

Effect of skull discontinuities on MEG and EEG: Experimental results

Stephan Lau^{a,b,c}, Lars Flemming^a, Jens Haueisen^{a,b}

^a*Biomagnetic Center, Department of Neurology, University Hospital Jena, GERMANY*

^b*Institute of Biomedical Engineering and Informatics, Ilmenau Technical University, GERMANY*

^c*Neuroengineering Group, Dept. of Electrical and Electronic Engineering, The University of Melbourne, AUSTRALIA*

Correspondence: S. Lau, Biomagnetic Center, Department of Neurology, University Hospital Jena, Jena, Germany
E-mail: stephan@biomag.uni-jena.de

Abstract. While the effect of skull discontinuities on electric surface potentials has been addressed frequently, only very few studies exist on the influence of such discontinuities on the magnetic field. We investigated the effect of holes in the skull on the simultaneously recorded electroencephalogram and magnetoencephalogram. Measurements were carried out in rabbits with two holes in the skull and an artificial current dipole positioned at various distances underneath one hole. Our results demonstrate that both EEG and MEG were significantly influenced by the holes with maximum MAGrel values of above 300% for EEG and above 30% for MEG. The strongest influence was observed when the source is under the edge of the hole. We conclude that discontinuities in the skull should be accounted for in volume conductor models used in the reconstruction of amplitudes of brain sources from EEG and MEG, particularly in infants, children and patients with post-surgical skull conditions.

Keywords: electroencephalography, magnetoencephalography, volume conduction, skull, dipole

1. Introduction

Neuronal activity in the brain is often analyzed based on magneto- and electroencephalographic recordings (MEG, EEG). For source reconstruction based on EEG/MEG a volume conductor model is required. Most volume conductor modeling approaches, such as the description of the head and its heterogeneous conductivity profile with a set of spheres or the description of the head with a set of compartments using the boundary element method typically ignore conductivity heterogeneities such as discontinuities in the skull. Skull discontinuities, such as fontanelles of the neonate skull or post-surgical skull conditions, are known to influence the EEG [Flemming et al., 2005]. However, their influence on the MEG has rarely been analyzed quantitatively [Barth et al., 1986; Okada et al., 1999]. Thus, our aim is to characterize and quantify the effect of skull discontinuities on the simultaneously recorded EEG and MEG. To achieve this goal, we experimentally investigate the influence of one and two holes in the skull of rabbits on the simultaneously measured MEG and EEG.

2. Material and Methods

We constructed an artificial miniaturized coaxial dipole and implanted it in rabbit brains. We simultaneously recorded a 64-channel EEG and a 4x4-channel MEG (MicroSQUID) [Nowak et al., 1999]. The EEG array was newly developed and shaped to match the outline of the superior skull and cortex surface. The EEG array only has about 1/3 of the size of a rabbit's superior cortex surface. This allows the array to sample different areas of the brain, in particular to study evoked potentials in the future. The EEG and MEG signals were amplified using SynAmps amplifiers (Compumedics NeuroScan, Charlotte, NC, USA). Figure 1 shows the artificial current dipole, the EEG array and the MEG array. The artificial current dipole was driven by a sinusoidal current (0.1 mA at 20 Hz).

The larger study that the results presented here are part of was approved by the ethics committee of the Friedrich-Schiller University Jena and the state government of the Thuringia in Germany (ethics registration 02-034/08). Rabbits were anaesthetized (10 mg Ketamine + 3.5 mg Xylacine per kg bodyweight per hour i.v.) and the physical dipole was implanted in the rabbit's brain approx. 4 mm below the superior skull and firmly attached to the skull. Here, we report on measurement, which were conducted with two holes in the skull. The holes had dimensions of approximately 4x4 mm and 2x2

mm and were drilled prior to the measurements. The dura mater was left intact. Both holes were filled with agarose gel of conductivity 1.0 S/m at 30°C (temperature of skull, not covered by skin). The dipole was moved in discrete steps of 0.691 mm (thread length of screw) and we measured at 14 dipole positions consecutively in 2 min intervals without altering the animal, the EEG or the MEG configuration in any way. The position of the source was determined from a CT coregistered with the EEG and MEG in a stereotactic coordinate system. The movement of the dipole during the measurements was realized with the help of a screwing mechanism allowing for a positioning accuracy of ± 0.2 mm.

Signals were band pass filtered (15-25 Hz), averaged and a PCA projection using the first component was applied. To quantify the topographical and magnitude deviation of the field maps with respect to the reference map in which the dipole is distant from the skull holes, we determine the relative difference measure:

$$RDM^* = \sqrt{\sum_{i=1}^n \left(\frac{reference_i}{\sqrt{\sum_{j=1}^m reference_j^2}} - \frac{sample_i}{\sqrt{\sum_{j=1}^m sample_j^2}} \right)^2} \quad (1)$$

and the relative magnitude difference:

$$MAG_{rel} = 1 - \frac{\sqrt{\sum_i sample_i^2}}{\sqrt{\sum_{i=1}^n reference_i^2}} \quad (2)$$

where i is the channel number, $reference_i$ is the value of the reference signal, here the recording with intact skull, and $sample_i$ is the value of the sample signal under investigation, here the recording with either one or two holes.

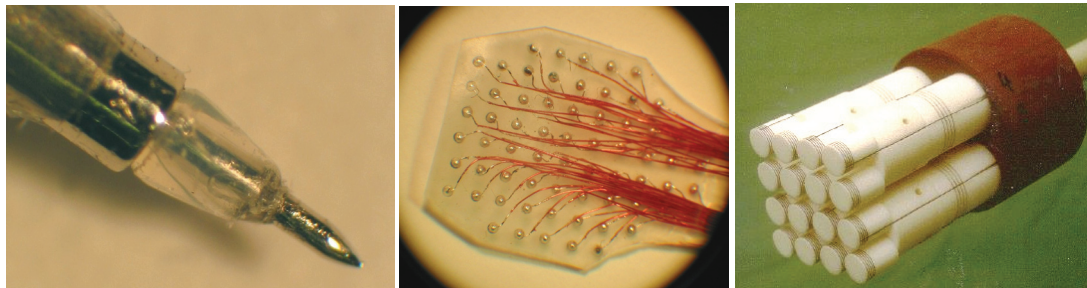


Figure 1. Left: Coaxial physical dipole to simulate an electric brain source. The distance between inner and outer platinum pole is 1 mm. Middle: 64-channel EEG for bioelectric measurements composed of Ag/AgCl electrodes with $\varnothing$ 0.6 mm and 1.4 mm neighbor distance. Right: 4x4 array of pick up coils with 8.41 mm distance between the center points of the coils.

3. Results

Results (Figure 2 and 3) show that the introduction of a hole in the skull filled with agar of higher than skull conductivity can cause an MEG magnitude deviation (MAG_{rel}) of more than 30% depending on the position of the dipole underneath the hole. As expected the magnitude deviations were more pronounced for EEG with relative magnitude differences of more than 300% depending on the position of the dipole underneath the holes. In both MEG and EEG, the magnitude increases when moving the source towards the hole, peaks when the source is under the edge of the hole and diminishes when the source is centrally under the hole (Figure 3).

The topography (RDM^*) gradually changes along the source shifting line which can be attributed in large parts to the movement of the source. RDM shows for MEG deviations of 20% over a distance of 5.5 mm (Figure 3 right) and for EEG 50%. Again the changes are stronger in EEG compared to MEG.

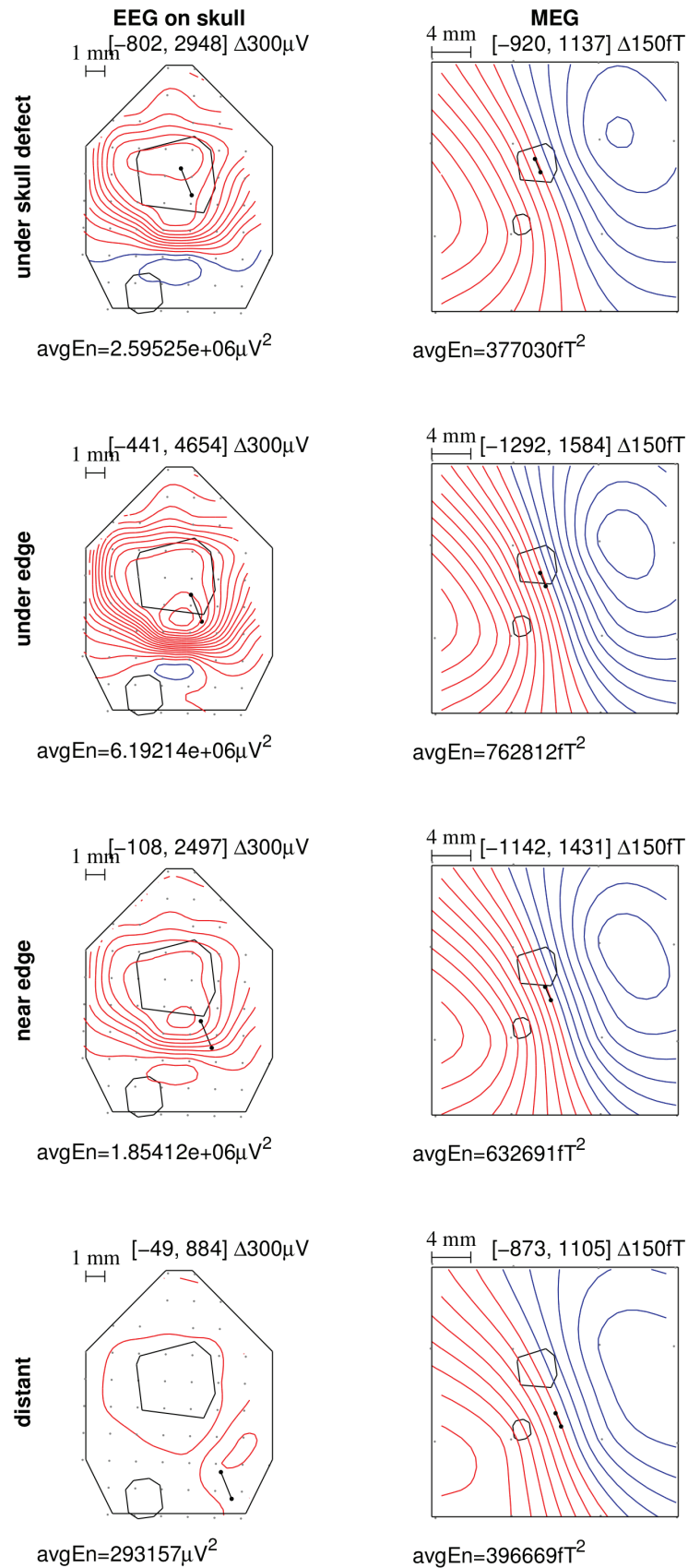


Figure 2. EEG mapping (left) and MEG mapping (right) for 4 different dipole positions: underneath the larger hole (1st row), under the edge of that hole (2nd row), near that hole (3rd row), and more distant from that hole (4th row). The dipole is indicated by the two black dots connected by a line. Minimum and maximum values of the potentials/fields are indicated above and average energy below each plot.

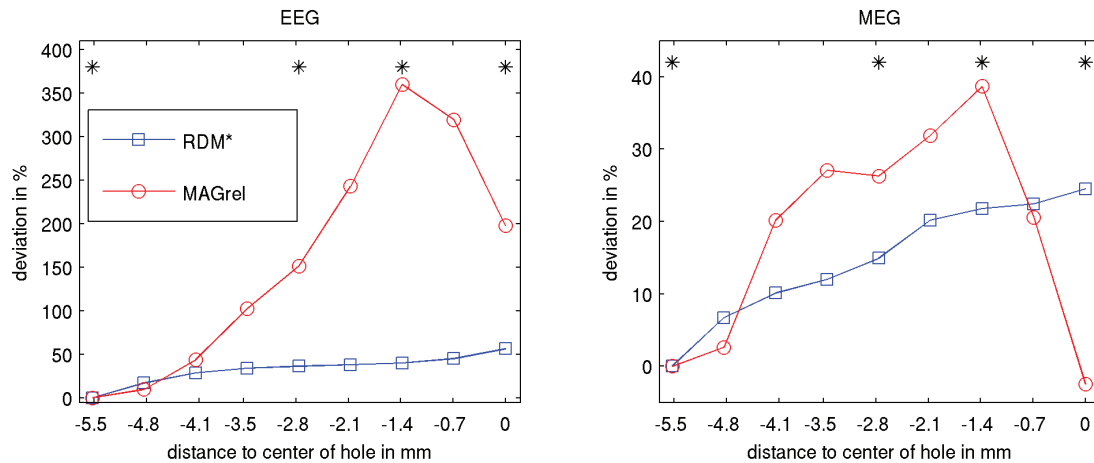


Figure 3. Topographical (RDM*) and magnitude (MAGrel) deviation of potential/field maps at different distances from the hole relative to the potential/field map of the location distant from the hole. Measurements marked with a star are displayed in Figure 2.

4. Discussion

Our data and findings are complementary to Barth et al. [1986], who investigated the effect on the MEG of a large craniotomy ($\varnothing$ 70 mm) in a formalin fixed human cranial specimen filled with conducting jelly using also an artificial coaxial dipole and qualitatively described measurements with and without the bone flap as very similar. The same is true for Okada et al. [1999] who compared the MEG of a somatosensory evoked brain activity in the juvenile swine and concluded that the absence of the skull has virtually no influence on the MEG for shallow sources, but causes attenuation for deeper sources. The principal difference in the experimental setup here is that the hole is much smaller, meaning the ratio between hole edge and hole area is different. This enables us to measure edge effects of the skull discontinuity. Our results indicate consistency in that the MEG recordings distant from the hole (Figure 2 bottom) and in the center of the hole (Figure 2 top) show very similar amplitude compared to the other conditions. In terms of EEG, our findings agree with Flemming et al. [2005].

For the translation of these findings to human MEG and EEG recordings and volume conductor models one has to consider the geometric relations, amplitude modulating factors and the sampling theory. The geometric relations in humans differ in that the skull is larger and the sources are deeper. The skull defects or discontinuities in humans, such as open fontanelles, will have a more naturally shaped edge that is not at right angles with the skull surface. The amplitude effects will be modulated by the conductivity of the tissue in the inter-skull space, e.g. cartilage, as well as the individual skull and skin thickness and conductivity. The spatial sampling density of human EEG and MEG relative to the skull and skull defect size is lower than in this experiment, e.g. 20-30 mm neighbor distance compared to our 1.4 mm for EEG and 8.4 mm for MEG. Additionally, the MEG sensors of a current whole head system integrate over a larger area, e.g. a square of 21x21 mm compared to a circle of $\varnothing$ 8.4 mm in our system, and are further away from the head, e.g. 20-30 mm compared to <10 mm in our system. In general, the demonstrated effects will be partially observable in human EEG and MEG and will gain more importance for new generations of EEG and MEG systems with higher spatial density and higher sensitivity.

Our next step is the modeling of the measured effects of the hole with the help of the finite element method [Güllmar et al., 2006].

5. Conclusions

We conclude that discontinuities in the skull should be accounted for in volume conductor models used in the reconstruction of amplitudes of brain sources from MEG, particularly in infants, children and patients with post-surgical skull conditions.

Acknowledgements

We wish to thank Stefan Clauss, Hannes Nowak, Ralph Huonker, Frank Gießler, Daniel Güllmar, Eric Lopatta, David Grayden, Simon Vogrin and Levin Kuhlmann for their support. This work has

been supported in part by the German DFG (Ha 2899/6-1), the Australian NHMRC, the German DAAD and the Australian Group of Eight. We thank the Research Workshop of the University Hospital Jena for the production of the high-density EEG array, the physical dipole model and the stereotactic device.

References

- Barth DS, Broffman J, Sutherling W, and Beatty J. Magnetic localization of a dipolar current source implanted in a sphere and a human cranium. *EEG and Clin Neurophys*, 63, 1986.
- Flemming L, Wang Y et al.: Evaluation of the distortion of EEG signals caused by a hole in the skull mimicking the fontanel in the skull of human neonates, *Clin Neurophys*, 116:1141–1152, 2005.
- Güllmar D, Haueisen J, Eiselt M, et al.: Influence of anisotropic conductivity on EEG source reconstruction: Investigations in a rabbit model, *IEEE Trans Biomed Eng* 53: 1041–1050, 2006.
- Nowak H, Gießler F, Huonker R, Haueisen J, Röther J, and Eiselt M. A 16-channel SQUID-device for biomagnetic investigations in small objects. *Med Eng & Phys*, 21, 1999.
- Okada YC, Lahteenmaki A, and Xu C. Experimental analysis of distortion of magnetoencephalography signals by the skull. *Clin Neurophys*, 110, 1999.