# Effect of Number of Electrodes, Electrode Displacement, and RMS Measurement Noise on the Localization Accuracy of ECG Inverse Problem

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## Abstract

*The effect of number of electrodes, electrode displacement, and RMS measurement noise was evaluated using an anatomically detailed computer model of the thorax as a volume conductor. The body surface potential distributions due to cardiac dipole sources were calculated by applying five different electrode montages: the 8 electrodes representing the independent leads of the standard 12-lead electrocardiogram (ECG), a modified 24-lead, Lux 32-lead full body, Montreal 64-lead, and Brussels 120-lead configurations. Inverse solutions were computed using the lead field concept in the presence of both erroneous locations of the electrodes and of RMS measurement noise added to the torso surface potentials. The results indicate that increasing the number of leads enhances the localization accuracy of the inverse problem. With 32 or more electrodes the localization accuracy remained stabilized despite the added RMS measurement noise. Similarly, increase of number of displaced electrodes to 32 improves the localization accuracy as compared to cases with fewer electrodes.*

## 1. Introduction

The measurement of the electrocardiogram (ECG) provides non-invasively obtained data for localizing the electric sources generating potentials on the surface of the thorax. During a past few decades, the ECG inverse problem has been widely studied in order to establish a way to determine the equivalent source configurations within the body based on this surface potential data. The lead field concept provides one possible approach for linking the information available for the nature of the source generating the currents and the properties of the thorax as a volume conductor [1].

Increased computing capacity has allowed the construction of anatomically detailed, inhomogeneous thorax models [2,3,4,5]. The redundancy of electrodes in the ECG has been widely studied but no consensus for an optimal number and arrangement has yet been found [6,7,8]. It is obvious, however, that the larger the number of electrodes, the more accurate information can be gained regarding the body surface potential distribution. However, as a generalized assumption, it has been shown previously that 32 leads provide a fairly good approximation [6,7].

The inverse problem is ill-posed by its nature, and thus several approaches have been used to attempt to solve it. The general scheme to solve the ECG inverse problem, i.e. to localize dipolar sources, has been to assume one source configuration, to calculate the forward solution, and then to compare the calculated potentials with the measured potentials until the optimal fit has been found. Inverse algorithms used for single dipole localization have been generally based on least squares approach or probabilistic methods.

The aim of the present study is to demonstrate to what extent the number of electrodes, errors in electrode locations on the surface of the body, and RMS measurement noise affect the accuracy of the inverse solution. In this study, the weight of these effects is evaluated based on simulations performed with an anatomically detailed 3-D finite difference (FDM) thorax model.

## 2. Material and methods

### 2.1. Application of the lead field concept and reciprocity theorem for the ECG inverse solution

The human body can be considered as a resistive, piecewise homogeneous and linear volume conductor [1]. The governing equation of the electrical properties of the body as a volume conductor may thus be represented by the Poisson's equation. In the FDM modeling approach applied in this study, the Poisson' equation is approximated by dividing the volume into a 3-D resistor network that reflects the human body both geometrically and as a conductor [9]. The structures are represented by a 3-D grid of discrete points called nodes, and a network of resistors is placed between these nodes. Resistor values depend on conductivity of the tissue type and the size of the element between the node points.

The lead vector and lead field concept were originally developed for describing the sensitivity of bioelectric measurements, but their principles are universal in the sense that they apply to any linear system. The direction of the lead vector identifies at which orientation a source dipole $\bar{p}$ will produce the maximum potential at the measurement electrodes $\Phi_P$. The magnitude of the lead vector identifies the effect dipole's magnitude has on the elicited potential at the electrodes. Hence, the elicited potential is the dot product of the lead vectors and the source dipole as follows (Eq.1)

$$\Phi_P = \bar{c} \cdot \bar{p} \qquad \text{(Eq.1)}$$

The lead field can be understood as a continuous vector field comprising of single lead vectors mapped as a function of the source location throughout the volume conductor. Thus, the lead field fully takes into account the effect of volume conductor boundary and internal inhomogeneities, i.e. the conductivity distribution.

The reciprocity theorem originally introduced by Helmholz in 1853 states that electric field *E* inside the volume conductor, e.g. the thorax, generated by a reciprocal unit current $I_r$ applied to the surface electrodes expresses how the same electrodes record potentials caused by dipole sources at any location within the volume conductor [1]. Thus, a reciprocal current flows through every network resistor. The Kirchoff's current law applies to this network resistor system, and the three reciprocal current components form a reciprocal current vector $\bar{I}$ at every node. The magnitude of a node's current vector is directly proportional to the magnitude of the node's lead vector $\bar{c}$ while their direction is identical.

## 2.2. Construction of FDM thorax model

The developed model of the human thorax as a volume conductor is based on the finite difference method. One MR image set consisting of 70 slices presenting the thoracic anatomy during diastole was segmented using the IARD method [10] and employed to construct an anatomically detailed model comprising of 250000 elements [11].

Equivalent bioelectric sources are used when solving the forward problem, where the solution provides the potential or current distribution on the model surface arising from the known sources of bioelectric origin. In this study, simulated potential data was generated by inserting an equivalent dipole source into the constructed volume conductor model and calculating the body surface potential distribution with the FDM solver [12]. Four single dipoles at different locations of the cardiac muscle were considered. Each of these dipoles was simulated in x, y, and z directions according the rectangular grid used for modeling resulting in 12 dipole settings.

## 2.3. Lead systems, electrode displacement, and RMS noise

The inverse solution algorithm was based on the lead field concept providing the sensitivity distributions of the leads. The analyzed ECG lead arrangements include the 8 independent leads representing the standard 12-lead ECG, a modified 24-lead based on studies by Kornreich [6], Lux 32-lead full body, Montreal 64-lead, and Brussels 120-lead electrode configurations providing the transfer matrices (Figure 1). The inverse solutions were calculated using the maximum likelihood method to estimate the location of the dipoles [13].

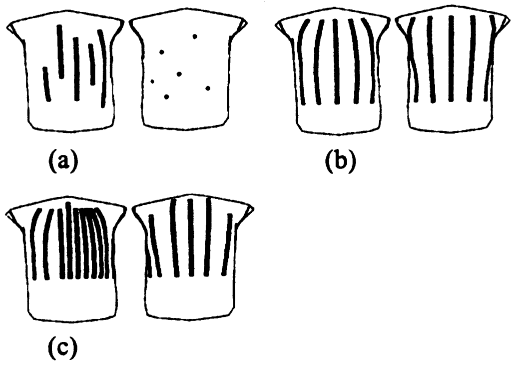

Figure 1. The electrode configurations used for simulations a) 32-lead Lux full body, b) Montreal 64-lead, and c) Brussels 120-lead system [14]

The localization procedure was executed in all cases for all electrode montages considered, and the total average localization accuracy in all dipoles in every orientation was calculated to evaluate the performance and the stability of the localization procedure. The lead field concept allowed the possibility to restrict the amount of possible source nodes within the heart area.

The effect of the number of electrodes was assessed by the absolute error of the spatial localization. The dipole magnitudes and moments were not compared. In the lead field approach an actual point dipole is used while in the simulated dipoles two nodes with finite grid distance formed the source and the sink of the dipole. Thus, the magnitude values are not directly comparable.

Also the effect of electrode positioning accuracy on the localization procedure performance was estimated by moving the electrodes on the surface of the body. In this study, the electrodes of 8, 24, and 32-lead systems were moved on the surface of the body 1.5 cm both in vertical and horizontal directions.

Finally, the performance of the localization procedure was tested by adding interfering RMS noise to the body surface potential values of each electrode. The noise was generated at three levels ranging from 10% until up to 30% of the original values for potentials of all five electrode montages.

## 3. Results

### 3.1. Effect of the number of the electrodes on the localization accuracy

The inverse solution using the simulated potential data and the calculated lead fields was obtained for all 12 dipoles. The solutions were restricted to the heart area, and thus the solution was to be found among 8219 nodes representing the cardiac muscle. The dependency of the localization accuracy on the electrode configuration was assessed and found to lie between 2 and 5 millimeters. The average values are calculated to include all four dipoles in all three orientations. These error values considered are summarized in Figure 2.

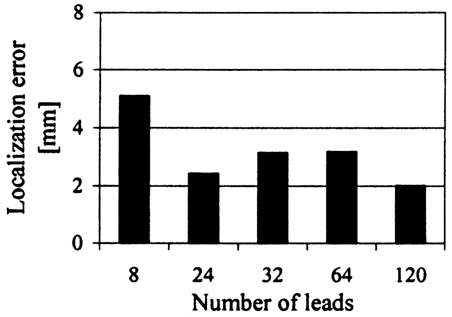

Figure 2. Average dipole localization error in millimeters for different electrode configurations considered.

### 3.2. Effect of electrode displacement on the localization accuracy

The effect of electrode dislocation was evaluated by moving the electrodes of the 12, 24, and 32-lead systems on the surface of the body. The results of the consequently obtained inverse solutions are represented in Figure 3. The localization error in case of using 8 lead system was more than 40 mm with vertical movement and more than 30 mm with horizontal movement. As the number of electrodes was increased to 32, the localization error is decreased to 15 mm in horizontal case and 18 mm in vertical case, respectively.

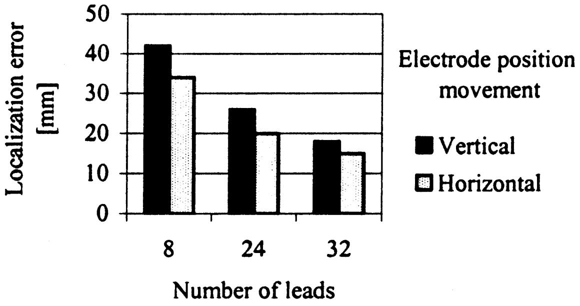

Figure 3. The effect of electrode dislocation on the localization accuracy of 8, 24, and 32-lead systems

### 3.3. Effect of RMS measurement noise on the localization accuracy

In order to assess the sensitivity of the inverse procedure used to measurement noise, the surface potentials of each electrode were interfered with 10%, 20%, and 30% RMS noise. The inverse solutions were calculated, and the corresponding localization errors were estimated. Again, the average values are calculated to include all four dipoles in all three orientations. The results for each analyzed electrode montage are shown in Figure 4.

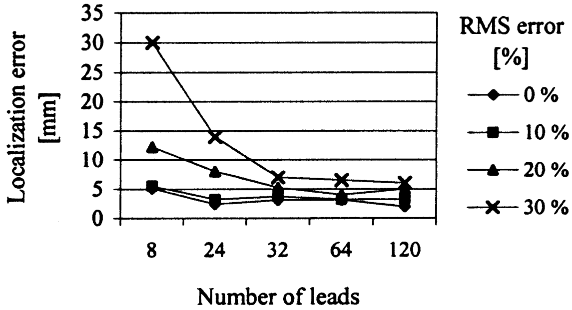

Figure 4. The effect of RMS measurement noise on the localization accuracy.

## 4. Discussion

In this study a computerized human thorax model as a volume conductor was constructed, and several single dipole sources were inserted into the cardiac muscle to simulate the electric sources generating the body surface potential distribution. The inverse problem was solved using this surface potential data and the information regarding the properties of the thorax obtained from the lead fields. Altogether five different lead montages were analyzed, and the effect of number of leads, of erroneous locations of electrodes, and of RMS measurement noise on the localization accuracy of the inverse solution was evaluated.

The effect of electrode configuration was assessed by comparing the source localization accuracy produced by five different electrode configurations. The localization error in case of using the 8-lead ECG is slightly higher than when increasing the electrode density. However, in noiseless case the accuracy of 8-lead system was surprisingly good, the localization error being only 5 mm, i.e., in almost within the model resolution. As the number of electrodes was increased, the performance of the inverse procedure was stabilized to approximately 3 mm.

The effect of electrode dislocation was considered with 8, 24 and 32-lead configurations. In cases of vertical electrode shift the localization error varies from more than 40 mm (8 leads) to 18 mm (32 leads). With horizontal electrode position change the error ranges from 33 mm (8 leads) to 16 mm (32 leads). This accuracy, however, may not be satisfactory for a reliable source localization procedure. Thus, either high level of precision must be obeyed while positioning electrodes to the surface of the body, or the number of electrodes must be increased in order to compensate for the error due to electrode dislocation.

RMS measurement noise was added at 10%, 20%, and 30% of the body surface potential values. With 20% or more added noise the performance of the 8-lead ECG was poor, while 24 leads improved the localization accuracy somewhat. With 32 or more electrodes the localization accuracy remained stabilized despite the added noise. This is in accordance with previous results obtained by e.g. Lux [6]. It must be stated, however, that the simulations in this study were based on one single fixed dipole model. If more complex sources are to be needed, more leads may be required.

## Acknowledgements

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