Effects of Activation Origin on the Subcutaneous ECG with Horizontal and Vertical Bipolar Lead Orientation

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Abstract

The present study applies modeling methods to study the simulated ECG of a subQ monitor with bipolar lead. The objective of the study was to analyze how different locations of ectopic activation affect the ECG obtained with horizontal and vertical electrode orientation. The ectopic activation was set to originate from 6 different locations and conduct through both ventricles. We had implants in 63 locations on anterior thorax. We analyzed the correlations between the ECG signals of horizontal and vertical orientations .The effects of activation origin on the correlation between vertical and horizontal orientations are smallest in the left thoracic region and right upper thorax. The effects of implantation and implant design on ECG should be studied by applying multiple activation sequences.

1. Introduction

Interest towards wearable and implantable electrocardiography (ECG) measurement devices has been continuously increasing during the 21st century [1-3]. The implantation is almost irreversible, time-consuming and expensive thus emphasizing the importance of electrode placement. The effects of electrode placement on the measured signal cannot be tested and reviewed by actually implanting the device into humans. Thus there is 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 location and orientation on the ECG. This information would be available without expensive and time-consuming in vivo trials. In the present study computational modeling methods were applied to provide information on how orientation of implant affects simulated ECG with different activation sequences. The methods applied were lead field and finite difference modeling (FDM) [4] approaches together with state-machine based cardiac activation model[5].

2. Methods

In the present study we simulate signals of the implantable ECG monitor by combining sensitivity distribution approach with cardiac activation source model. The measured signal, i.e. lead voltage *z[n]*, can be described with Eq. (1) [6, 7]. The lead voltage is dependent on the sensitivity distribution $\bar{J}_L$ and current source distribution $\bar{J}^i[n]$ in the volume conductor. The sensitivity distribution is unique for all measurement configurations but current source distribution is common. The sensitivity distribution in the volume conductor can be established by applying the principle of reciprocity. In [7] 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 sensitivity distribution. The essential benefit of this method is that the sensitivity of a measurement lead at all source locations in the volume conductor can be calculated with a single calculation.

$$z[n] = \sum_V \frac{1}{\sigma} \frac{1}{I_r} \bar{J}_L \bullet \bar{J}^i[n] \qquad (1)$$

Where *z[n]* is the lead voltage as a function of time *n*, $\bar{J}_L$ is the lead current density vector [A/cm^2] , I_r is the applied reciprocal current [A], $\bar{J}^i[n]$ is the current source density vector [A/cm^2] as a function of time, i is the source location, σ is the conductivity [1/Ωcm] of the source location in the volume conductor and V is the source volume.

Sensitivity Distribution Calculations

In this study we modeled the sensitivity distributions of implantable ECG monitor with a finite difference method (FDM) in a realistic model of a human thorax. 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 [8]. In the present study we applied a FDM model of the 3D male thorax based on the Visible Human Man dataset (VHM) [9, 10]. The applied dataset represents data on 95 segmented slices where resolution in the slices close to the heart was 1.67 mm x 1.67 mm x 4 mm and elsewhere 1.67 mm x 1.67 mm x 8 mm. Model contains 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 [11]. The muscles and myocardium of the model are isotropic. The model of the implant applied here was ~52 x 12 x 7 mm^3 and it has non-conducting body with 5 mm long electrodes in both ends. The implant is illustrated in Figure 1.

The aims of the paper were to study the effects of implantation orientation on the ECG and if effects are dependent on the cardiac activation sequences. The sensitivity distributions, $\overline{J}_L$,were calculated for the 63 implantation locations. The implant had horizontal and vertical orientations in all locations. The locations were selected based on the leads 5-68 of the Dalhousie lead system[12] and are illustrated in **Error! Reference source not found.** The depth of implantation in each case was approximately 5 mm from the body surface corresponding to implantation under the skin.

The current distributions were calculated in each node of the model by applying the principle of reciprocity thus the lead current density was generated into the volume conductor by applying the unit currents to the electrodes of the implant. The calculations were executed with bioelectric field software which applies the Incomplete Cholesky Preconditioner and Conjugate Gradient for solution [13].

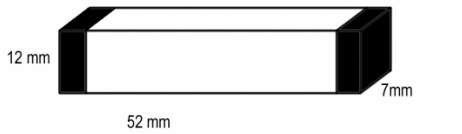


Figure 1. Horizontal illustration of the implant model. The insulated body in white and electrodes in black.

Cardiac Source Model

A state machine approach was applied as a model of

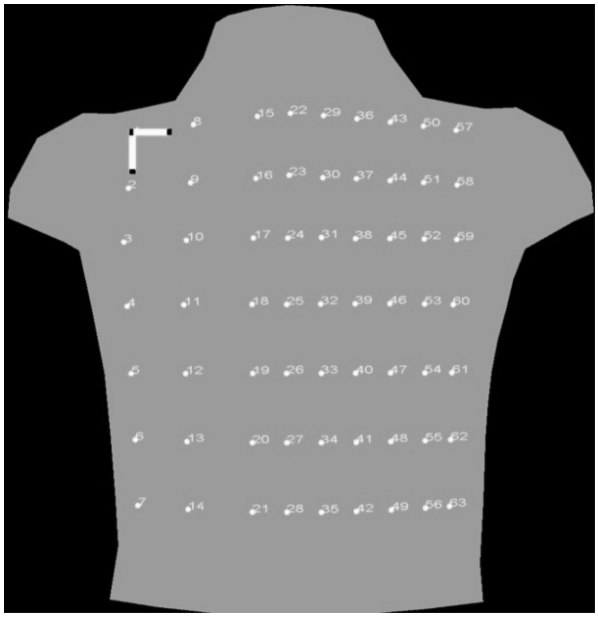
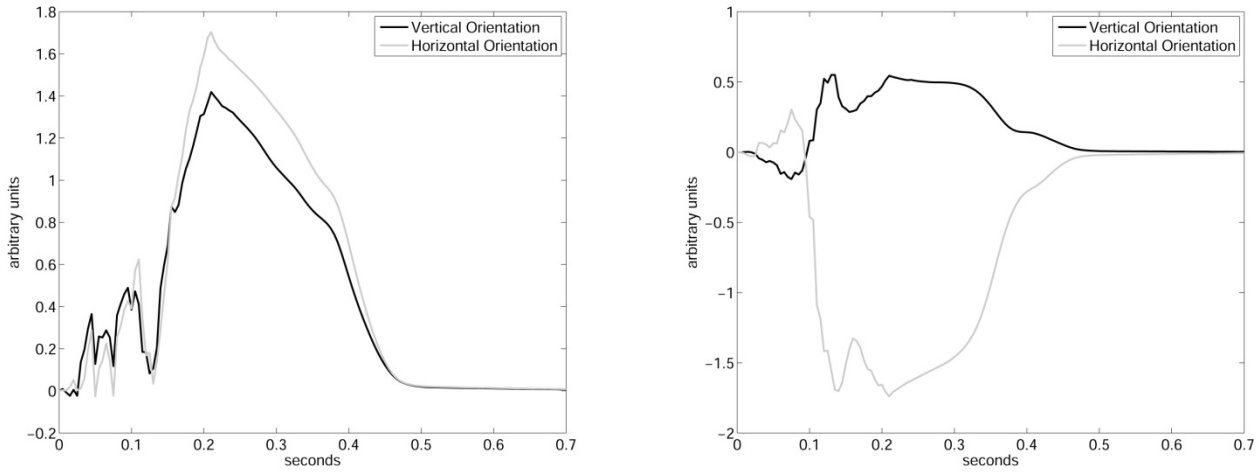


Figure 2. The 63 implant locations. As an example also the implant is depicted in the applied vertical and horizontal orientations at location 1.

cardiac activation $\overline{J}^i[n]$ [5]. The applied model of cardiac electric activity reproduces electric restitution of both, 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, i.e. the transition from *Rest* to *Refractory*1 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. Finally, non-conservative sources at each time *n* and location *i*, $\overline{J}^i[n]$, are solved based on the voltage differences and conductivities between neighboring elements.

Source distributions, $\overline{J}^i[n]$, in the ventricles were solved for the six different activation patterns starting from *AV-node*, *mid-septum, apex, posterior left ventricular wall, postero lateral LV wall and anteroseptal left ventricular wall*. The source distributions were combined with the sensitivity distributions to solve the ECG measured by the implant as described by (1). The signals contain 141 samples corresponding to 0.7 s.



a) **b)**

Figure 3. Simulated signals for implant in locations 60 (a) and 3 (b). Activation sequence starts from *apex*

The effects of implant orientation on morphology with different activation sequences were studied by calculating the correlation coefficients between vertical signals, $z_v[n]$ and horizontal signals, $z_h[n]$.

3. Results

Figure 3 illustrates simulated signals for implant locations 60 and 3 in both horizontal and vertical orientations when activation sequence originates from *apex*. It can be noticed that there is only minor difference between horizontal and vertical measurements in location 60. In location 3 the difference between signals is very large. The correlations between horizontal and vertical measurements are 0.963 and -0,910 for locations 60 and 3, respectively. The signal of the horizontal measurement in location 3 seems to be an attenuated inverse of the signal in vertical measurements.

Figure 4 presents examples of correlations values between horizontal and vertical measurements for all applied implantation locations and with 3 activation sequences, *mid-septum, posterior left ventricular wall and anteroseptal left ventricular wall*. There are implantation locations where correlation is high with all activation sequences. In these locations, e.g. 60, the effect of orientation on the measured signal is minor and the correlation is not dependent on the activation sequence. In most of the implantation sites, such as 50, the correlation is heavily depending on the activation sequence.

4. Discussion

The location of the implant has significant effects on the orientation effects. The applied methods serve effective means of studying the properties of subQ monitors with different activation sequences.

The present study applies a modeling based analysis in analyzing implantable ECG monitors with cardiac activation and lead field based methods. The lead field analysis together with cardiac automata applies fast and effective method to analyze different electrode setups and activation models. The limitations of the study are related to the anatomical model and cardiac automata. The model applied in the present study is of a single subject and myocardium is isotropic. Wei and colleagues [14] stated that isotropic heart models would give satisfactory results in simple simulations where cell dynamics are not concerned. Klepfer and colleagues [15] found in their study that accurate representation of inhomogeneties and skeletal anisotropy has significant effects on the accuracy of forward solutions. Ramon and colleagues [16] studied the effects of myocardial anisotropy on body surface potentials. Their results confirm the known fact that myocardial anisotropy has effects on surface potentials. Multiple activation sequences were applied to reduce the effects of isotropic myocardium to overall results.

The effects of orientation on the signal are smallest in the left thoracic region and highest on right upper thorax. In these regions the correlations are not depending on the activations sequence among these 6 tested ones. In other locations the correlations are depending on the activation sequence. This could be useful feature when monitoring changes in cardiac state. For example, one possibility could be to apply implant which monitors horizontal and vertical leads and if there exists major changes in the activation the correlation will change.

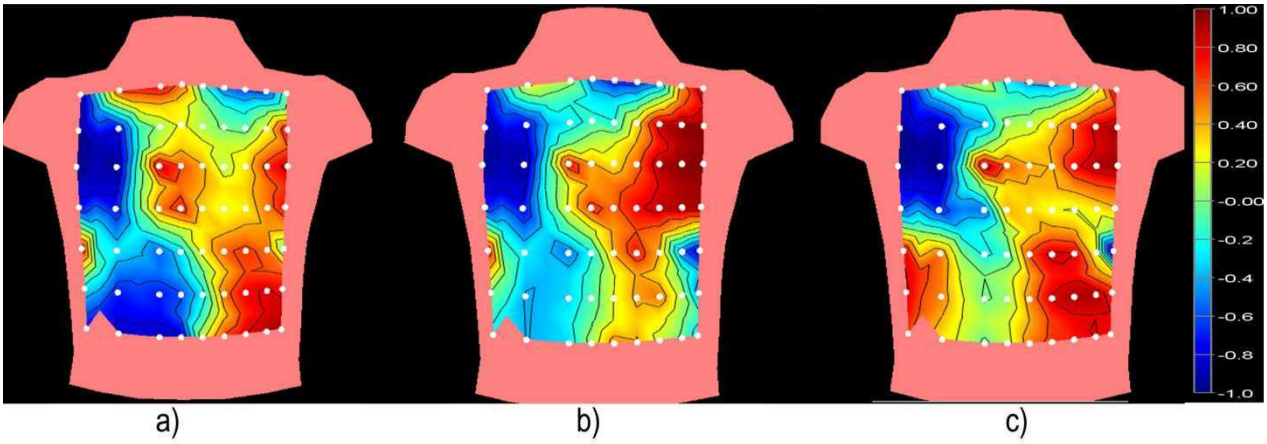


Figure 4. Correlations between signals of vertical and horizontal implant orientation. Activation sequences originate from mid-septum (a), posterior left ventricular wall (b), anteroseptal left ventricular wall (c). (visualized with *map3d* from www.sci.utah.edu)

In future studies we'll also observe effects on other features of signals such as, amplitude, total power. As a conclusion multiple activation sequences should be applied when studying effects of measurement configurations on simulated signals

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