Effect of measurement noise on the spatial resolution of EEG

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Introduction

The aim of the present study was to examine the spatial resolution of EEG (electroencephalography). The spatial resolution of traditional 10-20 –electrode system is insufficient for modern brain research. Nowadays even 256-channel measurement equipment are commercially available. The general interest is to evaluate the increase in spatial resolution obtained with these equipment.
In this study the objective was to evaluate the relationship between the number of EEG electrodes, measurement noise and the accuracy of the inverse solution of cortical potential distribution. This was done by means of model-based inverse EEG solution.
The spatial resolution of EEG is affected by blurring caused by volume conductor effects. The contribution of the low-conducting skull is the largest. If the spatial resolution is poor, localization of complex electrical activation is difficult. To improve spatial resolution the number of electrodes needs to be increased. In addition a number of numerical data enhancement methods have been applied. One of the most common of these methods is solving the cortical potential distribution.
The benefits of increasing the number of electrode depend strongly on the measurement noise. The main purpose of present study was to approximate the measurement noise and to study how it limits the spatial resolution provided by the high number of electrodes.

Methods

Volume conductor model. To obtain the source-field relationship of cortical potentials and scalp EEG field, a three-layer spherical Rush and Driscoll head model was applied. The model included the layers of scalp, skull and grey matter. The resistivity ratio between the tissues was different from the Rush and Driscoll model, being 1:15:1 [1]. In our study we constructed an FDM (finite difference model) of the head, though for this spherical model analytical methods could have been used.
Electrode systems listed in Table 1 were modeled by placing the point electrodes on the scalp surface according to their interelectrode distance. Electrodes were placed evenly on the entire spherical scalp surface. This allows the use of full spherical symmetry to reduce the number of calculations. The number of electrodes on half sphere thus corresponds to realistic electrode systems. The cortical sources were modeled as equal-sized areas with a specific potential value on the cortical surface. The number of source areas varied from 32 to 8450 between different simulations.
In the forward problem the system is described with equation:

$$\mathbf{b} = \mathbf{A}\mathbf{x} \qquad (1)$$

where **b** is a vector containing information on the measured EEG field, **A** is the forward transfer matrix and **x** is a vector containing information on the source. To solve the inverse problem the matrix **A** needs to be inverted. The problem is ill-posed and a regularization method is needed. In this study SVD (singular value decomposition) was applied.

Table 1 Studied electrode systems.

Electrode distance	Realistic electrode system	Number of electrodes on the entire spherical surface
60 mm	10-20 –system	34 electrodes
33 mm	64 electrodes	104 electrodes
23 mm	128 electrodes	232 electrodes
16 mm	256 electrodes	462 electrodes
11 mm	512 electrodes	938 electrodes

Singular value decomposition. In addition to being a convenient method to handle the ill-posedness of the forward transfer matrix, SVD is a practical means of studying the effect of measurement noise on the spatial resolution. We adopted the method from [2], where it was applied on ECG (electrocardiography). The nullspace of matrix **A** consists of the basis vectors, which lead to the signal smaller than the measurement noise:

$$\frac{\sigma_i}{\sigma_1} < \frac{\|\boldsymbol{e}\|}{\|\boldsymbol{b}\|} \qquad (2)$$

where σ_i are the singular values of **A**, $\boldsymbol{e}$ is the measurement noise in $\boldsymbol{b}$, including noise. The relation in the Equation 2 is known as noise level (NL). All basis vectors that lead to signal smaller than NL belong to this null space. The more there are reconstructable basis vectors (RBVs) the better is the spatial resolution.
Measurement noise. The definition of the measurement noise in our case, where the whole cortical potential distribution is to be solved, differs for example from the measurement noise in dipole localization. When the

cortical potential distribution is to be solved the background activity of the brain is not considered to be noise but actual signal. Thus the noise in our case is mainly composed of two different components: electrode contact noise and environmental 50 Hz noise. In the case of EEG we are more concerned with the electrode noise, because the 50 Hz noise can be eliminated by measuring the EEG in electrically shielded rooms or in some cases by applying a 50Hz notch filter. The electrode contact noise is mainly produced in electrolyte-skin –contact [3]. Many factors such as the electrode material, electrolyte and skin preparation affect to the amount of electrode noise. The noise is noticeable at low frequencies below 30 Hz [3]. This is a problem in EEG, because also the signal is in this frequency band and thus the noise cannot be filtered out. In [3] the electrode contact noise in Ag-AgCl electrodes using wet electrolyte is approximated to be on average 3,5µV(rms) and at minimum 1µV(rms).
In our study we estimated the measurement noise with two different approaches. In the first approach the measurement noise was measured from electrodes placed on the knee. We used Ag-AgCl electrodes with 10 mm diameter. The distance between electrodes was 25 mm.
In the second approach we estimated the measurement noise during EEG suppression measured under anaesthesia. We had data measured under two anaesthetics; propofol and etomidate. Both measurements were done using standard electrode locations of the 10-20 –system. Ag-AgCl electrodes were used. The reference in both measurements was close to location of Cz.
These two methods were chosen because we can assume that on the knee, the contribution of electromyography (EMG) is small and on the other hand during EEG suppression the brain activity is low.
We approximated the measurement noise as the standard deviation of the measured signal. We calculated noise estimates both on the whole frequency band and in frequency band between 0-30Hz.
Estimation of noise level. The noise level in EEG measurement depends both on the measurement noise and on the measured signal. The EEG amplitudes vary a lot between awake and sleep and also between children and adults. For example the mean amplitude of alpha waves is typically 50-70 µV and also values between 20 and 100 µV are normal. We applied a few normal values listed in Table 2 to our noise level calculations.

Table 2. Typical values of EEG amplitudes.

EEG	Amplitude (µV)	rms (µV)
alpha	20	14.14
alpha	50	35.36
alpha	70	49.50
alpha or delta(adults)	100	70.71
delta(adults)	200	141.42
delta(children)	300	212.13

Results

Measurement noise. The typical frequency spectrum of EEG during EEG suppression is sketched in Figure 1. In (b) the 50 Hz peak is clear and in (c) also noise components at lower frequencies can be seen. It can also be seen that EEG is not completely suppressed but there is a clear component at delta frequency (3Hz). The noise values in the channels where the brain activity was most suppressed, varied between 1.1 and 4.0 µV(rms).
In Figure 2 an example of knee measurement data is given. From the frequency spectrum it can be seen that there is a large component at low frequencies (<5Hz). This is most probably caused by movement and electromyography (EMG). The noise varied between 1.6-3.5µV(rms).

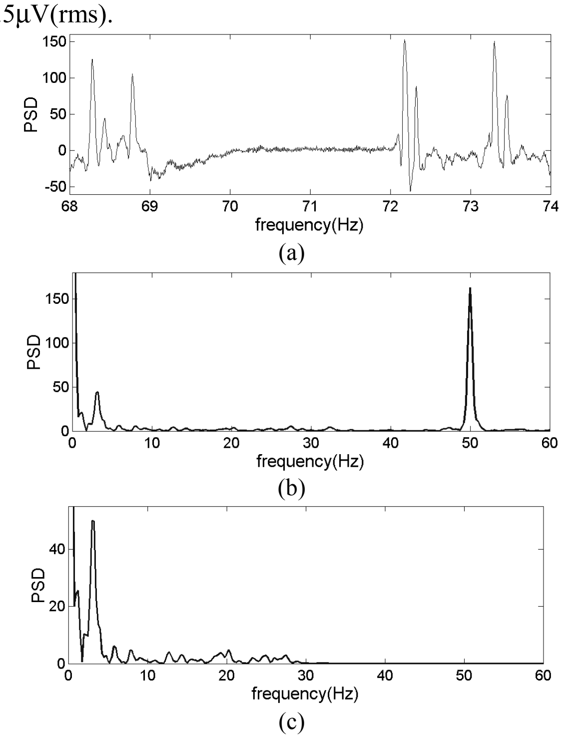

Fig. 1 In (a) the EEG suppression at time interval 70-72s is clear. In (b) the corresponding power spectrum density (PSD) is plotted. In (c) the PSD under 30 Hz is plotted. This measurement is done under propofol anaesthesia between channels Cz-O2.

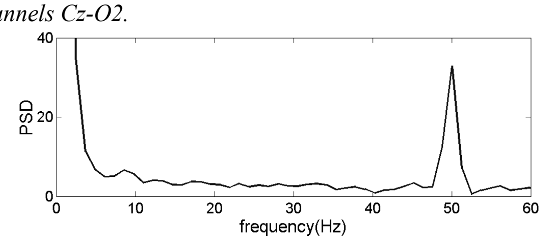

Fig. 2 Power spectrum of knee measurement. The large component under 5Hz is caused by movement and EMG.

In Table 3 the minimum values for noise voltages obtained with different measurements are given. The noise estimates are given both for the whole frequency band and the band under 30 Hz. In Table 4 the noise levels corresponding to typical EEG values and to estimated noise values of 1.1μV(rms), 1.4μV(rms), 2.0μV(rms) and 4.0μV(rms) are calculated.

Table 3. Minimum noise values obtained with different noise measurements. The noise estimates are given both for the whole frequency band and the band under 30 Hz.

noise estimation method	noise /μV(rms)	noise /μV(rms) < 30 Hz
EEG suppression (profol)	1.7	1.1
EEG suppression (etomidate)	1.4	1.1
Knee measurement	1.6	1.5

Table 4. Noise levels estimated from typical EEG amplitudes and measured noise amplitudes.

	NOISE LEVEL			
EEG/ μV (rms)	n=1.1 μV	n=1.4 μV	n=2.0 μV	n=4.0 μV
14.14	0.078	0.099	0.141	0.283
35.36	0.031	0.040	0.057	0.113
49.50	0.022	0.028	0.040	0.081
70.71	0.016	0.020	0.028	0.057
141.42	0.008	0.010	0.014	0.028
212.13	0.005	0.007	0.009	0.019

The accuracy of the cortical potential distribution at certain noise level can be studied from RBV figures (Fig. 3.) In this figure the number of RBVs is plotted for different electrode systems when noise level is 0.02. From this figure it can be seen that with this noise level only slightly better spatial resolution is obtained with 512 electrodes than with 256 electrodes.

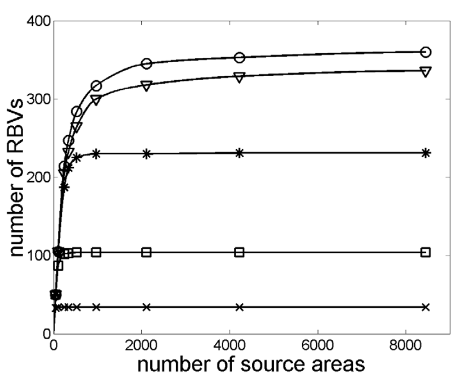

Fig. 3. Accuracy of inverse solution. In this example the NL=0.02, O=512 electrodes, ∇=256 electrodes, ✷=128 electrodes, □=64 electrodes and ×=21 electrodes. The number of RBVs is plotted as the function of number of source areas.

In Table 5 the limits for the noise level below which a certain of studied electrode system gives the best possible spatial resolution are collected.

Table 5. Noise level limits below which a certain of studied electrode systems gives the best possible spatial resolution.

Realistic electrode system	Noise level limit
512	NL < 0.027
256	NL < 0.04
128	NL < 0.1
64	NL < 0.3

Discussion

From the results it can be concluded that in optimal measurement environment, where the measurement noise can be limited below 1.5 μV, improved spatial resolution can be achieved with 256 or even 512 electrodes. From our measurements it can also be seen that in standard clinical surrounding such noise levels are realistic, where it is reasonable to use at least 64 electrodes to improve the spatial resolution.

In our EEG suppression measurements there was also some EEG activity present as was seen in Figure 1. Also in knee measurements some EMG was present as it is seen in Figure 2. Thus we can assume that even smaller noise voltages are attainable. As low as 1μV (rms) noise voltages for biopotential measurements are mentioned in literature [3].

References

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Acknowledgements

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