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The Solution for the Independence of Bioelectric and Biomagnetic Signals is Confirmed*

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***Abstract*— The theoretical solution for the independence of bioelectric and biomagnetic signals rising from volume sources was published by Jaakko Malmivuo in 1995 [1]. In 2000 his research group published a clinical study on electro- and magnetocardiography which confirmed this result [2, 3]. In 2005 Iwasaki and co-workers published a clinical study on the detection of epileptic foci with electro- and magnetoencephalography [4]. They came to similar result as Malmivuo et al. in their study on ECG and MCG. Because the theoretical solution is now confirmed independently by two research groups with two different clinical studies and different volume sources, there is no doubt that the problem of the independence of bioelectric and biomagnetic signals from volume sources is now solved.**

I. Introduction

In the application of biomagnetism, the fundamental issue is: how much new information the biomagnetic signals give from the source in addition to that obtained by the bioelectric ones. In the beginning of the biomagnetic research there were two fully opposite opinions on this issue: In 1972 Robert Plonsey suggested on the basis of Helmholtz's theorem that the biomagnetic signals are fully independent on the bioelectric ones [5]. Three years later Stanley Rush suggested on the basis of Maxwell's equations that the bioelectric and biomagnetic signals are fully interdependent meaning that the biomagnetic signals do not include new information in addition to that of the bioelectric ones [6]. This fundamental controversy was finally solved theoretically by Jaakko Malmivuo [1] in the way that the lead fields of the dipolar bioelectric and biomagnetic measurements are fully independent, but the signals are only partially independent.

II. II. Materials and Methods

A. Theoretical considerations

Helmholtz's theorem states that: *"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 which is solenoidal."* [7, 8] These vector fields are referred to as *flux source* and *vortex source*, respectively. It may be seen from the equations of bioelectric and biomagnetic fields, that the origin of the bioelectric fields is the flux source and that the origin of the biomagnetic fields is the vortex source [1].

Robert Plonsey concluded, that *"Since the flux and vortex sources are independent, ECG and MCG are similarly independent."* [5]

Based on the Maxwell's equations [9, 10] Stanley Rush came to the fully opposite conclusion that *"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."* [6]

These two completely opposite opinions gave rise to confusion in the biomagnetic community until the problem of independence of bioelectric and biomagnetic signals rising from volume sources was solved by Jaakko Malmivuo in 1995 in the following way [1].

Let us discuss the problem on dipolar level. The electric dipole moment of the volume source is detected with a lead system, which has three orthogonal, linear lead fields. These three lead fields are independent, i.e. none of them can be synthesized as a linear combination of the two other ones. The magnetic dipole moment of the volume source is detected with a lead system, which has three orthogonal, tangential lead fields. These three lead fields are independent, i.e. none of them can be synthesized as a linear combination of the two other ones.

If a dipolar source element is oriented in the direction of one of these component lead fields, it is detected by that, but not by the two other lead fields. However, most of the source elements are oriented somewhere between these lead fields and are therefore more or less detected by all the three lead fields. Therefore the three signals which these leads detect are only partially independent. This holds similarly for the three dipolar magnetic lead fields, Fig. 1.

What Helmholtz's theorem says is that *the three electric lead fields are independent on the three magnetic lead fields,* i.e. we have six electromagnetic dipolar lead fields and none of them can be synthesized as a linear combination of the five other ones. The six signals which they detect are, however only partially independent. The same holds also on quadrupolar, octupolar etc. levels.

If we know the electric field of the source completely throughout the space including the source region, with Maxwell's equations we may calculate the corresponding magnetic field and vice versa. Thus the total electric and magnetic fields are fully interdependent. However, measuring the total field is not possible. In practice, it is usually the dipolar field which is recorded. From the dipolar electric field it is not possible to calculate the dipolar magnetic field and vice versa. Therefore recording both the

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dipolar electric and magnetic fields increases the amount of information from the volume source.

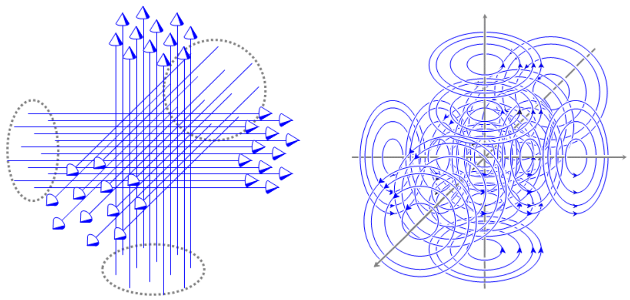

Figure 1. Dipolar electric (left) and magnetic (right) lead fields.

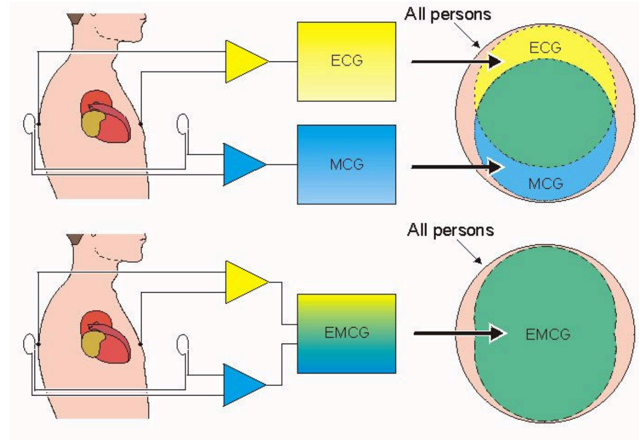

Figure 2. The ECG and MCG diagnose correctly about the same number of patients, but not the same patients. Combining these groups increases the number of correctly diagnosed patients [1].

III. Results

A. Proof of the theoretical result with clinical recording of ECG and MCG

To proof the theoretical solution of the problem Jaakko Malmivuo and co-workers made a clinical study on ECG and MCG [2, 3, 11].

They had three patient groups: Old inferior myocardial infarction (IMI), old anteroseptal myocardial infarction (AMI) and normal healthy persons the following amount:

	Male	Female	Age	No
IMI	73	17	59 +/- 19 years	90
AMI	59	12	59 +/- 5 years	71
Normals	85	67	54 +/- 11years	152
			Total	313

The diagnosis of all patients was confirmed with non-electrocardiac diagnostic methods.

In statistical analysis they found, that for 152 normals / 90 IMI and 152 normals / 71 AMI the correct classification was:

	Norm/IMI	Norm/AMI
ECG	90.1 %	88.4 %
MCG	91.7 %	87.4 %
EMCG	95.5%	91.3 %

This clearly indicates that the patient groups classified correctly with ECG and MCG are about equal size but they are not the same patients. Therefore, when combining the ECG and MCG to EMCG it is possible to increase the number of correctly classified patients. The amount of increase is such that the number of incorrectly classified patients decreases to one half.

B. Proof of the theoretical result with clinical recording of EEG and MEG

Masaki Iwasaki and co-workers made a clinical study where they recorded epileptiform activity with EEG and MEG from 43 patients [4]. The EEG was recorded with the standard 10-20 electrode system and MEG with a 122 channel planar gradiometer instrument. The recordings were made simultaneously. Raw EEG and MEG waveforms were reviewed independently by two experienced epileptologists, one for EEG and one for MEG, blinded to the other modality and to the clinical information. The number patients where interictal spikes were captured in EEG or MEG alone, in both modalities EMEG and in neither modality were the following:

	No of patients
EEG	1
MEG	8
EMEG	31
Neither	3
Total No of Patients	43

IV. Conclusions

The theoretical solution for the independence of bioelectric and biomagnetic signals from volume sources is now confirmed independently by two research groups with two different clinical studies and two different volume sources. Therefore the solution can be considered proved.

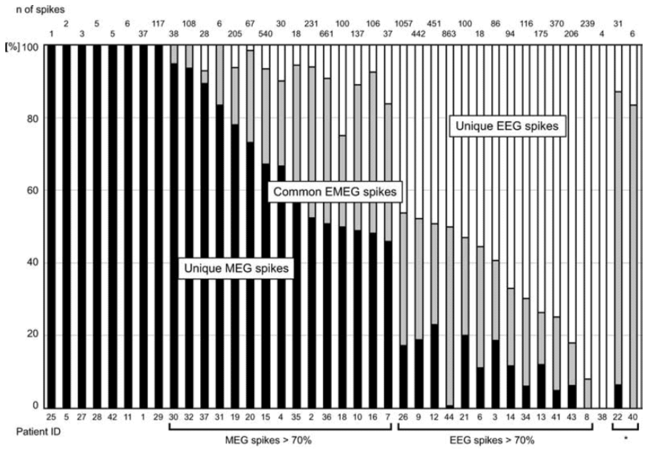

Figure 3. Populations of spikes that were detected only in MEG (black), only in EEG (white) and commonly in both EEG and MEG (gray) [4].

V. Discussion

The theoretical solution concerns of signals from volume sources. There is no accurate numerical value for the independence for the bioelectric and biomagnetic signals. That depends on the nature and location of the source to be detected. But the order of magnitude appears to be that with the combined use of bioelectric and biomagnetic method of the same order, the number of incorrectly diagnosed cases may be decreased to one half of that of diagnosed with either method alone.

In the beginning of biomagnetic research it was promoted the technology by claiming that the bioelectric and biomagnetic methods are complementary, i.e. that sources that are detected with bioelectric method cannot be detected with the biomagnetic method and vice versa. The clinically verified proofs of the theoretical solution presented in this paper demonstrate that this is not the case. If that had been the case, the biomagnetic methods had been able to bring from the source the same amount of new information as the bioelectric ones had brought. It had been a tremendous increase in the diagnostic performance.

This solution demonstrates that the improvement of the diagnostic performance by application of the biomagnetic methods is moderate, but it is statistically significant.

There exist, however, special cases, where the biomagnetic methods may be considered complementary for the bioelectric ones. This is when the lead fields of the bioelectric and biomagnetic detectors are orthogonal and where the bioelectric source element of the volume source is in the direction of either lead field. Then only one of the methods may detect the signal. However, most of the source elements are oriented somewhere between. But this is nothing new. Such situation exists already within the three components of the detection of the electric dipole moment of the volume source, or similarly in the detection of the magnetic dipole moment of the volume source.

In addition, there exist other special properties like:

- the magnetic detector has spherical lead field, which is not affected by the high resistivity skull
- despite of this, the EEG and MEG have about equal spatial resolution [12]
- the magnetic detector detects only tangential sources as the electric one detects both radial and tangential ones
- the magnetic detector is not capable to detect deep sources in the center of the volume source.

The biomagnetic measurements bring additional diagnostic information over the bioelectric ones. However, it is important to understand the capabilities and limitations of both methods, especially, because the biomagnetic methods are at least an order of magnitude more expensive than the bioelectric ones.

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