UNIVERSITY OF WATERLOO
Faculty of Mathematics

MAGNETOENCEPHALOGRAPHY IN NEUROIMAGING

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Maher Quraan
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Dear Maher Quraan:

I have prepared the enclosed report, "Magnetoencephalography in Neuroimaging", as my 2A work report for the Dr Agnes Wong's Eye Movement Laboratory MEG team at The Hospital for Sick Children. This report, the second of four work reports that the Co-operative Education Program requires that I successfully complete as part of my BMath Co-op degree requirements, has not received academic credit.

The team that you lead uses MEG in the study of amblyopia. My job as Research Assistant consisted in the modification of computer models, designed to analyze the data produced by the MEG readings. This report is an analysis of the use of MEG as a neuroimaging technique

The Faculty of Mathematics requests that you evaluate this report for command of topic and technical content/analysis. Following your assessment, the report, together with your evaluation, will be submitted to the Math Undergrad Office for evaluation on campus by qualified work report markers. The combined marks determine whether the report will receive credit and whether it will be considered for an award.

I would like to thank you for your assistance in preparing this report.

Sincerely,

Manuel Alejandro Candales

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EXECUTIVE SUMMARY

Magnetoencephalography is a neuroimaging technique use to localize brain activity. It measures the tiny magnetic fields produced by the small currents that flow in the neural system when information is processed. From this data the locus of brain activation is calculated using advanced computational models. This information is displayed on top of an MRI scan, to produce a final image of brain's activation.

MEG has the benefits of being a completely non-invasive technique, and having a great time resolution. However, many institutions still do not make use of this advance technique, since it is quite expensive.

In this report we analyze the benefits and drawbacks of MEG, and compare it to two other techniques: Functional Magnetic Resonance Imaging (fMRI) and Electroencephalograpy (EEG) regarding time and spatial accuracy. We arrive to the conclusions that MEG is a better tool that fMRI, since it has a much better time resolution. We also conclude that it is beneficial to use MEG and EEG as complementary technologies.

1.0 INTRODUCTION

The human brain is the most complex organized structure known to exist. Most of the brain information processing is done in its outermost layer, the cortical cortex. When information is being processed, small currents flow in the neural system and produce a weak magnetic field. Magnetoencephalography (MEG) is a neuroimaging technique that uses an array of sensors positioned over the scalp that are extremely sensitive to minuscule changes in those magnetic fields. This technique is used to localize brain activity, and produce images that show which part of the brain is active at some point in time. At the present time, MEG has grown to be a significant neuroimaging technique, with an increasing number of users.

In this report we analyze the use of MEG as a neuroimaging technique. We describe the process of localizing brain activity using MEG, and explain the key issues that arise during the localization. We analyze the benefits and drawbacks of this technique and them proceed to compare it to other existing neuroimaging techniques such as EEG and fMRI, focusing on the time and spatial resolution that they provide.

2.0 ANALYSIS

2.1 Localizing the sources

The cortical cortex is a 2-4 mm thick sheet of gray tissue, with a total surface area of about 2500 squares centimeters, folded in a complicated way, so that it fits into the cranial cavity formed by the skull. The processing of the information coming from the different senses (vision, audition, touch, etc) as well as the integration of muscular activity, are done in different regions of this area. MEG allows us to localize where in the cortical surface is the activity occurring at some specific point in time, by detecting the tiny magnetic fields coming from it.

2.1.1 The measurement

Neuromagnetic signals are typically 50-500 fT, one part in a billion of the earth's geomagnetic field. This is considerably smaller than the ambient magnetic noise in an urban environment, produced by moving vehicles and elevators, radio, television, etc. Therefore, the main problems in measuring the brain's magnetic field are to be able to detect the tiny fields and to avoid the external competing noise.

MEG uses an array of very sensitive magnetometers called SQUID that are based on superconducting rings. The SQUID sensors are contained within the MEG helmet which is worn by patients in a sitting or supine position (see Figure 1b). The big container on top of the helmet contains liquid helium that is used to achieve superconductivity (see Figure 1a). The measurements take place in a shielded room, in order to minimize the external noise. Besides the main array of magnetometers (called sensors) located right above the scalp, MEG uses another array of magnetometers (called references) located far apart the head, which would mainly measure the noise. The field measured by the references is then subtracted from the one measured by the sensors, in order to eliminate the noise.

Figure 1a. MEG equipment

Figure 1b. Patient in the MEG

2.1.2 Processing the data

The measurement is only the first step. The challenge is to determine the location of the electric activity within the brain from the measured field. This problem is known as the inverse problem. The primary difficulty is that it does not have a unique analytical solution, since the number of possible sources (tens of thousands of points around the cortical surface) overcomes the number of sensors (just over a hundred). Assumption of brain activity, constraints in the possible source and localization algorithms are therefore used, in order to find the best possible solution. There are different computational methods, each having pros and cons. One of the methods works as follows. The system is initialized with a first guess. A loop is started, in which a forward model is used to simulate the magnetic field that would result from the current guess. The guess is adjusted to reduce the discrepancy between the simulated field and the measured field. This process is iterated until convergence.

2.1.3 Producing the image

Magnetic Resonance Imaging (MRI) provides accurate images of the brain's anatomy with millimeter resolution. One can combine this imaging method with MEG to create magnetic source images. Provided that the coordinate systems for MEG and MRI have been aligned, one can superimpose the location of brain activity, found by MEG, on the MRI's. In this way, the goal of producing an image of brain activation is achieved.

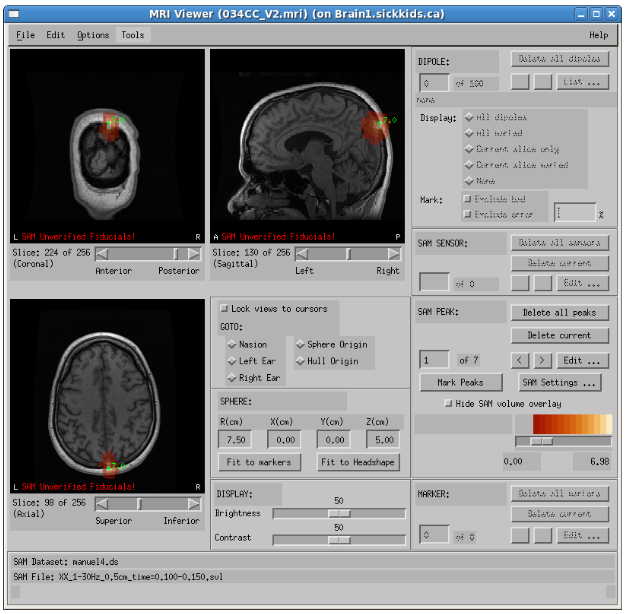

Figure 2. Brain's activation image. The whiter spot is where the peak activity is. The more red it gets, the lower the activation is.

2.2 Benefits of MEG

The high sensitivity of the SQUID magnetometers utilized by current MEG systems combined with advanced hardware and software noise cancellation techniques allow the detection of the weak magnetic fields generated by the human brain with good spatial accuracy. The ability to directly observe the neuronal fields allows MEG to have millisecond (ms) time resolution, which is several orders of magnitude higher than other neuroimaging techniques. This is particularly important as fundamental brain processes can occur in much less than a second. In this way MEG can take common activities that everyone does like swallowing and show, in chronological order, what precise areas of the brain are involved during this apparently simple, but essential and neurologically complex activity. This makes MEG a very good tool for clinical purposes. Currently it is used to study and aid in the treatment of brain diseases and disorders such as epilepsy, tumors and tuberous sclerosis. On top of all this benefits, MEG is also a completely noninvasive technique. This means that it does not have any bad consequences in the short or long run on the person whose brain activity is being measured, no matter how many times it is done. This is because one only measures the magnetic field, as a result of completely inoffensive sensory stimuli such as sounds, touch or light.

2.3 Drawbacks

The time resolutions of MEG are unrivalled. Nevertheless, MEG has a basic limitation in that the neuronal signals are only recorded from the scalp. Consequently, there is no unique solution to the problem of reconstruction where exactly the sources of the signals are localized within the brain. The standard approach to overcome this non-uniqueness is to introduce constraints on the possible solutions. Thus the localization of brain sources depends to some degree on the models used on the corresponding assumptions, and therefore will have some degree of uncertainty. This contrasts with the spatial accuracy of MRI brain images. Another problem is that MEG needs rather costly facilities. The MEG together with its shielded room costs around 2.5 million. In addition, the liquid helium that it contains needs to be replaced very frequently, adding an extra maintenance cost.

2.4 Comparison with other techniques

Because of its costly requisites, some institutions have hesitated in start using MEG as a clinical tool, and continue using less expensive techniques such as Functional Magnetic Resonance Imaging (fMRI) and Electroencephalograpy (EEG). Nevertheless, MEG has become increasingly popular during the last years among researches based on the argument that it is much more accurate. In what follows, we compare MEG to the two techniques mentioned above in terms of accuracy.

2.4.1 fMRI

Functional Magnetic Resonance Imaging is a neuroimaging technique that measures the blood oxygenation that accompanies neuronal activity. This technique has relatively high spatial resolution, of about 2-3 mm, but lower temporal resolution (a few seconds). On the other hand, MEG has 4-5 mm of spatial resolution and an impressively good temporal resolution of less than 1ms. Even though fMRI has spatial resolution slightly better that MEG, the later MEG has the great advantage of having a much better temporal resolution.

Time resolution is something of great importance. For example, suppose that we want to study the brain activity during a fast incident, like a driver's reaction to avoid a car accident. Many complex sensory processing, object recognition, cognitive decision and motor events occur in a time window of perhaps 750 ms or less. It is possible to track the sequence of neural events with at least 750 snapshots of sensor data, using MEG. In that way we can reconstruct 750 images (one each 1 ms) of the activity distribution in the brain. This would allow us to study what was happening inside the brain at each stage of the reaction. However, fMRI indirectly measures the neural activation, via local changes in the level of blood oxygenation, and as a consequence, the neural activation occurring in that time window of 750 ms, would be compressed to one measured brain volume. Therefore it provides no real-time information of neural involvement and is therefore less than ideal to track the brain activity related to such rapid decision-making that would be of vital importance in an accident.

2.4.2 EEG

Electroencephalography (EEG) is another neuroimaging technique, which directly measures the electrical impulses of the brain. It is a widely applied method, and it is closely related to MEG. Their time and spatial resolution is very similar, however MEG has advantages over EEG because EEG results can be altered or blocked by the skin, fluid or skull surrounding the brain. MEG reads magnetic impulses directly, which are not distorted by skin, fluid or bone. The result is better spatial localization of areas of the brain targeted for surgical removal and more accurate spatial localization of areas of the brain that should be preserved because they control functions such as language, movement or touch.

On the other hand, MEG has some limitations since magnetic fields generated deep within brain tissues decay rapidly over distance and may be less likely to be detected at the surface compared with electrical fields. EEG is therefore sensitive to activity in more brain areas, but activity that is visible in MEG can also be localized with more accuracy. Therefore, it would be beneficial to use EEG and MEG as complimentary technologies.

3.0 CONCLUSIONS

MEG is found to be an excellent tool to measure brain activation, with the advantage of being completely non-invasive

MEG's superior time resolution makes it the ideal tool to study fast decision-making situations; and makes it a much more accurate tool than fMRI

MEG and EEG are similar in accuracy, but it is beneficial to use them as complementary techniques.

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