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Effect of Source Depth on the Specificity of Bipolar EEG Measurements

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Abstract—**The purpose of the present study was to evaluate how the brain sources located at different depths can be most effectively measured with bipolar EEG leads. The specificity of an EEG lead to detect sources was studied with a new parameter called region of interest sensitivity ratio (ROISR) by employing a spherical head model. We studied the specificity as a function of electrode distance and further as a function of scalp:skull:brain resistivity ratio. The simulations indicate that the closer to the surface of the brain the source is located, the shorter is the interelectrode distance in the optimal lead. Also in the case of superficial sources, the small misplacement of the electrodes results in a substantial decrease in specificity. The resistivity ratio has the largest effect on the specificity, when the source is located close to the surface of the brain. However in the case of deep sources, the resistivity ratio has only minimal effect on the specificity**.

I. Introduction

THE purpose of the present paper was to evaluate how the depth of the signal source affects to the specificity of bipolar EEG leads. This study was based on the application of the lead field theory. In [1] and [2] the half-sensitivity volume (HSV) concept was applied to study the spatial resolution of EEG and MEG. HSV is defined as the volume within the volume source where the magnitude of the detector's sensitivity is at least half of its maximum (in the volume source region). Thus the smaller the HSV is, the more focused the measurement is. In [2] it has been shown that the shorter the interelectrode distance is and further the lower the scalp:skull:brain resistivity ratio is, the smaller is the size of the HSV. In a submitted paper [3] we have presented new parameters, which describe how well the sensitivity is concentrated for example within the HSV compared to other source regions. The new parameter that describes how well the measurement is concentrated within HSV is called the half-sensitivity ratio (HSR). HSR defines how specific the measurement is to the sources in HSV. Thus HSR gives additional information on the properties of the sensitivity distribution and it can be applied together with HSV to analyze the quality of different leads [3].

With every electrode distance the HSV is located below the measurement electrodes. The interest in EEG is not always to measure signals that are generated on the surface of the brain. For example many evoked potentials are generated at the deeper structures of the brain. To analyse the specificity of the leads to sources that are not located within HSV, we presented in [3] another parameter called the region of interest sensitivity ratio (ROISR). The interest in the present paper is to introduce one application of ROISR and to study how the specificity of bipolar leads is affected by the interelectrode distance and the scalp:skull:brain resistivity ratio, when the depth of the region of interest is varied.

This study has practical applications for example in the designing of monitoring devices and evoked potential measurements, where it is possible to apply only a limited number of electrodes. In these applications it would be highly beneficial to know the optimal electrode locations. Studying the specificity of different leads with ROISR would aid in determining the optimal electrode locations to measure the signal generated within ROI with the highest possible quality. In addition to applying ROISR for defining optimal bipolar EEG leads, it can be applied to study the specificity of other bioelectric and biomagnetic measurement leads.

II. Methods

A. Model and Electrode Configurations

As a volume conductor model we applied the three-layer spherical Rush and Driscoll head model [4]. The model includes the layers of scalp, skull and brain, the radii of the spheres being 92 mm, 85 mm and 80 mm, respectively. We applied the principle of reciprocity and calculated the sensitivity distributions within the brain volume by using the analytical equations derived by Rush and Driscoll [4]. In the literature there exists a large variation of the skull resistivity and thus we applied five different resistivity ratios for scalp:skull:brain. Those were 1:80:1 given by Rush and Driscoll [4] and more realistic values of 1:30:1, 1:15:1 [5] and 1:8:1 [6]. We also studied the homogeneous model in which the resistivity ratio is 1:1:1.

In our analysis we wanted to study how the electrode distance affects to the specificity of bipolar leads to detect sources in various depths. For that purpose we studied 35 different leads, where the angle between electrodes was

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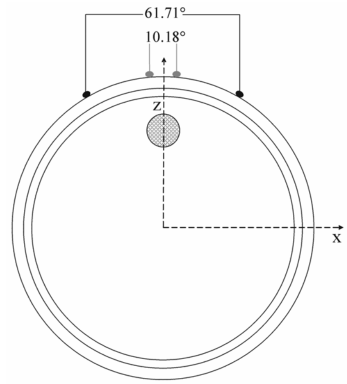


Fig. 1. The bipolar measurement leads. Here two different leads with electrode separation 10.18° and 61.71° are shown. Also one location of ROI, where the center is at location z = 6.0 cm is presented.

increased at 5.14° intervals from 5.14° to 180°. Two examples of the studied electrode distance are illustrated in Fig. 1.

As a region of interest we defined a spherical volume with a radius of 1.0 cm. Because we were interested in evaluating the effect of source depth on the specificity of different bipolar leads, the location of the ROI was varied along the z-axis, from position z = 0.0 cm (at the center) to z = 7.0 cm (close to surface) at 1.0 cm intervals. Example of a ROI at location z = 6.0 cm is illustrated in Fig. 1.

B. Sensitivity Distribution

We applied the lead field theory and reciprocity theorem to calculate the sensitivity distributions of different EEG leads. The lead field in the volume conductor can be obtained by feeding a unit current to the lead, according to the reciprocity theorem of Helmholtz. The current field arised in the volume conductor by the reciprocal current is equivalent to the distribution of the sensitivity of the lead [7].

Equation (1) describes the relationship between the measured signal V_{LE} in the lead and the current sources $\overline{J}^i$ in the volume conductor, when a unit reciprocal current is applied to the lead [7]:

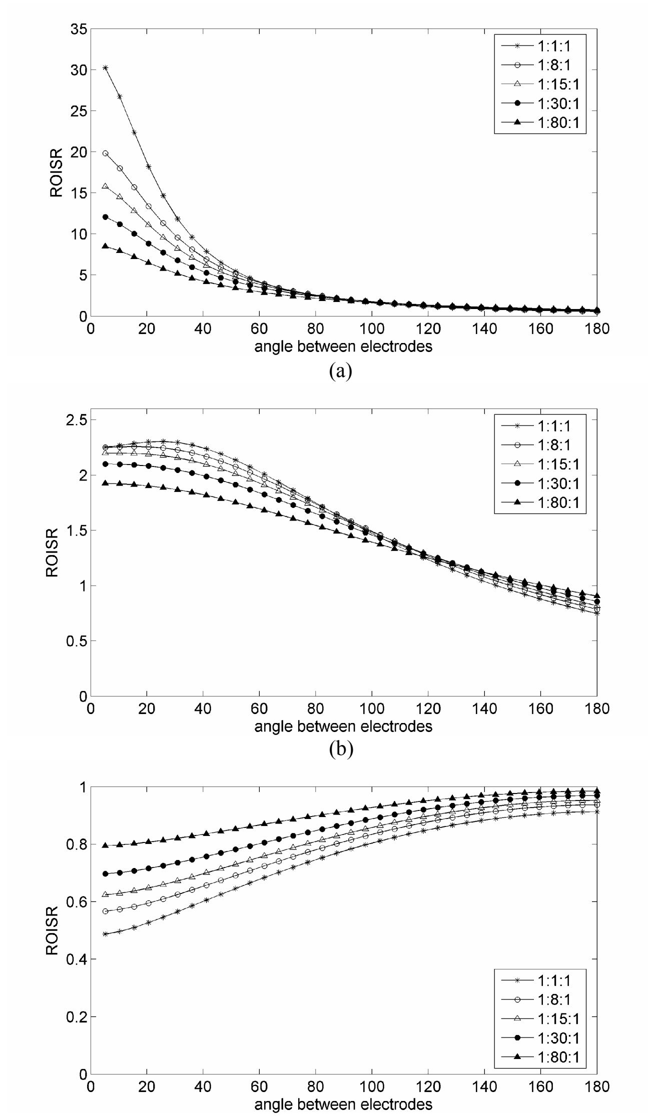
$$V_{LE} = \int \frac{1}{\sigma} \overline{J}_{LE} \bullet \overline{J}^i \, dv \qquad (1)$$

, where $\overline{J}_{LE}$ is the lead field current density, $\overline{J}^i$ is the current source density and σ is the conductivity of the volume conductor. We calculated the sensitivity distributions of the 35 leads for 5 different scalp:skull:brain resistivity ratios.

C. ROI Calculations

The specificity of different leads to sources in different regions of interest was evaluated with the ROISR-parameter [3]. The ROISR defines how much more sensitive on average the detector is to individual sources within the ROI than to individual sources outside it:

$$ROISR = mean(\|\overline{J}_{LE,ROI}\|) \big/ mean(\|\overline{J}_{LE,nonROI}\|) \qquad (2)$$



(c)

Fig. 2. ROISR plotted as a function of the angle between electrodes for 5 different scalp:skull:brain resistivity ratio. In (a) the center of ROI is at location z = 7.0 cm, in (b) at z = 4.0 cm and in (c) at z = 0.0 cm.

, where $\|\overline{J}_{LE,ROI}\|$ are the magnitudes of lead field current density vectors within ROI and $\|\overline{J}_{LE,nonROI}\|$ are the magnitudes of lead field current density vectors at the brain volume excluding the ROI.

In the case it is assumed that the noise sources are distributed homogeneously outside the ROI, it can be assumed that the ROISR has a high correlation to the signal-to-noise ratio (SNR) of the lead. It should be noted that in this assumption the wanted signal is generated within ROI. The noise on the other hand consists only of the brain noise generated within the rest of the brain volume.

We calculated the ROISR of all 8 ROI depths for different leads and different scalp:skull:brain resistivity ratios. We also evaluated for each ROI depth the optimal electrode distance i.e. the distance which gives the highest ROISR.

TABLE 1. MAXIMUM ROISR FOR EACH ROI LOCATION FOR DIFFERENT SCALP:SKULL:BRAIN RESISTIVITY RATIOS.

	MAXIMUM ROISR				
ROI location	**1:1:1**	**1:8:1**	**1:15:1**	**1:30:1**	**1:80:1**
z = 7.0 cm	30.26	19.84	15.79	12.10	8.50
z = 6.0 cm	9.31	7.48	6.51	5.46	4.27
z = 5.0 cm	4.14	3.79	3.52	3.18	2.70
z = 4.0 cm	2.30	2.26	2.20	2.10	1.92
z = 3.0 cm	1.53	1.54	1.53	1.51	1.46
z = 2.0 cm	1.15	1.17	1.18	1.19	1.19
z = 1.0 cm	0.97	0.99	1.01	1.02	1.03
z = 0.0 cm	0.91	0.94	0.95	0.97	0.98

III. RESULTS

In Fig. 2. the ROISRs are plotted for three different ROI locations. In Fig. 2(a) the center of the ROI is at z = 7.0 cm, in (b) at z = 4.0 cm and in (c) at z = 0.0 cm. The ROISRs are plotted as a function of the angle between electrodes and for all studied resistivity ratios.

The maximum ROISR value for each ROI location is listed in Table 1. The values are given for all studied resistivity ratios. The electrode distances at which the maximum ROISRs are obtained are illustrated in Fig. 3 for resistivity ratios 1:8:1, 1:15:1 and 1:30:1. In Fig. 3. the optimal electrode distance for each source depth is connected to the corresponding ROI location with the dashed line. The optimal electrodes distance is the smallest of the studied ones, 5.1°, for ROI locations from z = 4.0 cm – 5.0 cm to z = 7.0 cm, depending on the resistivity ratio. In Fig. 3. the limits for the electrode locations within which the ROISR is at least 99.5 % of its maximum value are sketched with segments of line. The limits are given for those ROI locations, which are connected to corresponding electrode locations with black dashed lines. The superficial ROI locations are considered in Fig. 4., where the limits for the optimal electrode distances, within which the ROISR is at least 90 % of its maximum value, are illustrated. In the Fig. 4, the resistivity ratio is 1:15:1.

As it can be seen from Equation (1) also the orientation of the source affects to the strength of the measured signal. An example of the lead field in the bipolar setting illustrated in Fig. 1. is presented in Fig. 5 (a). If the ROI is located on the z-axis, as in the above calculations, the bipolar lead will pick up signals that are generated by dipolar sources that are oriented tangentially. The lead illustrated in Fig. 5 (b) is more sensitive to radial sources. Even a more optimal lead to measure signals from radially oriented sources, can be obtained by applying a three electrode lead described in [1].

IV. DISCUSSION

A. Effect of ROI Depth on the Specificity

The specificity of bipolar EEG leads decreases rapidly as the ROI is located closer to the center of the brain. The relative skull resistivity has the largest effect on the value of ROISR, when the ROI is located close to the surface of the brain; the lower the relative skull resistivity is the higher is

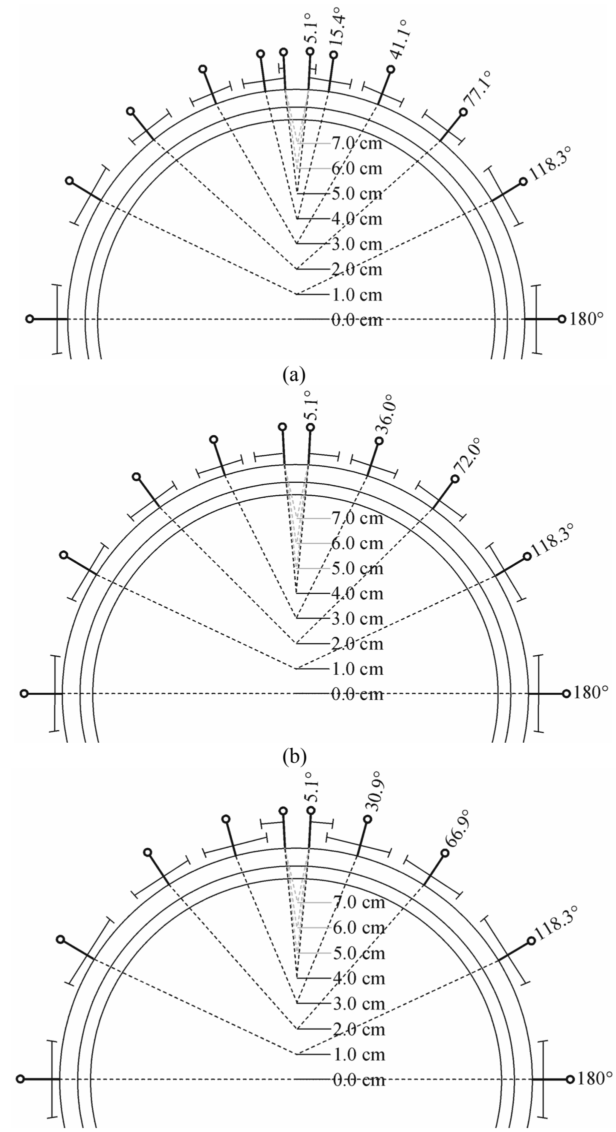


Fig. 3. Optimal electrode distances for ROIs located at 8 different depths. The ROI location is connected to the corresponding optimal electrode locations with a dashed line. In (a) the resistivity ratio is 1:8:1, in (b) 1:15:1 and in (c) 1:30:1. The limits for the electrode locations, within which the ROISR is at least 99.5 % of its maximum value, are marked with black segments of line. These limits are illustrated only for those ROI locations, which are connected to the electrodes with black dashed lines.

the ROISR. When the ROI is located deeper in the brain, the effect of relative skull resistivity on the ROISR is smaller; the ROISR is slightly larger for higher relative skull resistivities. The scalp:skull:brain resistivity ratio has a significant effect on the value of maximum ROISR only, when the ROI is located close to the surface of the brain. The lower the resistivity ratio is the higher is the maximal ROISR. For deep ROI locations, the maximum ROI is practically equal with different resistivities.

B. Effect of Optimal Electrode Distance on the Specificity

The closer the ROI is located to the surface of the brain, the shorter is the optimal electrode distance. On the other

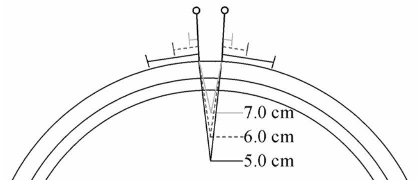


Fig. 4. The resistivity ratio is 1:15:1. The optimal electrode distance for ROI locations z = 5.0 cm, z = 6.0 cm and z = 7.0 cm is 5.14°. The limits for the electrode locations, within which the ROISR is at least 90 % of its maximum value, are sketched with segments of line.

hand when the ROI is located at the center of the brain, the optimal electrode distance is 180°.

The resistivity ratio has an effect on the optimal electrode distance when the ROI is located between z = 2.0 cm – 4.0 cm. Basically, the higher the resistivity ratio is the shorter is the optimal electrode distance.

The closer to the surface the ROI is, the more accurately the electrodes need to be placed at their optimal position, to obtain the highest possible ROISR. If the ROI is located superficially at distances z = 5.0 cm – 7.0 cm, even a few degree shift from the optimal electrode positions decreases the ROISR substantially. Thus if the region of interest is located close to the surface of the brain, special attention needs to paid on the correct placement of the electrodes.

On the other hand if the ROI is located deep in the brain, even the misplacement of electrodes by many degrees has practically no effect on the value of ROISR. If the relative skull resistivity is low, the misplacement of the electrodes causes relatively a little bit larger change to the ROISR than if the relative skull resistivity is high.

C. Application of ROISR

The application of the new ROISR parameter for selecting optimal bipolar leads with high specificity requires that the region of interest is known.

It can be assumed that the ROISR has a high correlation to the signal-to-noise ratio in the case the noise sources are homogeneously distributed within the brain, and the only noise component considered for SNR is the noise generated within the brain. To study the correlation of ROISR and SNR in realistic measurements, a series of clinical tests need to be conducted.

Results from a preliminary visual evoked potential experiment have shown that the HSR and SNR have a strong correlation [8]. This strongly suggests that at least for superficial ROI locations, the ROISR and the SNR have a high correlation. For deep ROI locations, the value for ROISR is extremely low, independent of the relative skull resistivity. Thus the optimal lead selection alone does not result in a high enough specificity. A general practise in evoked potential measurements is to record several epochs and to apply averaging to improve the SNR. In the case of deep ROI location also the properties of the volume conductor differ substantially from the properties of the spherical model and thus the application of realistically shaped head model might be required.

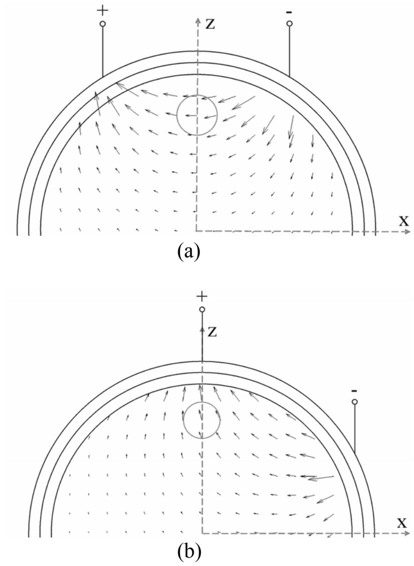


Fig. 5. Orientation of the lead field in different leads. (a) Bipolar lead that is sensitive to tangentially oriented sources. (b) Bipolar lead that is more sensitive to radially than tangentially oriented sources. The angle between electrodes in both of these leads is 61.71°.

In the above discussion only the magnitude of sensitivity was considered but also the source orientation has an effect on the specificity of the lead. Thus to obtain the best possible specificity for radially or tangentially oriented sources, the electrodes need to placed differently with respect to the region of interest.

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