings affect the obtained results.

The results of the present study are inline with the findings of the study where only properties of lead fields were analyzed [17]. The results of both studies show that the electrode distance is the major characteristic of the implant affecting the measurement. The shape of the implant has effects only on the amplitudes of the signals and not on the morphology. Although only one activation pattern and implant location was applied in the present study it still strengthens previous assumptions that measurement setups can be studied and compared by analyzing lead fields without any particular activation model. This should be confirmed in the future studies by

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modeling different activation patterns and different implant locations.

Acknowledgements

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