Magnetic Source Imaging

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Abstract: We consider the requirements for recording and analyzing information on the three-dimensional pattern of neuronal activity within the human brain, through measurements of the magnetic field pattern across the scalp.

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1 Introduction

A magnetic source image (MSI) is a representation of the distribution of intracellular currents of a region of the body at a particular moment in time. It is obtained from an analysis of the magnetic field pattern that these currents naturally produce in the surrounding space. Most commonly, the term is applied to studies of neuronal activity within the human brain, although important applications are being made in studies of the heart. The proceedings of a recent international conference provides introductory tutorials and up-to-date research reports for the entire field of biomagnetism [1]. With modern instrumentation and procedures, it is possible to locate the center of neuronal activity in sensory areas of the human brain with an accuracy of better than 3 mm [2]. In this way, function and structure of the human brain can be related by comparing an MSI with the anatomical structure provided by a high-resolution magnetic resonance image (MRI).

Extensive studies of electric voltages between pairs of electrodes attached to the scalp (the electroencephalogram, or EEG) have revealed many temporal features that correlate with the brain’s response to sensory stimuli and to certain cognitive functions. Magnetic fields near the scalp, as well as these electric voltages, are much weaker than the fields and voltages produced by ongoing activity of the brain. Therefore, it is necessary to average the signals from successive presentations of a stimulus in order to bring them above the background brain “noise”.

Recent studies [3] have revealed that much of this “noise” actually provides useful information about higher level processes in the brain. The comparatively fine spatial resolution provided by magnetic field measurements reveals that the ongoing spontaneous activity in the alpha bandwidth (8-12 Hz) is locally suppressed when a specific area of cortex becomes engaged. For instance, when a person mentally compares the image of an object just seen with images of objects previously seen, spontaneous activity over the visual area of the brain remains suppressed until the person indicates by pressing a switch whether or not it matches one of them. Moreover, tasks that call on different cognitive processes, such as finding a rhyme to a word displayed on a monitor, cause suppression to begin first over the visual area and approximately 100 ms later over the temporal area. In this way, it is possible to follow the sequential participation of various regions of the brain, thus indicating the individual’s strategy for dealing with a particular cognitive task.

2 Locating Neuronal Activity

Magnetic fields of the human brain are only 10^-9 of the earth’s steady field, so that a sensor of high-sensitivity is required. The conventional method is to employ the cryogenic instrument known as a SQUID (Superconducting QUantum Interference Device) [4]. Commercial systems consisting of arrays of SQUID sensors are available to measure at several positions over the scalp simultaneously, with a field sensitivity of about 6 fT. Figure 1 illustrates an arrangement with a single sensor positioned near a confined region of neuronal activity. The corresponding neuromagnetic field emerges from one region of the scalp and enters another. The term “field extrema” denotes the pair of locations where the normal component of the emerging and entering field is strongest. The source lies under the midpoint between the extrema, with its current oriented tangential to the scalp and perpendicular to the line joining the extrema. The
distance between these extrema, in comparison with the radius of the head, determines the depth of the source. The strength of the field at an extremum and the depth of the source determine the strength of the source. This is specified as a current dipole moment $Q$, whose magnitude is the product of the current and length of its path. These simple prescriptions rely on modeling the head as a conductive medium having spherical symmetry[5]. In this case the source strength may be deduced quite independent of the values of the conductivity for brain tissue, cerebrospinal fluid, and skull. More generally, for this simple approach to provide adequate accuracy, it is necessary that only the region of the inner surface of the skull above the source be well approximated as a portion of a sphere [6].

As illustrated in Fig. 1, the magnetic field of the brain is detected indirectly by the SQUID, through use of a detection coil. This coil has a larger area than the SQUID and therefore obtains more signal energy. Moreover, the geometry of the coil can be chosen to reject the relatively uniform fields of distant noise sources. This detection coil forms part of a continuous loop of superconducting wire, which includes a smaller "input" coil (not shown in Fig. 1) mounted close to the SQUID. A property of such a closed loop is that whenever a field is applied to the detection coil, a current flows around the loop to keep the net magnetic flux within the loop invariant. The SQUID senses the field of this current flowing through the input coil, and the SQUID's response is monitored by an electronic system at room temperature. The output voltage is directly proportional to the original magnetic flux applied to the detection coil. In this way the SQUID provides wideband response, from true dc to several kilohertz in commercial systems.

To properly sample the spatial frequency content of the field pattern across the scalp would require an array of approximately 128 sensors, spaced at intervals of about 2 cm. The largest array of sensors now available commercially consists of 37 sensors. This is sufficient to monitor the field pattern from a single confined neuronal source at a depth as great as about 5 cm. However, sequential measurements, obtained by placing the array at different recording positions on the scalp, would be required to obtain a complete field map of brain activity. This is a significant limitation of the present generation of sensing systems.

The recording bandwidth of interest ranges from dc to about 100 Hz. Steady fields can be detected in association with the onset of migraine and certain epileptic seizures. Low frequency features in the range from 0.1 Hz to 5 Hz are associated with cognitive processes of the brain, such as the detection of semantic mismatch in a spoken sentence or experiencing an event having a low probability of occurrence. Features with spectral components of higher frequency are normally encountered in studies of sensory related responses. Therefore, we expect that the typical recording bandwidth in MSI studies of the future will be about 0.1-100 Hz. This registers the relatively slow activity of ionic currents flowing along the length of dendrites of pyramidal cells. These cells comprise the largest population in cerebral cortex, and they are preferentially aligned perpendicular to the cortical surface. Spectral components of even higher frequency are found in the fluctuations of ionic intracellular currents. They are associated with the propagating action potentials ("spikes") which neurons use to communicate across long distances. However, such high-frequency activity is yet to be identified in magnetic recordings, aside from the very earliest stages of processing within the brain stem.

3 Multiple Sources

The principal challenge in determining the spatial distribution of neuronal activity comes from the fact that the inverse problem does not have a unique solution. This is true if the magnetic field pattern is known everywhere over the head, or the electric potential is known everywhere across the scalp. It even remains true if both sets of data are at hand. A given
field pattern can be accounted for by many different configurations of source currents. One example of this is clearly recognized when the head is considered to have spherical symmetry. Then a current element that is oriented exactly radially produces no magnetic field outside the head. Another "magnetically silent" source would be one with spherically diverging currents. The presence of any combination of such sources could not be inferred from measurements of the field pattern outside the head.

Fortunately, neuromagnetic measurements indicate that the feature of non-uniqueness does not impose a serious limitation in practice. We would attribute this to the fact that most of the computational elements of the brain are distributed across its surface, not throughout the volume. One uniquely human aspect of our brain is its large ratio of area to volume. Evolution has enhanced the amount of cerebral cortex (gray matter) while minimizing the volume devoted to connections (white matter). This was accomplished by wrinkling the surface. Some two-thirds of cerebral cortex lies within the sulci and fissures that form its infoldings. This provides an orderliness that we can take advantage of. Pyramidal cells in fissures and sulci are therefore oriented largely tangential to the overlying scalp and contribute strongly to the observed field. Even those on the exposed surface of cortex have an appreciable tangential component, except at the outermost convexity of the gyri that thrust outward.

Neuronal activity of interest is also found deep within the brain, as in the hippocampus that forms part of the medial surface of the left and right temporal lobes. But here, also, the pyramidal cells form orderly arrays. Other sources of interest are located in the brainstem, near the center of the head. Their magnetic signals would be considerably attenuated because of geometrical considerations alone (a source at the center of a spherical head is a limiting case of a radial current). Also, the architecture of neuronal circuits is less obvious, although certain areas, such as the lateral geniculate nucleus — important for vision — provide examples of a layered organization.

The surface organization of cortical circuits has permitted their activity to be successfully modeled by one or more current dipoles for the purpose of interpreting neuromagnetic field patterns. In many studies of sensory evoked responses, it is possible to manipulate the stimulus to emphasize one source over another, and in this way establish high reliability for determining the parameters of the individual current dipoles. Auditory cortex is the sensory area that has received most attention in magnetic studies [7]. For instance, at one instant of time there are at least 4 distinct sources in the superior surface of the temporal lobe in each hemisphere that are simultaneously active during certain time intervals. Distinguishing between the signals that arise from separate hemispheres is easily accomplished magnetically. Since field strength diminishes rapidly with distance from the source, measurements over a given hemisphere detect the activity of only that hemisphere. However, distinguishing among the four sources within a given temporal lobe is more difficult. Even so, they can be separated by the fact that signals from two of them overlap signals from the other two for only a portion of their periods of activity. Choosing the non-overlapping time intervals for localizing these sources provides a way to model them individually. Additional separation is provided by the fact that the remaining undifferentiated pair of sources have different adaptation rates when a sequence of stimuli are presented. Therefore, it is possible to first model the one whose amplitude does not diminish as markedly as the other, and then carry out a two-dipole fit when the other is measured under conditions where its amplitude is robust as well.

3 Data Processing

It should be clear from the previous discussion that the procedure for obtaining an MSI is quite different from that for an MRI. In particular, the state of the person being studied may well vary during the course of the measurements. Attention, alertness, and emotional factors may well vary over the course of an hour. For this reason, it is important to provide real-time information to the operator who is responsible for the recordings, so that the protocol may be varied to meet changing conditions.

We consider now the performance of a system that is based on an array of 128 SQUID sensors. Each output is filtered to pass the range 0.1-100 Hz, and is digitized at 256 Hz with 12 bit resolution. A typical recording of 50 sensory evoked responses each lasting for 2 s, or a recording of a time series of spontaneous activity for a period of 100 s, would produce a data file of about 5 Mbytes.

Even with the use of gradiometer detection coils and a magnetically shielded room, environmental noise may well dominate the low frequency region of the recording bandwidth. Therefore, there is an advantage to employ 3 additional sensors to monitor orthogonal components of the environmental field. With this data, an adaptive filtering algorithm could minimize
the correlated component found in the output of each of the 128 signal channels. This procedure could be carried out in real time by continuously updating the weights given each reference before subtracting them from the individual signal channels.

3.1 Pattern Recognition

Neuronal sources are indicated in a field pattern by temporal variations in the magnetic field that are coherent across a set of several adjacent sensors. If the underlying source is a dipole, there will be a second region on the scalp (the other field extremum) where a second set of sensors shows strong negative correlation with the first set. In essence, algorithms designed to detect activity from one or more neuronal sources may rely on the evolution of such spatio-temporal correlation patterns across the scalp. Devising such strategies is where much of the opportunity lies in developing MSI techniques.

Alternative representations of the underlying sources exist, such as a minimum norm estimate based on the concept of lead field theory [8]. This provides a description of the current pattern at a chosen depth that would account for the observed measurements. Unfortunately, the method does not provide an unambiguous estimate for the depth of the activity. For this reason, the application of multiple dipole models to account for the field pattern from one moment to the next appears to be the most attractive for establishing an MSI.

As data are collected, it is valuable to carry out an analysis on a continuing basis to determine the accuracy with which parameters of dipole models are being established. The operator could have a continually updated display that indicates the deduced locations of the current dipoles with respect to an MRI, to determine whether the results are anatomically reasonable. Additional important information would include the uncertainty in parameter fits as well as measures of the quality of the fits to the field pattern. In this way, the recording session need continue no longer than is required to achieve a given level of accuracy and completeness. It is feasible with a computer workstation to employ a realistic model for the individual subject's head, taking into account departures from a spherical shape [9].

It is important when recording to periodically include standard sensory stimuli, and perhaps cognitive tasks, chosen to provide a gauge of the subject's attention and mental state. If a deviation from the norm is observed during recordings, the operator may well take steps to correct the situation. Very little is known as to how the MSI of an individual will change under different mental loads or emotional states. Therefore it is all the more important to maintain proper controls in order that the characterization be meaningful.

References