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Comparison of the Properties of EEG and MEG

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Abstract. In the beginning of the magnetoencephalography research it was believed that: 1) on the basis of the Helmholtz Theorem, EEG and MEG record independent information, 2) because of the high resistivity of the skull (1/80) MEG has better ability to focus the recording than EEG and that 3) with MEG it is possible to get more information from the electric activity of the brain. This paper discusses these issues and draws the conclusion that EEG is much better in recording the brain's electric activity than what has been previously believed.

Keywords: electroencephalography, EEG, magnetoencephalography, MEG

1. Historical Aspects

The earliest written reference to the brain is in an Egyptian papyrus, written in the seventeenth century BC, known as the Edwin Smith Surgical Papyrus. The papyrus was translated by James Breasted in 1930 and is in the Rare Book Room of the New York Academy of Medicine. The word "brain" occurs only eight times in ancient Egyptian, seven of them on the two pages of the Edwin Smith Surgical Papyrus. This work describes the symptoms, diagnosis, and follow-up of two patients who sustained depressed skull fractures, [Kandel and Schwartz, 1985].

René Descartes (1596-1650) wrote the first textbook in physiology *"Tractus de homine"* in 1662, [Descartes, 1662]. He understood that the stimulus, e.g. heat, stimulates the sensory nerve, which transmits the information to the brain, where the pain sensation is located.

Hans Christian Örstedt (1777-1851), Professor of University of Copenhagen, Denmark, experimentally demonstrated the connection between electricity and magnetism in 1819, [Örstedt, 1820]. This invention laid the basis for bioelectromagnetism. It also gave the possibility to develop the first instrument, which was sensitive enough to detect bioelectric signals. This was done by Leopold Nobili (1784-1835), who in 1825 invented the astatic galvanometer, [Nobili, 1825].

2. Theoretical Properties of EEG and MEG

EEG Lead Fields.

The EEG lead fields in a three layer spherical head model were fist calculated by Rush and Driscoll [1969]. They presented the results with isopotential surfaces. The lead field problem was recalculated by Malmivuo and Suihko and presented with lead field current flow lines, Figure 1, [Malmivuo and Suihko, 1997]. This presentation is more informative because the direction of the sensitivity is seen as the direction of the flow lines and the magnitude of the sensitivity is indicated with the density of the flow lines. In this publication Malmivuo and Suihko also presented the isosensitivity lines which give more accurate, quantitative information on the magnitude of the sensitivity.

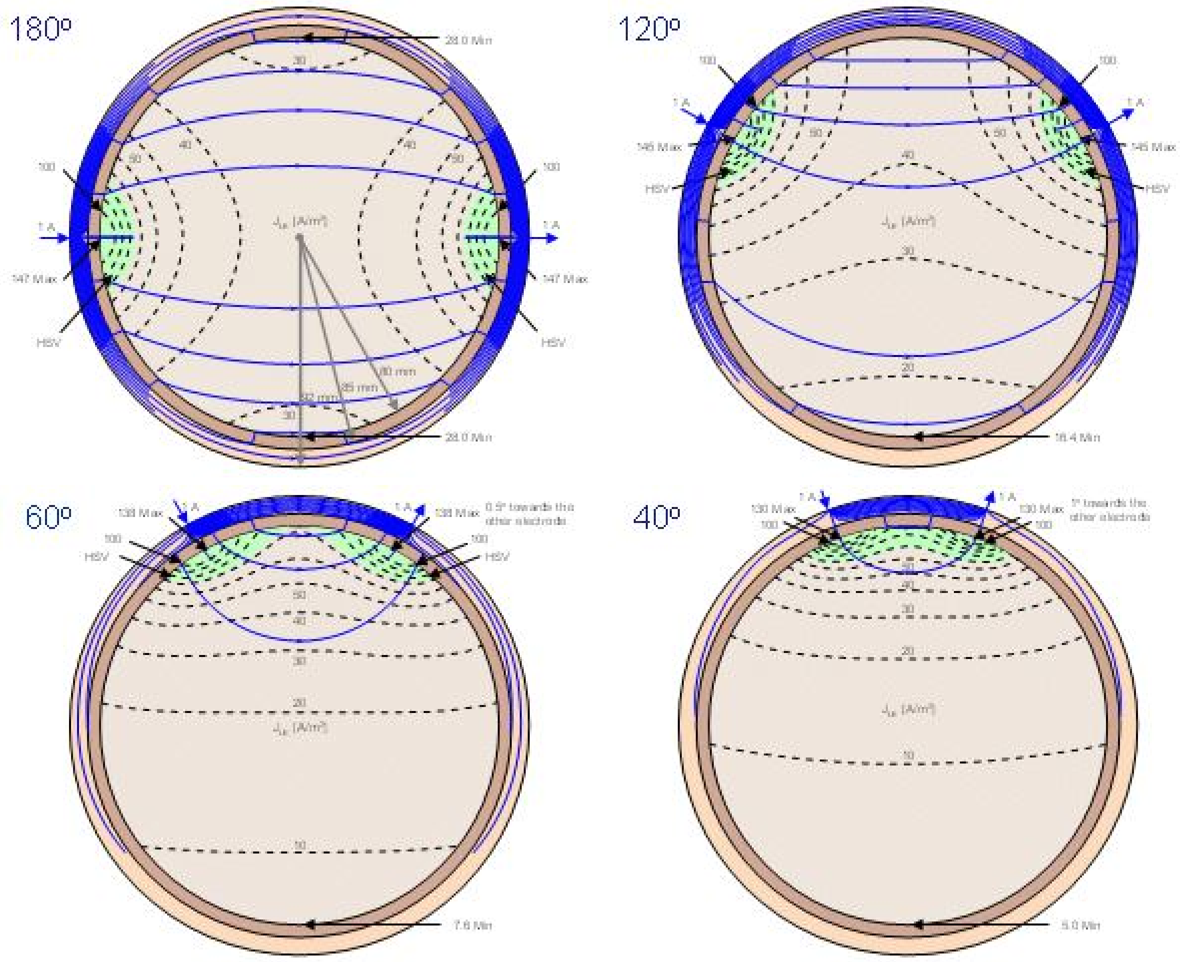

Figure 1. EEG lead fields calculated by Malmivuo and Suihko in the Rush-Driscoll head model.

In their calculations Rush and Driscoll assumed that the resistivity of the skull is 80 times higher than that of the scalp and the brain. This value was also used by Malmivuo and Suihko in their 1997 paper. The calculations show clearly that the high resistivity skull has a strong effect to the lead fields decreasing the spatial resolution (in the brain region).

Later it has been shown that the skull resistivity is much lower, being in the order of 10 times of the other tissues [Oostendorp et al., 2000], [Hoekema et al., 2001]. Malmivuo and Suihko later repeated the lead field calculations with lower skull resistivity values [Malmivuo and Suihko, 2004].

MEG Lead Fields

The MEG lead fields for axial and planar gradiometers were first calculated by Malmivuo and Puikkonen [1987]. From these simple calculations the axial gradiometer results apply also for spherical conductors but the planar gradiometer results apply only for a half-space model. The planar gradiometer lead fields were later calculated also for a spherical model [Malmivuo and Plonsey, 1995].

The MEG lead fields for a single coil or an axial gradiometer are concentric circles around the coil axis, Figure 2. The magnitude of the sensitivity is proportional to the radial distance from the coil axis, thus being zero on the coil axis. If the coil axis coincides the spherical volume conductor axis, the inhomogeneities do not affect the lead fields. The maximum sensitivity is on a toroidal space with radius somewhat larger than the coil axis.

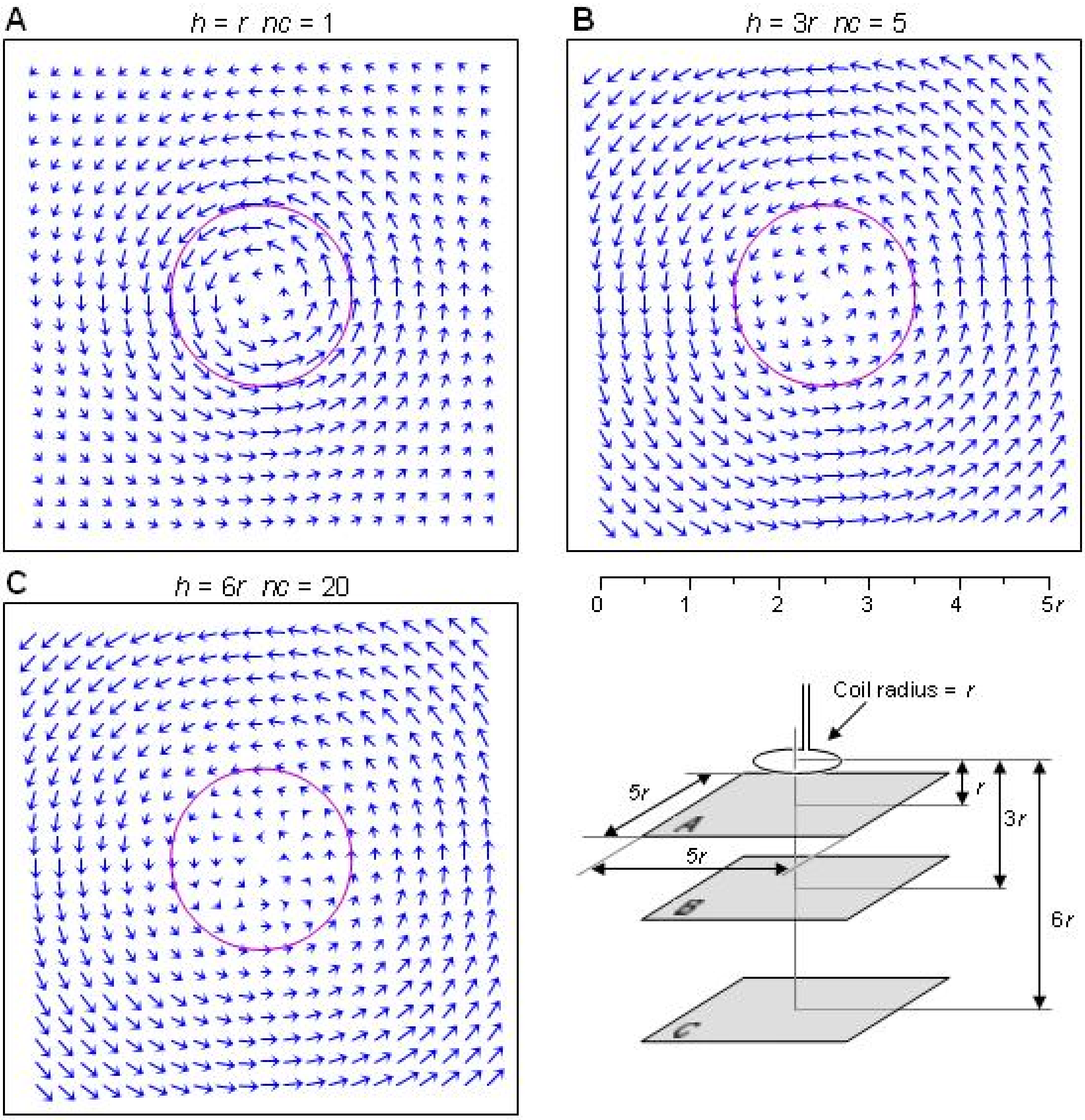

Figure 2. MEG lead fields for the axial gradiometer. Lead fields are calculated for planes at distances 1r, 3r and 6r from the coil plane, where r is the coil radius. Please note, that the lead field current density vectors are in B and C multiplied with coefficients 5 and 20, respectively, to make them visible.

The planar gradiometer lead fields are easily calculated by superposition by summing up the lead fields of the two coils, Figure 3. The planar gradiometer lead field is quite linear under the center of the two coils, Figure 4. The sensitivity distribution, and therefore the recorded MEG signal, resembles that of a bipolar EEG.

In a cylindrically symmetric case, like in a spherical volume conductor coinciding the coil axis, the inhomogeneities do not affect the lead fields, Figure 5. Therefore in the beginning of MEG it was believed that MEG has better spatial resolution than EEG. Later on it has been shown that this is not the case, eg. [Malmivuo and Suihko, 1997].

In addition, it was earlier assumed that the EEG and MEG signals are independent and therefore MEG records information which does not exist in the EEG signal. Later on it has been shown that this is not either the case.

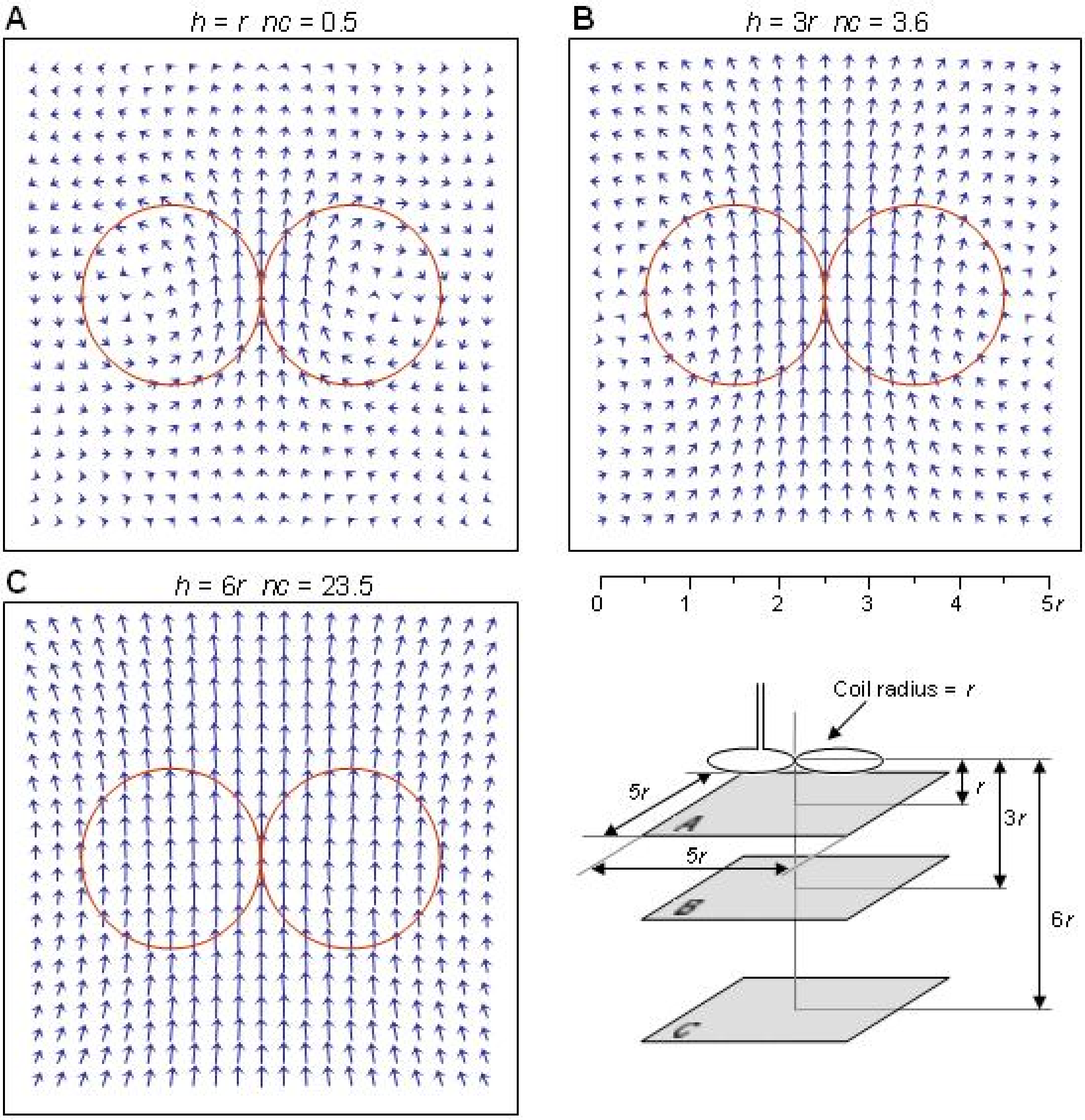

Figure 3. MEG lead fields for the planar gradiometer. Lead fields are calculated for planes at distances 1r, 3r and 6r from the coil plane, where r is the coil radius. Please note, that the lead field current density vectors are in B and C multiplied with coefficients 3.6 and 23.5, respectively, to make them visible.

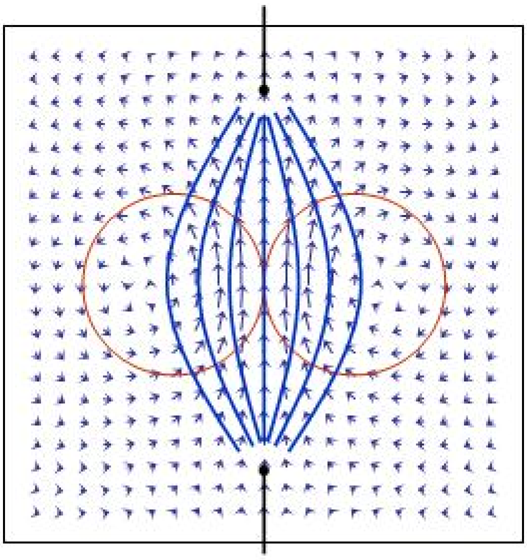

Figure 4. The planar gradiometer MEG lead field is linear and it resembles the bipolar EEG lead field. Therefore, the information content of these recordings resemble each other.

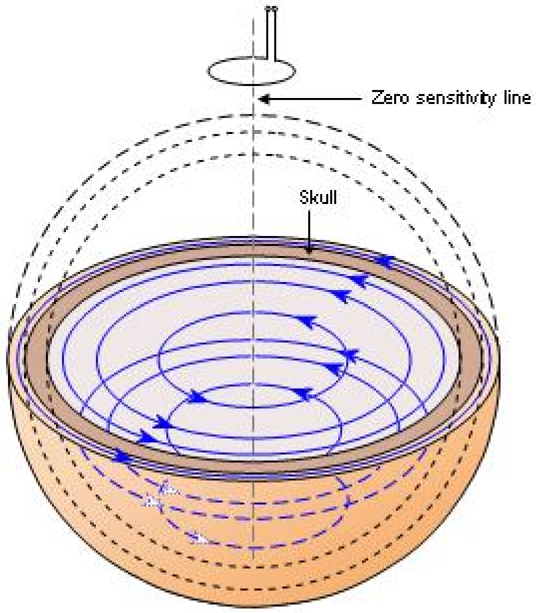

Figure 5. In a cylindrically symmetric case, as in a sphericl head model, the inhomogeneities do not affect the magnetic lead fields.

3. Independence/Interdependence of EEG and MEG

The fundamental issue in the clinical application of biomagnetism is: Do the biomagnetic signals include information which is independent on that of the bioelectric signals? In the beginning of MEG-research it was believed that this is the case. This issue is discussed here with the help of the Helmholtz Theorem.

Helmholtz's theorem

The Helmholtz Theorem states: *A general vector field which vanishes at infinity, can be represented as a sum of two independent vector fields, one that is irrotational and another one which is solenoidal* (1).

$$\overline{J}^i = \overline{J}^i_F + \overline{J}^i_V \quad (1)$$

These vector fields are referred to as *flux source* (2) and *vortex source* (3) [Malmivuo and Plonsey, 1995].

$$\overline{J}^i_F = -\nabla \bullet \overline{J}^i \quad (2)$$

$$\overline{J}^i_V = -\nabla \times \overline{J}^i \quad (3)$$

Bioelectric signals originate from the *flux source* (4).

$$V_{LE} = \int \Phi_{LE} \nabla \bullet \overline{J}^i \quad (4)$$

Biomagnetic signals originate from the *vortex source* (5).

$$V_{LM} = \frac{\mu}{2} \int \Phi_{LM} \overline{r} \bullet \nabla \times \overline{J}^i dv \quad (5)$$

Flux and vortex sources are universal concepts, not specific only for bioelectromagnetism.

Controversy in the discussion on the independence of ECG and MCG (as well as of EEG and MEG)

In the beginning of biomagnetic research there were published two fully controversial papers on the independence/interdependence of bioelectric and biomagnetic signals.

Robert Plonsey published in 1972 a paper in the IEEE Transactions on Biomedical Engineeering [Plonsey, 1972], where he on the basis of Helmholtz theorem stated that bioelectric and biomagnetic signals are fully independent. He stated that: *"Since the flux and vortex sources are independent, ECG and MCG are similarly independent."* In the beginning of biomagnetic research this article was strongly encouraging, because on this basis it was believed that from recording of biomagnetic signals, as much new information will be obtained as has been already obtained by recording bioelectric signals.

Three years later Stanley Rush published a paper in the IEEE TBME [Rush, 1975] with a completely opposite opinion. He stated: *"The independence of the flow and vortex sources is only a mathematical possibility. The flow and vortex sources are one-to-one with each other."* This means that the magnetic signal may be calculated from the electric one and therefore it does not bring any new information.

This fundamental controversy of the two completely opposite opinions about the independence/interdependence of bioelectric and biomagnetic signals confused the biomagnetic research for about 20 years. This controversy was finally solved by Jaakko Malmivuo in the following way [Malmivuo and Plonsey, 1995], [Malmivuo, 2000], [Malmivuo et al., 2002], [Malmivuo 2004].

What Helmholtz theorem says is that the *vector fields of the distributions of the electric and magnetic sources* are fully independent. This means that the *lead fields* of electric and magnetic measurements are fully independent. The electric and magnetic *signals are only partially independent*.

If we know the electric field of the source completely, also including the source area, we may accuratery calculate the magnetic field (as claimed by Rush). However, in practice, recording of the total electric field is not possible. For instance in recording the cardiac electric field, it is possible to record the dipolar component of the field and partially the quadrupolar component. Therefore, the recording of the dipolar component of the magnetic field brings additional information of the source.

Independence of the (dipolar) electric and magnetic lead fields

Recording a dipolar electric source is made with a lead system including three component lead fields which are linear and homogeneous and are in the directions of the coordinate axes, Figure 6, [Malmivuo, 1976]. These three electric component lead fields are mutually independent.

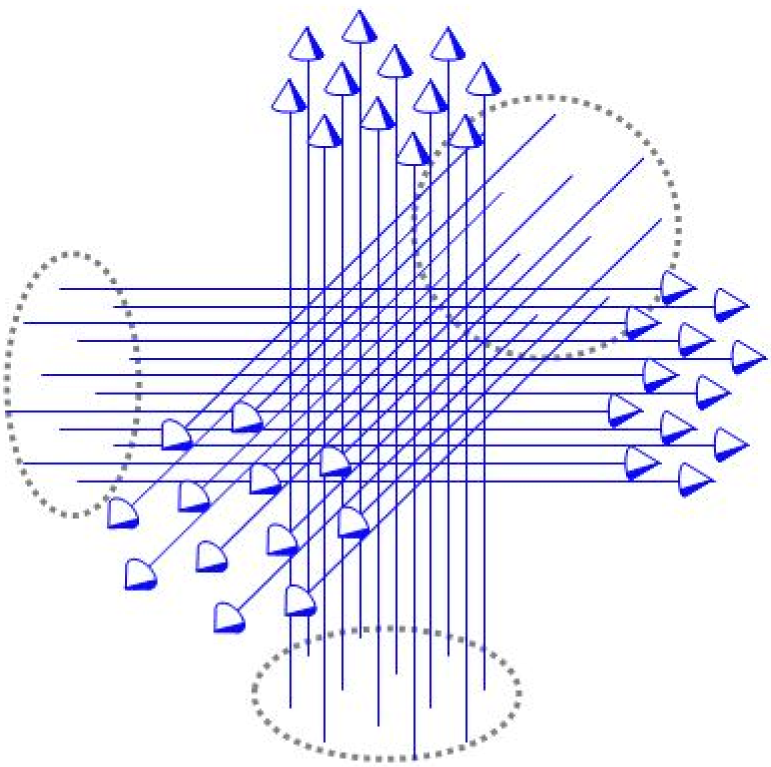

Figure 6. The lead system for detecting the electric dipole moment.

Recording a dipolar magnetic source is made with a lead system including three component lead fields which are tangential around the three coordinate axes with lead field current density proportional to the radial distance from the coordinate axis, Figure 7, [Malmivuo, 1976]. These three magnetic component lead fields are mutually independent.

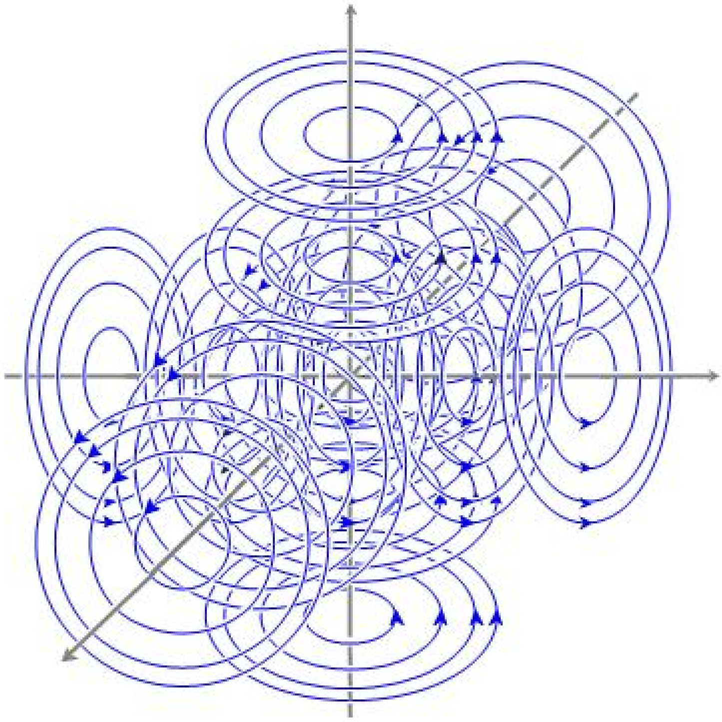

Figure 7. The lead system for detecting the magnetic dipole moment.

On the basis of the Helmholtz Theorem, the electric and magnetic *lead fields* are mutually independent. None of the six components of the electric and magnetic lead fields is a linear combination of the other five. However, the electric and magnetic *signals* are only partially independent.

4. Comparison of the spatial resolutions of EEG and MEG

Malmivuo and Suihko published in 1997 a work where they compared the spatial resolutions of EEG and MEG, [Malmivuo and Suihko, 1997]. The comparison was made by using the Half-sensitivity volume (HSV) concept. The HSV denotes in the source region the volume, where the magnitude of the measurement sensitivity is at least half of the maximum sensitivity, Figure 8. The idea in the HSV concept is that if the source is assumed to be homogeneously distributed, most of the measured signal originates from the HSV. Therefore, the smaller the HSV of the lead system is, the better is its ability to concentrate the measurement, i.e. the better is the spatial resolution.

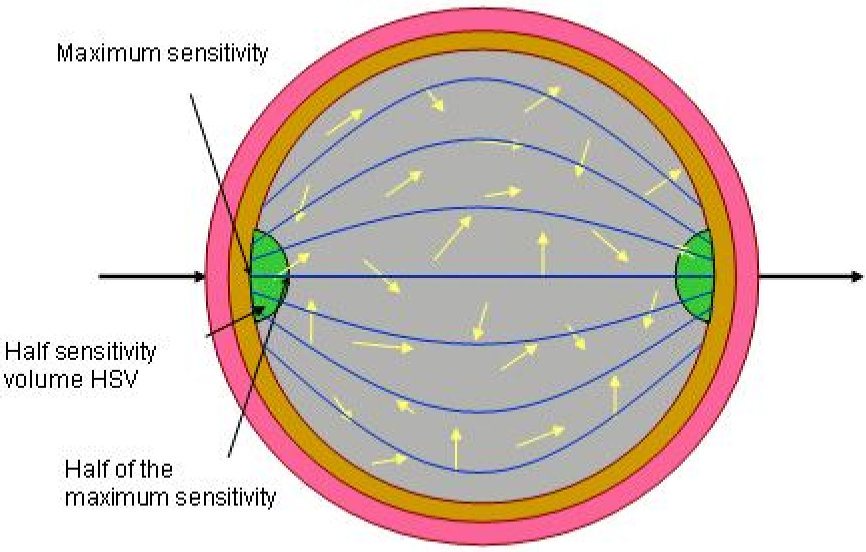

Figure 8. Definition of the Half-sensitivity-volume, HSV.

The comparison of the spatial resolutions of EEG and MEG was made by calculating the HSV in the Rush-Driscoll head model for two- and three-electrode EEG leads and axial and planar gradiometer MEG leads with the electrode or coil distance as a parameter.

The results show that with small electrode/gradiometer distances, which are relevant for high-resolution measurements, the two-electrode EEG and planar gradiometer MEG have the HSVs of about the same magnitude, Figures 9 and 10. The axial gradiometer has much larger HSV, i.e. worse spatial resolution. The three-electrode EEG has smaller HSV, i.e. better spatial resolution. This, however, is not directly comparable to the other lead systems because it has more electrodes. The reason why it was included to the comparison is that it has the measurement sensitivity mainly in the radial direction.

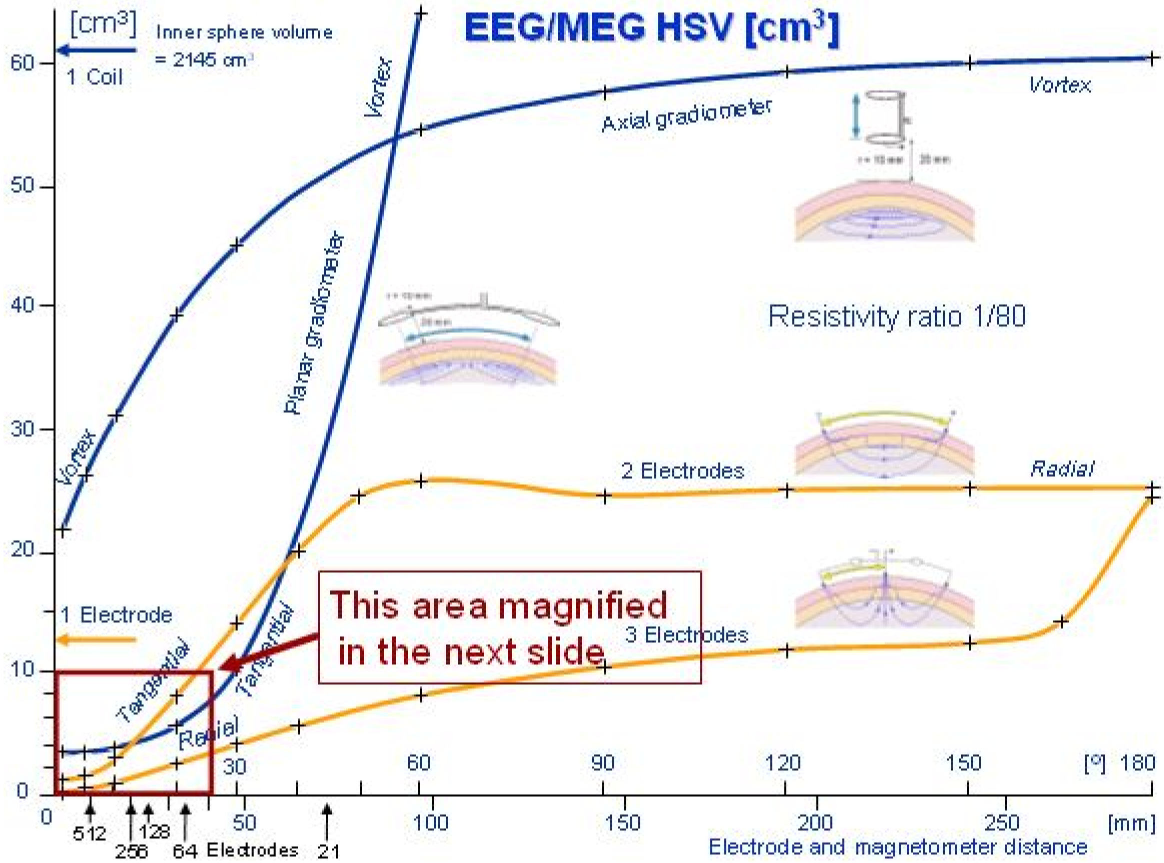

Figure 9. Half-sensitivity-volumes for two- and three-electrode EEG and axial and planar gradiometer MEG as a function of baseline.

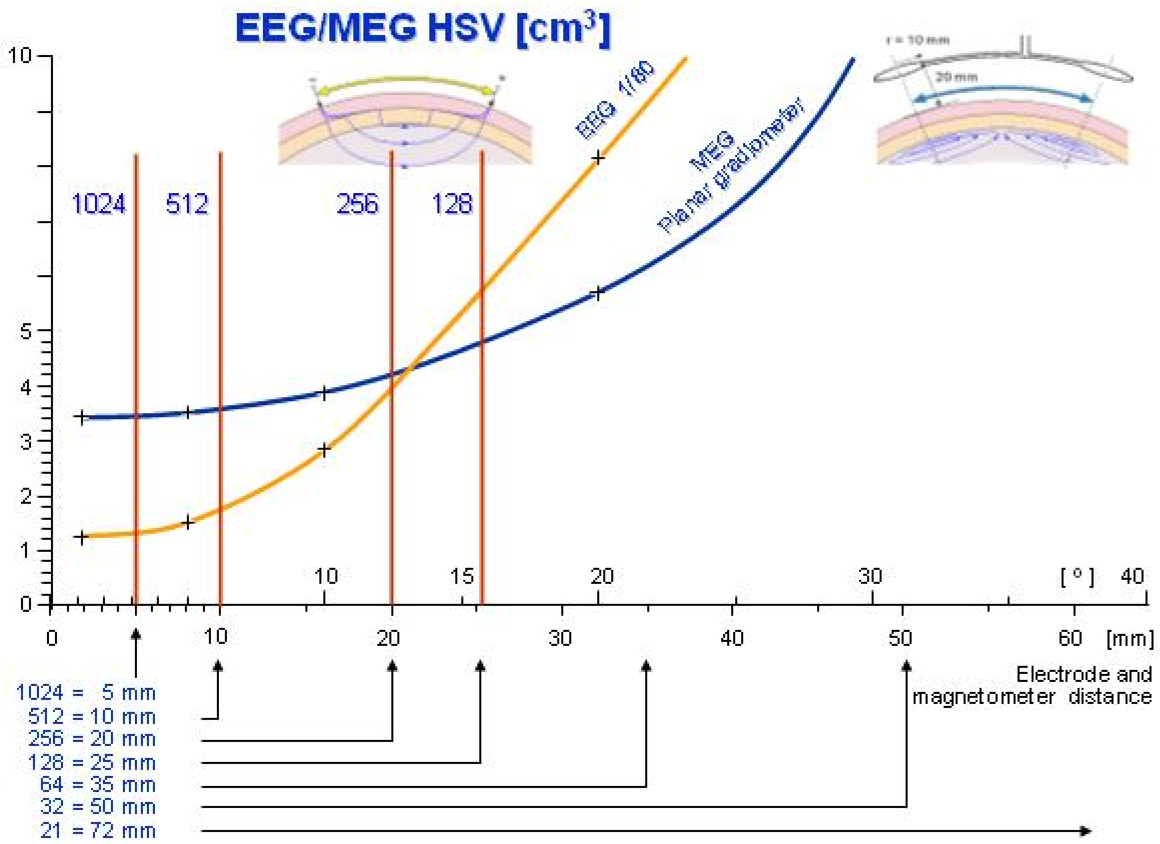

Figure 10. Half-sensitivity-volumes of Figure 9 for baselines relevant in high-resolution recording.

Skull resistivity is lower

The latest information indicates that the resistivity of the skull is only about 8 …15 times that of the other tissues in the head, [Oostendorp et al., 2000], [Hoekema et al., 2001]. With this resistivity value the ability of the EEG to focus its sensitivity is even better than that of the MEG [Malmivuo and Suihko, 2004].

Our original finding that the MEG does not have an order of magnitude better spatial resolution than the EEG but that their spatial reolutions are of the same order, was confirmed by Liu and colleagues [Liu et al., 2002]. Similar results have also been obtained by other scientists. For instance Hauskamp [2004] states that: *"A simultaneous 151 channel MEG and 72 channel EEG (sampling rate 625 Hz) were measured from the patient. Results show that source localization errors remain limited to 0.5 cm, both for EEG and MEG."*

5. Effect of noise on EEG

With low realistic measurement noise, a more accurate inverse cortical potential distribution can be obtained with an electrode system where the distance between two electrodes is as small as 16 mm, corresponding to as many as 256 measurement electrodes. In clinical measurement environments, it is always beneficial to have at least 64 measurement electrodes. [Ryynänen et al., 2004]

TABLE I. Approximated Relative Noise Level Ranges in Which Specific Electrode Systems are the Most Optimal for Obtaining the Best Possible Spatial Resolution [Ryynänen et al., 2004]

Realistic Electrode System Number of Electrodes	Relative Noise Level Range
512	NL < 0.02
256	0.02 < NL < 0.04
128	0.04 < NL < 0.1
64	0.1 < NL
21	0.1 << NL

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6. Comparison of other properties of EEG and MEG

In the beginning of MEG-research it was believed that with the MEG it is possible to get more information from the electric activity of the brain.

It was shown above, that the spatial resolution of EEG and MEG are about the same order. In addition it was shown that these signals are only partially independent.

In addition, EEG and MEG differ in the direction of their measurement sensitivities. MEG measures only tangential sources but EEG measures both tangential and radial sources. Tangential sources are recorded with bipolar EEG-leads and the radial ones with unipolar leads, Figure 11.

In addition to the aforementioned differences, it has to be noted that the MEG instrumentation is many times more expensive that the EEG instrumentationa. A great deal from the costs are caused by the necessary magnetic shielding.

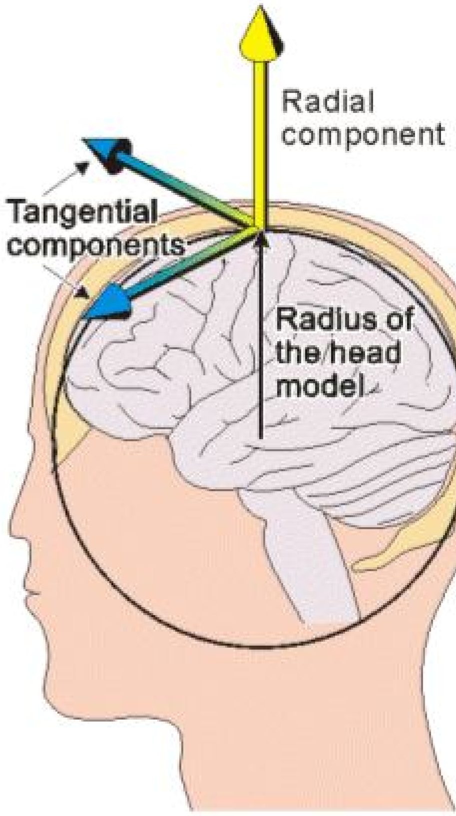

Figure 11. MEG records only tangential sources. With EEG it is possible to record both tangential and radial sources.

6. Challenges for MEG

Combined use of EEG and MEG

Liu et al. [2002] found that the combined use of EEG and MEG brings benefits in increased spatial resolution. The combined use may also give additional tools for separating the tangential/radial sources.

Fetal MEG

During the late pregnancy the fetus has under the skin the *Vernix Caseosa*, which is a white, cheesy waxy substance. It has the electric resistance of the order of $\rho = 5$ MΩm, which is very high compared to the electric resistance of the maternal abdomen $\rho = 0.5$ Ωm. This high resistivity prevents the measurement of the fetal EEG.

Because the lead field of the MEG is tangential, the *Vernix Caseosa* does not make any restriction to fetal MEG (as well as MCG) measurement.

DC- MEG

One technical benefit of the biomagnetic measurements is that the frequency range of the SQUID reaches 0 Hz. This gives a possibility to record very low frequency electric activity of the brain with MEG.

6. Conclusions

The conclusions are summarized as follows:

- The EEG and MEG signals are only partially independent.
- The sensitivity distribution of planar gradiometer MEG resembles that of bipolar EEG.
- EEG measures radial and tangential sources, MEG measures only tangential sources.
- EEG has better spatial resolution than MEG.

The High-resolution EEG cap needs further development to satisfy the needs of high quality recording.

I REPEAT THE GOOD NEWS:
EEG IS MUCH BETTER THAN THOUGHT BEFORE!

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