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Estimation of ECG signal of closely separated bipolar electrodes using thorax models

M. Puurtinen, J. Hyttinen, J. Viik, P. Kauppinen, J. Malmivuo
Ragnar Granit Institute, Tampere University of Technology, Tampere, Finland

Abstract—New miniaturized portable ECG measuring devices may require reduced electrode size and distance. Modeling tools can be useful in predicting the behavior of electric field between electrodes. This paper introduces a project where the effect of interelectrode distance (IED) of ECG precordial electrodes was studied with a model of the thorax as a volume conductor and with Body Surface Potential Map (BSPM) data. The objective was to study how the IED affects the signal strength and how well the modeling data corresponds to the clinical data. 2D and 3D Finite Difference Method (FDM) torso models based on Visible Human Man data were used. On these FDM models, the electrodes' sensitivity to measure the electric field of the heart was derived. The results were compared to clinical 120 channel BSPM data. It was found out that reducing the IED obviously decreases the signal strength. According to the clinical data, the magnitude of this effect depends on the electrode location. This study indicates that modeling the volume conductor can predict the signal strength obtained with given electrode configurations. 3D modeling is more accurate in predicting the signal strength from clinical recordings; however, also simple and fast 2D modeling results show comparable values.

Keywords—ECG, FDM, IED, modeling, BSPM.

I. INTRODUCTION

The cardiac activity is commonly monitored by the standard 12-lead ECG system or by Body Surface Potential Map (BSPM). However, the advancements in wireless and portable technology suggest that the possibilities for smaller measurement devices and configurations taking advantage of miniaturization should be surveyed.

It is obvious that decreasing the interelectrode distance (IED) decreases the measuring depth. Accordingly, this causes that signals arising from deeper sources, such as the heart, decrease. Nevertheless, the magnitude of the effect of reducing the IED has not been widely studied. Investigating the functionality of electrode systems may be tedious if numerous clinical trials are needed. However, modeling tools can be useful in predicting the behavior of electric signals. In this paper, the effect of reducing the IED on the signal strength was modeled with 2D and 3D torso models and tested with real BSPM ECG database. The main aim of this project was to evaluate how well 2D and 3D modeling can predict the actual signal strength in clinical data. 2D model was tested since it can provide very fast calculation.

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II. METHODOLOGY

In this project, two methods were used: model of a thorax as a volume conductor and clinical BSPM data. These methods were used for studying the measuring sensitivity and the signal strength in bipolar electrode pairs located in the area of precordial electrodes V1-V6. In addition to the standard precordial electrode locations, the study utilized additional interposed electrodes, in order to study the effect of drastically reduced IED. In models, the minimum IED was $\frac{1}{4}$ of the original distance between two adjacent standard precordial electrodes, and in the clinical data $\frac{1}{2}$. The location of electrodes on 2D model is visualized in Fig. 1. The results obtained from the model data were compared to the clinical data in order to evaluate the accuracy of the models.

A. Models and clinical data

In this project two models were used: 2D model and 3D model, both representing the same human torso. The anatomy of these models was based on Visible Human Man (VHM) data and extracted from full thorax model [1] [2]. The models represent segmented slice images of a male cadaver thorax, and they include all visible details and 36 tissue types. The 2D thorax model illustrated in Fig. 1 was an axial slice of the full torso model. The 3D model illustrated in Fig. 2 was a complete model of the torso including 60 slices. The outlook of heart and blood masses is also visualized in Fig. 2.

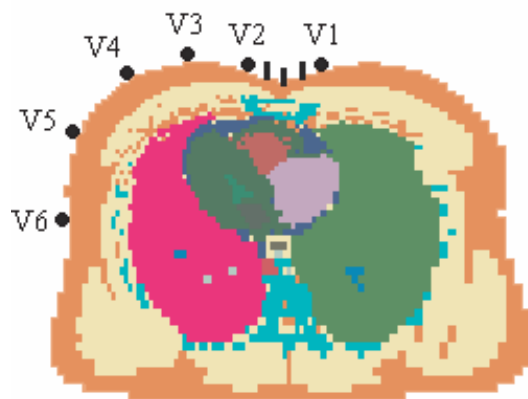


Fig.1. 2D thorax model based on Visible Human Man data showing the location of standard electrodes (circles) and an example of interposed electrodes (bars) used in model calculation.

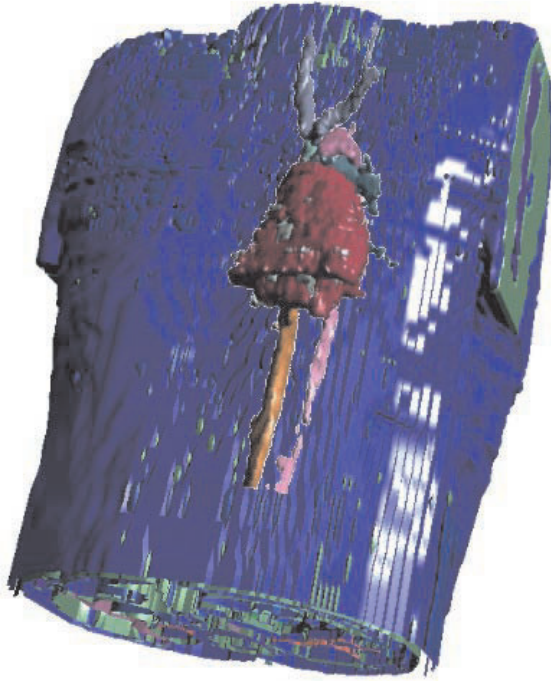


Fig.2. 3D torso model based on Visible Human Man data.

Both models were based on Finite Difference Method (FDM), in which the model composes of cubic elements and connective nodes forming a resistor network [3]. The resolution of the 2D thorax model was 250x250 pixels (pixel size 1,67 mm x 1,67 mm), and the corresponding FDM model included a total of 98 994 nodes. The resolution of the 60 sliced 3D torso model was lowered to 92x93 pixels, in order to ease the calculation process. However, the resolution of the 3D model was adapted according to the area of interest. The model resolution was the highest (1 mm x 1 mm x 4 mm) around the area of the heart and of the precordial electrodes. The 3D FDM model included a total of 258 442 nodes.

For evaluating the modeling results, clinical BSPM data of 120-leads ECG acquired from 236 normal patients was analyzed [6]. In this data, signals were recorded with Wilson's central terminal as a reference, but for this study, bipolar signals were obtained by subtracting the signals from adjacent electrodes. The BSPM data provided signals recorded with $\frac{1}{2}$ of the standard electrode distance between two adjacent precordial electrodes.

B. Calculations

The relationship between the measured signal V_{LE} in the lead and the cardiac current sources $\vec{J}^i$ in the volume conductor can be formulated as follows:

$$V_{LE} = \int \frac{1}{\sigma} \vec{J}_{LE} \cdot \vec{J}^i dv \quad (1)$$

,where $\vec{J}_{LE}$ is the lead field and σ is the conductivity of the volume conductor [5]. Thus, if the lead field and the properties of the volume conductor are known, the strength of the measured signal can be estimated.

In FDM models, the calculation of the sensitivity of the electrodes to measure hearts electric activity, lead field, was based on the reciprocity theorem. Reciprocity theorem states that the location of the source and the detector can be interchanged without any change in the signal amplitudes [5]. A reciprocal current was applied on a pair of electrodes located on the model, and the resulting lead field in the heart muscle was calculated. This resulting lead field in the heart muscle represented the leads i.e. the electrodes' sensitivity to measure the electric source of the heart. The modeling study utilized a bioelectric field software based on FDM created by Noriyuki Takano [4] at Ragnar Granit Institute.

Bipolar leads were constructed using electrodes positioned corresponding to the standard 12-lead ECG system precordial electrode locations V1-V6, and with additional interposed electrodes. The additional electrodes were placed between two adjacent standard precordial electrodes with distances $\frac{1}{4}$, $\frac{1}{2}$, and $\frac{3}{4}$ of the original distance. In 3D model the electrodes were in their original location, but in 2D model the electrode locations had to be projected to the same level so that they corresponded axially to the location of the precordial electrodes.

The lead field was calculated for each bipolar electrode pair consecutively; firstly between standard electrode locations (i.e.V1-V2) and then for reduced interelectrode distances. The number of bipolar leads analyzed with both models was 31.

From the clinical data the signal strength was derived by detecting the maximum QRS amplitude. The QRS amplitude from given bipolar lead was calculated for each patient and then the average over the population was calculated. The number of bipolar leads analyzed here was 14, since the clinical data provided only a part of the electrode locations analyzed with models.

For assessing the strength of relationship between the model data and clinical data, a linear regression analysis was conducted and the correlation coefficient was calculated. The correlation coefficient indicates to which extent datasets are linearly associated [7].

III. RESULTS

A. Signal strength vs. interelectrode distance

Fig 3. and Fig. 4 illustrate normalized results calculated with bipolar measurement between electrodes V1-V2, V5-V6, and with their interposed electrodes. On the y-axis are the signal strength values (arbitrary units) obtained from 2D model, 3D model, and clinical data. On the x-axis, the interelectrode distance 1 corresponds to the original distance between standard adjacent precordial electrodes.

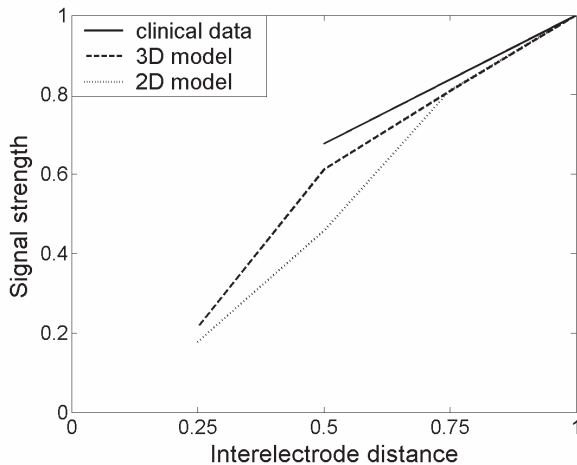


Fig. 3. Signal strength vs. interelectrode distance in bipolar electrode pair V1-V2. Recorded in clinical BSPM data and modeled with 2D and 3D models. Axes are in arbitrary units.

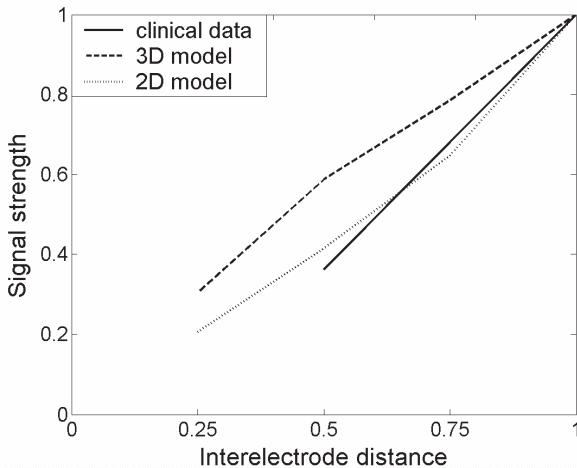


Fig. 4. Signal strength vs. interelectrode distance in bipolar electrode pair V5-V6. Recorded in clinical BSPM data and modeled with 2D and 3D models. Axes are in arbitrary units.

The results show that reducing the IED evidently decreases the signal strength, but according to the clinical data, the degree of this decrease varies depending on the lead. When decreasing the IED to half of the original, the signal strength decreases to 68 % in electrode pair V1-V2, and to 35 % in

electrode pair V5-V6. According to the results, both 2D and 3D model data correspond quite well to the clinical data.

B. Correlation between 2D and 3D model data and clinical data

Fig. 5 illustrates the correlation between 3D model data and clinical BSPM data. A linear regression analysis showed that the correlation coefficient between these data was 0,7924. Accordingly, Table 1. shows that the correlation coefficient between 2D and clinical data was 0,6913 and the correlation between 2D and 3D model data was 0,8969. In the case of correlation between model and clinical data, it was observed that when two outliers (bipolar electrode pairs detecting the direction of hearts' electrical axis, V2-V4 and V2-V5) were ignored, correlation between 2D and clinical data increased to 0,9169 and correlation between 3D and clinical data increased to 0,8896. Also the correlation coefficient between 2D and 3D data increased to 0,9188.

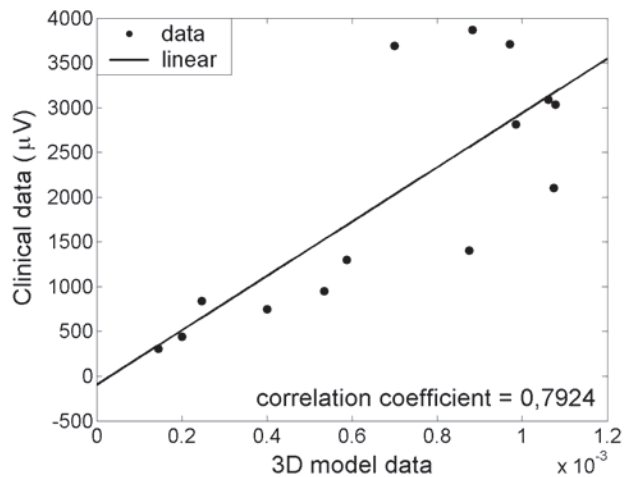


Fig. 5. Linear correlation between clinical BSPM data and 3D model data. The x-axis is in arbitrary units.

TABLE 1.
CORRELATION BETWEEN 2D, 3D, AND CLINICAL BSPM DATA.

Correlation coefficients between 2D, 3D, and clinical BSPM data	
Data	Correlation coefficient
2D – clinical	0,6913
3D – clinical	0,7924
2D – 3D	0,8969

IV. DISCUSSION

The results show that reducing the IED obviously decreases the signal strength in ECG. The magnitude of this effect depends on the electrode location. The results obtained from the model represent fairly well the clinical data. Even though the models are only a sample of human

chest representing one person, the results show that model calculations give an indicative of the signal level to be obtained. As expected, the results from 3D model are superior to the 2D model results. There exist certain error sources involved in the 2D model, such as the location of the precordial electrodes on the same axial level, and the lack of volume representation. Nevertheless, 2D model is useful in predicting the signal strength, as it is quite fast to calculate.

According to the linear regression analysis, the 3D model data and clinical data have a fairly high relationship, as the correlation coefficient is higher than 0.7. When the leads detecting the direction of heart's electric axis were ignored, the correlation increased. This is because in the clinical data, for those leads measuring the main direction of heart's electric activity, particularly high values are measured. In the model data, the heart's electric activity is not included. Models only take into account the torso anatomy, and therefore they do not consider the direction or the exact location of heart's electric source. For this reason, only the signal strength can be estimated, not the pattern. The accuracy of the models could be improved e.g. by including the heart's electric activity into the models. Nevertheless, this activity is highly dependent on individual, so the variation within population should be taken into consideration. The model data could be improved by weighting the results with a scaling factor based on an average direction of the heart's electrical axis, which could be calculated from the BSPM data.

V. CONCLUSION

This paper introduced a project where the effect of reducing the IED on signal strength was studied with 2D and 3D FDM models and with clinical BSPM data. Also the correspondence between model data and clinical data was evaluated. The results demonstrate the fact that reducing the IED decreases the signal strength. The results indicate that models' lead field can be used to predict the signal strength and thus to optimize the electrode distance and location. Further study on the correlation between 3D model and BSPM clinical data will be conducted with a larger number of leads.

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