Abstract

The human cerebral cortex, consisting of six layers and billions of neurons and synapses, processes sensory input from numerous sensory receptors. Noninvasive magnetoencephalographic (MEG) recordings provide a view through the skull to electrophysiological signals of the cortex on a millisecond timescale. For example, magnetic somatosensory evoked fields (SEFs) to a given peripheral somatosensory stimuli, reflect sequential activation of an extensive cortical network. Several cortical areas contributing to the SEFs can be evaluated in time and space by using source modeling. This brief review focuses on MEG studies of the human somatosensory networks with a special emphasis on tactile stimulation. © 2000 Elsevier Science Ltd. All rights reserved.

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1. Introduction

1.1. Magnetoencephalography

In magnetoencephalography, weak magnetic fields due to the neuronal currents of the brain are measured outside of the head by means of a neuromagnetometer (Fig. 1). Neuro-magnetic measurements are typically carried out in a magnetically shielded room to attenuate ambient noise from the environment. The theory and instrumentation of the MEG method have been reviewed in detail by Hämäläinen, Hari, Ilmoniemi, Knuutila, and Lounasmaa (1993).

The MEG method has developed gradually since the first measurements with induction coils in the late 1960s and the invention of magnetometers based on the superconductive quantum interference device, SQUID (Josephson, 1962), in 1970s. Multichannel sensor arrays were soon available providing simultaneous mapping of the magnetic field above a given brain region. The first whole-scalp neuromagnetometers were introduced in 1992 (Ahonen et al., 1993; Vrba et al., 1993). Modern whole-scalp MEG instrumentation, with hundreds of channels and an user-friendly control interface, provides a noninvasive tool to investigate human brain functions with a millisecond time resolution.

MEG signals are mainly generated by the postsynaptic currents of the pyramidal neurons of the cortex. Both anatomical and electrophysiological factors contribute to the generation of neuromagnetic fields. The magnetic signal of a single postsynaptic potential (PSP) is far too small to be detected outside the head with current instruments (Vvedenski, Hari, Ilmoniemi, & Reinikainen, 1985)

However, one PSP lasts about 10 ms providing a temporal window in which magnetic fields may summate. When thousands of adjacent pyramidal neurons are activated, a net current normal to the cortex and corresponding magnetic field are generated.

Since the head resembles a sphere and the currents are normal to the cortical surface, some cortical areas are magnetically silent due to radial currents. However, fissural cortex, giving rise to magnetic signals, covers roughly 2/3 of the cortex and thus most of the cerebral cortex can be reached by MEG recordings.

The layered structure of the head distorts the electric potential distribution on the scalp, i.e. electroencephalogram (EEG), whereas the magnetic field distribution is not affected. Thus, MEG is more suitable to study multiple spatially and temporally overlapping activations of the brain.

The usefulness of MEG depends largely on source modeling, i.e. the ability to estimate the current distribution from the measured magnetic field distribution. The ambiguity of this neuromagnetic inverse problem can be restricted by introducing constraints based on physiology and anatomy of the brain. For example, the sources can be constrained to...
the cortex and only currents normal to the surface need to be considered.

The measured and modeled data can be compared by calculating the magnetic field ensuing from a given current distribution, i.e. by solving the neuromagnetic forward problem. Once the distribution of the electromagnetic parameters is given, the neuromagnetic forward problem can be solved from Maxwell’s equations applying quasistatic approximation (Hämäläinen et al., 1993).

A current dipole approximates well a cortical source of small extent, typically of the order of few cm$^2$. The parameters of the dipole can be computed at a given time by a nonlinear least-squares search (Tuomisto, Hari, Katila, Poutanen, & Varpula, 1983). Several spatially or temporally separated dipolar sources can be modeled from the same data by using a time-varying multidipole model (Scherg & von Cramon, 1985; Mosher, Lewis, & Leahy, 1992). As a result, time dependencies of the modeled sources can be evaluated (e.g. see Fig. 5).

### 1.2. Somatosensory network

The peripheral somatosensory systems are specialized to touch, temperature, proprioception, and pain. Tactile and proprioceptive information is mainly mediated through the spinal cord and the thalamus to the contralateral primary somatosensory (SI) cortex. Afferent pathways reach also directly the secondary somatosensory (SII) cortices bilaterally and to the contralateral posterior parietal cortex (PPC) (Kaas, 1990), although major input to these areas is probably mediated through corticocortical connections from the SI cortex.

In humans, the SI cortex is located in the anterior parietal
cortex, on the posterior bank of the central sulcus and in the postcentral gyrus (Fig. 2). It consists of several cytoarchitectonic areas, the Brodmann’s areas 3a, 3b, 1, and 2, which are all interconnected at the cortical level. Thalamic input terminates mainly in Brodmann’s areas 3a and 3b.

The human SII cortex is buried in the upper lip of the Sylvian fissure (Fig. 2). The SII cortex is activated bilaterally to unilateral tactile stimulus. The human SII was first described by Penfield and Jasper (1954) by means of direct electric stimulation of the cortex during epilepsy surgery. In this review article SII refers to parietal operculum, known to include multiple somatosensory representations in monkeys (Burton, 1986), and apparently in humans, too.

The human PPC, also known as the parietal association area, is situated in the post-central sulcus, medial and posterior to the SI cortex hand area. The PPC integrates sensory and motor processing, combines tactile and proprioceptive input with other sensory modalities, and is associated with higher cognitive functions (Hyvärinen, 1982).

1.3. Tactile stimuli

In most studies on human somatosensory system, electric stimuli have been used. Typically, electric stimulation is applied over the peripheral nerve bundle at the wrist. Electric stimulus activates nerve fibers close to the stimulus site without activating the receptors. When the intensity of a given stimulus increases, the number of activated nerve fibers increases together with the synchrony of the generated action potentials. The resulting activation of the cortical somatosensory network has been explored with various functional imaging tools. A recent article (Hari & Forss, 1999) reviews SEF studies elicited mainly with electric median nerve stimulation.

Cutaneous mechanoreceptors (rapidly adapting Merkel disks and Ruffini endings, and slowly adapting Meissner corpuscles and Pacinian corpuscles) play a crucial role in tactile discrimination and in precise finger movements. Each mechanoreceptor contributes to somesthesia in a unique way (Bolanowski Jr., Gescheider, Verrillo, & Checkosky, 1988). For example, Pacinian corpuscles sense tactile, high-frequency vibrations with the lowest thresholds in the 250–350 Hz range. In humans, the glabrous skin of the hand has the highest density of Pacinian corpuscles and, consequently, the best tactile acuity for vibration (Birder & Perl, 1994; Vallbo, 1995).

In contrast to electric stimuli, tactile stimuli such as mechanical tapping, vibration, and airpuffs, activate mechanoreceptors selectively. Obviously, natural tactile stimuli are more meaningful to a human being than electric pulses. Tactile stimuli elicit reproducible cortical responses and thus provide a tool to investigate the human somatosensory system. However, cortical responses to tactile stimulus compared with those to electric stimulus may differ in amplitude, waveform and peak latencies. Differences in amplitude and waveform is probably due to selective activation of given receptors and less synchronous action potential volley in the afferent pathway. Differences in peak latencies is partly explained by receptor delay.

1.4. Tactile stimulators

In MEG experiments, stimuli are not allowed to produce electromagnetic artifacts. For example, solenoids and other electronic systems commonly used in electrophysiological studies are not compatible with MEG due to strong magnetic fields associated with the stimulus generation. In addition, some commonly used materials, such as iron and nickel, are magnetic producing huge magnetic artifacts while moving close to the neuromagnetometer.

Mechanical stimulation, such as tapping, can be generated by a pneumatic stimulator consisting of a small circular rubber bladder encased in a plastic outer shell, and a pneumatic tube controlled with electronics (Yang, Gallen, Schwartz, & Bloom, 1993). The resulting tapping, with a
2. Somatosensory evoked fields

MEG signals elicited by various sensory stimuli can be evaluated in time and space to follow and localize the corresponding activity in the cortical network. Typically, a given sensory stimulus is repeated several times and MEG signals are averaged with respect to the onset of the stimulus to increase signal-to-noise ratio. In case of somatosensory stimuli, the averaged signal is called somatosensory evoked field (SEF).

2.1. Electric stimulation

Electric stimulation the median nerve at the wrist results in a activation of the hand area of the SI cortex, contralateral to the stimulation (Hari et al., 1984). In addition, several other somatosensory cortices are activated depending on the stimulus rate and intensity (Forss et al., 1994a; Jousmäki & Forss, 1998; Maguierre et al., 1997).

The SI response to electric median nerve stimulation at the wrist has peaks latencies at about 20 and 30–35 ms. In contrast, the SII response peaks at about 100 ms.

The electric stimulation of the skin activates most of the nearby mechanoreceptors. The corresponding cortical activation arises from the SI cortex following the homuncular organization of the SI cortex (Penfield & Jasper, 1954). Compared with nerve stimulation, skin stimulation results in responses which are smaller in amplitude. In addition, peak latencies are ‘delayed’ due to a transduction time at the skin receptor.

SEFs to electric stimulation of the median nerve and skin produces strong responses which can be used to localize in the SI and SII cortices as a functional landmarks in the brain.

2.2. Mechanical stimulation

Pneumatic stimulator (Gallen et al., 1994; Yang et al., 1993) has been used widely in MEG experiments to stimulate fingers (Biermann et al., 1998; Elbert et al., 1994; Elbert, Panetz, Wienbruch, Rockstroh, & Taub, 1995; Gallen et al., 1994; Sterr et al., 1998), lip and oral cavity (Yamashita et al., 1999), and scalp (Hoshiyama et al., 1995). The SI responses to finger stimulation peak at about 40–50 ms. In contrast, lip stimulation elicits responses at about 20–40 ms and scalp stimulation at about 40–100 ms.

MEG enables studies of cortical maps of the SI cortex to mechanical stimulation. Disordered and altered cortical maps in amputees (Elbert et al., 1997; Knecht et al., 1998), tactually well-trained musicians, and Braille readers (Elbert et al., 1995; Sterr et al., 1998) indicate a sign of cortical plasticity which can be explored noninvasively by means of MEG. Interaction between adjacent and non-adjacent fingers have been studied by means of mechanical stimuli (Biermann et al., 1998).

Human tactile system seems to be very sensitive to a weak mechanical tapping. Even a very weak tapping of the table associated with the button-press can produce reliable SI responses (Hari & Imada, 1999).

All in all, mechanical stimulation provides a comfortable way to stimulate various body parts without stimulus artifacts and elicits reliable cortical responses originating mainly from the SI cortex.

2.3. Airpuff stimulation

Airpuff stimulation, corresponding to a very light touch, elicit responses from the SI, SII cortices, and PPC (Huttenen, 1986; Forss et al., 1994a). The contralateral SI peak latencies are observed at 30–60 ms. The contra- and ipsilateral SII peak latencies are about 90–100 ms for the. Also a PPC activation can be detected peaking at about 90 ms.

Compared with electric stimulation of the median nerve, airpuff stimulation of the fingers elicits SI responses which are smaller in amplitude and longer in latency, whereas the responses from the other somatosensory areas do not differ significantly. Variation of timing to different stimuli suggests different functional roles of these areas.

Airpuff stimulation, although it may be associated with a concomitant auditory stimulation due to pneumatic valves used in the stimulator, is a very pleasant way to stimulate cutaneous mechanoreceptors selectively.

2.4. Vibrotactile stimulation

Abrupt vibrotactile stimuli elicit replicable somatosensory evoked fields and evoked potentials, with the main deflections at about 45–60 ms to palm stimulation and at about 60 ms to finger stimulation. Responses to
palm stimulation originate in the SI cortex, contralateral to the stimuli, typically a few mm deeper and more anterior from those sources activated by electric stimulation of the median nerve (Jousma¨ki & Hari, 1999).

Piezoelectric stimulator was introduced by Jagow et al. (1992) and the same principle has been used in several studies to stimulate, e.g. the lip (Mogilner et al., 1994) and the fingers (Hashimoto, Mashiko, Kimura, & Imada, 1998, 1999a; Hashimoto et al., 1999c). Although the source locations follow the homuncular organization of the SI cortex, the evidence of a frequency map in the SI cortex has been shown only to vibrotactile lip stimulation.

Hashimoto et al. have explored carefully the cortical representation of the palm and index finger using the contralateral SI response peaking at about 50 ms as a functional landmark. The distal vs proximal stimulation of the finger and palm resulted approximately the same cortical source (Hashimoto et al., 1999a,b). In addition, they have observed an insignificant trend towards frequency and spatial map organization in the SI cortex (Hashimoto et al., 1998, 1999c).

Another vibrotactile stimulator construction, based on a loudspeaker, has also been introduced (Jousmäki & Hari, 1999; Levänen et al., 1998). This system has been used to generate concomitant audiotoctile stimulation (Jousmäki & Hari, 1999) and to study cortical plasticity in a congenitally deaf subject (Levänen et al., 1998).

3. Discussion

In this review, the main emphasis was on tactile stimuli that activate selectively cutaneous mechanoreceptors. Until
now, the use of natural tactile stimuli has been limited, possibly due to difficulties in producing such stimuli in a precise manner without generating artifacts. At present, new compatible tactile stimulators are available to be used in various functional brain-imaging modalities. The use of natural tactile stimuli is a step towards more ecologically relevant stimuli that helps to reveal how the somatosensory network acts under normal environmental conditions. For example, natural stimuli can be employed to study binding of the sensory information obtained by means of one or more sensory modalities, i.e., multisensory integration.

Despite of the inverse problem and magnetically silent areas in the brain, MEG can be efficiently used to evaluate somatosensory network activated by various somatosensory stimuli. The excellent temporal resolution of MEG is obviously an advantage that many other functional imaging modalities lack.

Synchronous neuronal activity gives rise to MEG signals which can be modeled, e.g., with current dipoles to identify centers of gravity of active brain areas. The millisecond time resolution of the method makes it possible to define the order of the activation of the cortical network. Furthermore, noninvasive MEG recordings can easily be replicated to test the effect of the experimental design on the cortical network on an individual level. Thus the functional roles of various cortical areas contributing to a given sensory process can be efficiently tested both in patients and control subjects.

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References


