Cortical Magnetic and Electric Fields Associated with Voluntary Finger Movements

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Summary: Multichannel recordings of both movement-related magnetic fields (MRMFs) and movement-related cortical potentials (MRCPs) were simultaneously recorded in association with voluntary unilateral self-paced index finger abduction movement in two normal volunteers. 1) Slow magnetic field (readiness field ; RF) can be detected several hundred msec before the movement onset, and its field distribution indicates the existence of the largest generator source over the contralateral primary motor area. Taken together with the vertex-maximal Bereitschaftspotential which corresponds to the earlier part of the RF, the complexity of this magnetic field suggested by relatively low correlation value in single dipole model indicates the co-activation of other underlying generators besides this largest dipole. 2) The utilization of MRMF with MRCP facilitates the separation of two distinct electrophysiological events in proximity to the movement onset, which are difficult to be determined by the technique of MRCP only. Those are the motor field (MF) and the movement evoked field I (MEFI) in MRMF, and the parietal peak motor potential (ppMP) and the frontal peak motor potential (fpMP) in MRCP, which occur approximately 20 and 100 msec after EMG onset, respectively. These two subcomponents may imply the culmination of motor cortex and sensory feedback activation, respectively. Combined study of MRMF and MRCP will provide better definition of cortical events related to voluntary movement than the study of either modality alone.

Key words: Movement-related magnetic field; Movement-related cortical potential; Magnetoencephalography; Readiness field; Motor field; Movement evoked field.

Introduction

Movement-related cortical potentials (MRCPs) (Kornhuber and Deecke 1965; Vaughan et al. 1968; Shibasaki et al. 1980) and more recently movement-related magnetic fields (MRMFs) (Deecke et al. 1982; Hari et al. 1983; Weinberg et al. 1983) have been investigated to clarify the mechanisms of voluntary movements in humans. These non-invasive techniques provide exquisitely detailed temporal information about the electrophysiologic events accompanying self-paced movements. Furthermore, the use of multichannel MRCP (Tarkka and Hallett 1990) and MRMF (Cheyne and Weinberg 1989; Kristeva et al. 1991; Chiarenza et al. 1991) recordings has improved the spatial resolution for these results, and has allowed the formulation of possible generator sources for both the electrical (Toro et al. 1993) and magnetic signals (Cheyne and Weinberg 1989; Kristeva et al. 1991; Chiarenza et al. 1991). Understanding the relation between these two kinds of electrophysiologic signals and the underlying anatomical substrate is of particular importance to the study of physiology of voluntary movements in normal subjects and patients with disordered motor control (Lang et al. 1991). Despite the fact that both the electroencephalographic (EEG) and magnetoencephalographic (MEG) signals result from the same physiologic events, the two recording modalities seem to provide different and yet complementary information (Cohen and Cuffin 1983; Williamson and Kaufman 1987). Although a simultaneous recording of MEG and EEG has been attempted (Chiarenza et al. 1991), no one has attempted to clarify the difference between the distribution of MEG field and that of EEG potential.

In this study we sought to compare the movement-related EEG and MEG activities preceding and following self-paced unilateral finger movements. Special emphasis was placed on a comparison of waveform mor-

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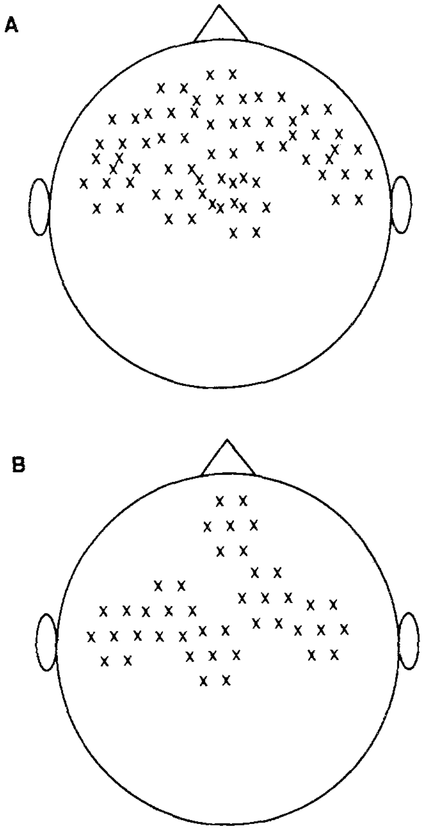

Figure 1. Location of magnetometer probes; 9 probe positions (overall 63 sensor locations) for Subject I (A), and 7 probe positions (overall 42 sensor locations) for Subject II (B).

phology and distribution in the scalp-recorded electrical and magnetic signals occurring in proximity to the movement onset.

Methods

Subjects and movement tasks

Two right-handed male normal volunteers with ages 34 and 52 years participated in this study after informed consents were obtained. The subjects were asked to repeat brisk abduction movements of the right index finger at a self-paced rate of about 0.1 Hz. They were also instructed to keep their eyes open, fixating on a target placed 3 m in front. The MEG recordings spanned 3 to 4 recording days in order to allow sampling from various MEG probe positions over the scalp on both hemispheres and midline. EEGs were simultaneously recorded from 7 electrodes (see below) for all MEG recordings, and furthermore, multichannel EEG recordings were completed on another single recording day.

Data acquisition

The MEG recordings were conducted in a dimly lit, quiet, magnetically shielded room using a 7-channel DC-SQUID neuromagnetometer with a second order gradiometer configuration (Biomagnetic Technologies, Inc., Model 607). The subjects lay down on a wooden bed in supine or lateral decubitus position depending on the desired position of the MEG coil over the scalp. At least two sessions were employed for each probe position, so that data from 100 or more movements were collected. In order to validate the comparability of the MEG responses across different sessions and among the various probe positions, EEG was simultaneously recorded in each session with gold electrodes placed at Fz, FCz, Cz, Pz, C3, C1 and C4 following the International 10-20 System and referenced to the linked-ears. Gold electrodes were used in spite of their rather poor capacity in sampling lower frequency signals, since preliminary recordings with silver/silver chloride electrodes showed relatively big slow magnetic background noise. The electromyogram (EMG) was recorded with surface electrodes placed over the right first dorsal interosseus muscle with a band-pass of 20-120 Hz. The electrooculogram (EOG) was recorded from two electrodes positioned above the left and below the right outer canthus. The rectified EMG signal was fed into a Schmidt trigger set to obtain a trigger pulse at the onset of each EMG burst. Five sec epochs (2.5 sec each before and after the movement onset) were digitized at a sampling rate of 256 Hz with 12 bit resolution on a Hewlett Packard 9000 (Model 300) computer. Filter settings were 0.3-50 Hz for the MEG and 0.16-70 Hz (-3dB) for the EEG and EOG. Environmental noise prevented the use of a lower high-pass filter for the MEG recordings. The raw data from each single sweep were stored on a magnetic tape for off-line analysis. In each recording session, the head shape, EEG electrode positions and probe positions were recorded with the probe position indicator (Biomagnetic Technologies, INC.). Three Cartesian coordinates were determined by the landmarks of nasion and bilateral preauricular points. The digitized electrode positions showed minimum difference among experimental days, which were within several millimeters in distance. Figure 1 shows the final arrangement of the magnetometer sensor locations for the two subjects as viewed from the top of the head. In Subject I, data were collected from a total of 63 channels by 9 sensor locations, and in Subject II, 6 sensor locations for a total of 42 channels were available for analysis.

The multichannel recording of MRCPs was carried out with the subject sitting in a comfortable chair. The motor task was identical to the one used for the magnetic field recordings. Each subject completed a total of 250 individual movements in a single recording session

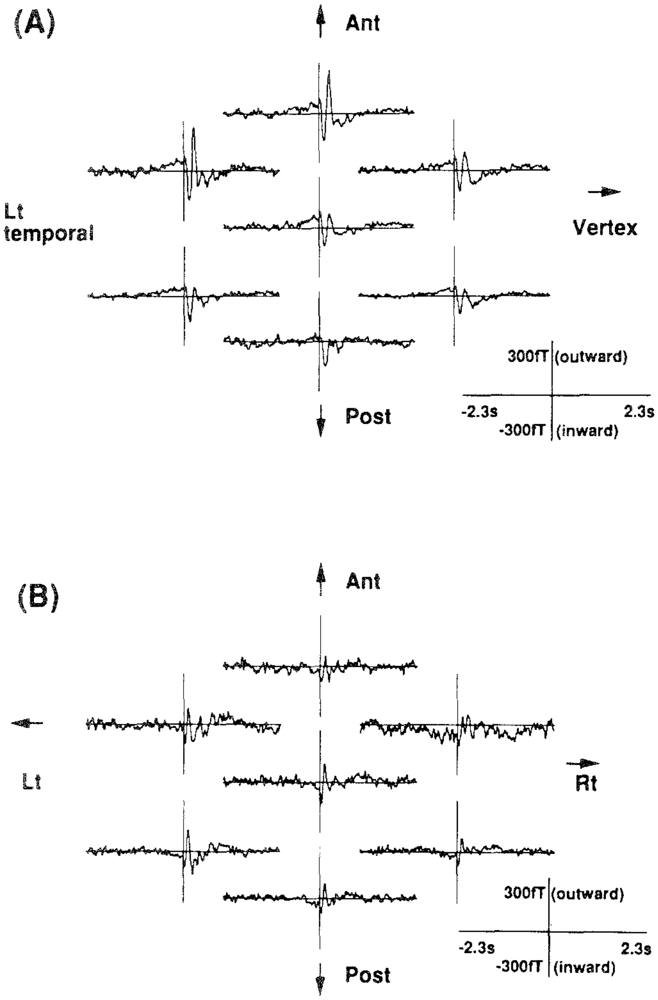

Figure 2. A typical set of averaged MEG waveforms recorded over the left temporo-central region (A) and over the vertex area (B) associated with voluntary, self-paced abduction of the right index finger in Subject I. A slow magnetic field can be seen several hundred msec before the EMG onset, which is outward over centro-temporal region (A) and inward over vertex region (B).

divided into blocks of 50 movements each. Twenty-nine electrodes were applied to the scalp with collodion according to the conventional International 10-20 System including some intermediate positions, and referenced against the linked-ears. Electrode impedance was kept below 5 kohm. The EEG was amplified with the filter setting of 0.16-70 Hz. The EMG and EOG were recorded in a similar fashion to MEG recordings. The signals were amplified with Grass model 12 amplifiers and digitized at a sampling rate of 200 Hz with 12 bit resolution and stored in their raw format for off-line analysis.

Analysis of data

Data for each single movement was reviewed off-line. Trials containing eye motion and other forms of magnetic or electric artifacts, or those associated with ambiguous EMG burst onset were rejected from the analysis. Selected trials in each session were entered into the average after precise alignment with respect to the EMG burst onset using the methods similar to those described by Barrett et al. (1985). Although simultaneous recordings of EEG (MRCP) showed similar appearance among sessions beyond experimental days, only the reproducible averaged waveforms among sessions over the same MEG sensor position were used for the grand average. The MEG and EEG averages were digitally filtered with a band-pass of 0.3-20 Hz. Various fields were identified on the average MEG waveforms, and isocontour maps were generated at each of those peak instants for both the MEG and EEG averages using a second order linear interpolation algorithm. At these peaks, dipole localization was performed using a spherical head model with inclusion of volume currents. This imaginary concentric spherical head was determined by the sampled digital head surface positions, assuming that the best-fit sphere had the same center position among different sensor locations.

Results

Figure 2 shows two representative samples of the averaged magnetic activities recorded in Subject I over the left centro-temporal regions (figure 2A) and vertex region (figure 2B). A slow magnetic field developed several hundred msec before the EMG onset. This activity peaked shortly after the EMG onset and it was followed by a rapid reversal of the field direction, forming a second peak at about 100 msec after the EMG onset. A third peak developed at approximately 200 msec after the EMG onset. A schematic representation of a typical MEG waveform recorded over the left temporal region is given with the various components in figure 3 using the nomenclature proposed by Kristeva et al. (1991). The readiness field (RF) corresponds to the slowly increasing magnetic activity preceding the movement onset. This activity peaks soon after the EMG onset, and that peak is known as motor field (MF). A peak of opposite direction at approximately 100 msec after the EMG onset corresponds to the movement evoked field I (MEFI) and the following peak at about 200 msec corresponds to the movement evoked field II (MEFII). Further components after MEFII were also identified, but those waveforms were variable between the two subjects and hence are not discussed in this paper. The peak latencies and the maximum and minimum locations of the corresponding

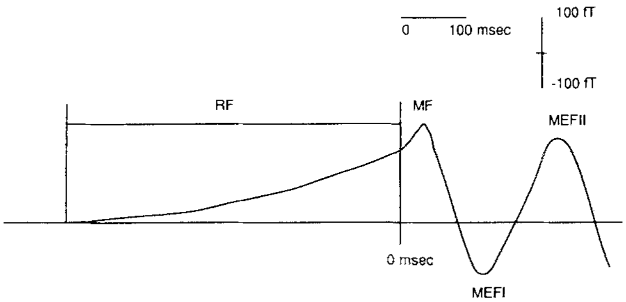

Figure 3. Schematic representation of various components which constitute the movement-related magnetic fields. A slowly rising magnetic activity develops from several hundred msec before the movement onset (readiness field; RF). This activity rapidly increases after the movement onset and peaks at 20-50 msec after the EMG onset (motor field; MF). A rapid reversal in the field direction takes place peaking at 100 msec after the EMG onset (movement evoked field I; MEFI). A further peak develops at approximately 200 msec after the EMG onset (movement evoked field II; MEFII). (Based on Kristeva et al. 1991).

magnetic fields are shown in table I.

Figure 4 shows an overview of the waveform features at various scalp locations in Subject I. During the time interval corresponding to RF, an outward magnetic flux (upgoing activity) was seen over the left temporal area starting several hundred msec before the EMG onset, while an inward flux (downgoing activity) was seen predominantly over the vertex, parietal and right parasagittal areas. Although some outward flux was seen also over the right temporal regions corresponding to this time period, we excluded this area from our further analysis because of the big noise around movement onset, which would probably introduce poor outcome in source localization. At the time of the peak of MF the outgoing flux attained further strength and focality over the left temporal regions. The MEFI showed a topographic distribution quite similar to the MF, but an almost complete field reversal took place at this instant. A further reversal of the magnetic flux took place again between MEFI and MEFII.

The averaged movement-related electrical potentials

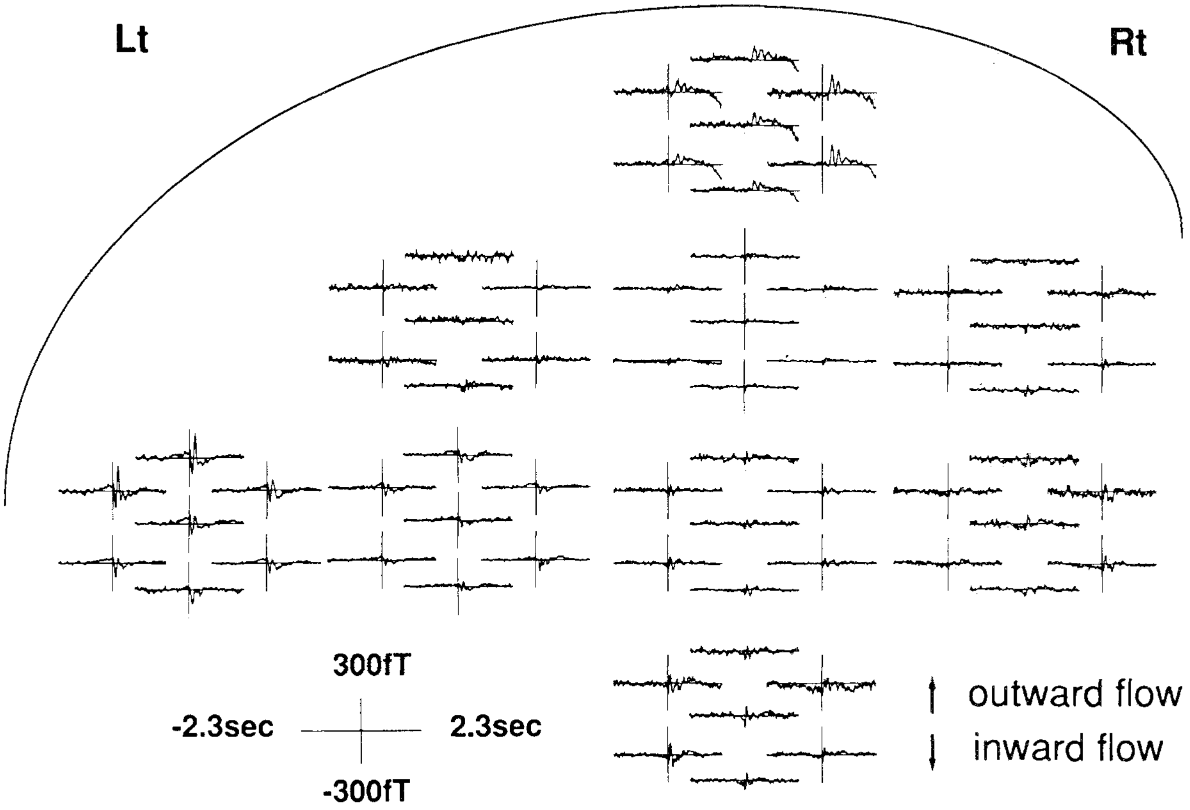

Figure 4. Overview of the averaged MEG waveforms from the 63 sensor locations associated with voluntary, self-paced abduction of the right index finger in Subject I. Several hundred msec before the onset of EMG, an outward slow magnetic flux is seen predominantly on the left temporal area and an inward slow flux on the vertex area (RF). Twenty to 50 msec after the onset of EMG, the outgoing flux makes a prominent peak over the left temporal regions (MF). The almost reversed field distribution can be seen at around 100 msec after the onset of EMG (MEFI), followed by the second reversal at around 200 msec (MEFII).

Table I. Latency, distribution and amplitude of the local maxima and minima of the MRMFs, and those of the peaks of MRCPs in the two subjects.

	SUBJECT I			SUBJECT II		
	Latency (msec)	Position	Amplitude	Latency (msec)	Position	Amplitude
MRMFs						
RF Onset	-500	C4		-600	C1	
		C3			C3	
MF	51	C4	-130 fT	20	C1	-80 fT
		C3	80 fT		C3	150 fT
MEFI	126	C3	-170 fT	106	C3	-360 fT
		CPz	120 fT		FCz	106 fT
MEFII	243	CPz	-120 fT	239	C2	-110 fT
		C3	260 fT		C3	170 fT
MRCPs						
BP onset	-700	Cz		-1350	Cz	
Peak NS′	-65	C3	-4.5 μV	-78	Cz	-5.1 μV
ppMP	62	P3	-3.9 μV	43	C3	-4.7 μV
fpMP	123	Fz-F3	-6.5 μV	96	Fz	-12.4 μV

RF, readiness field; MF, motor field; MEFI, movement evoked field I; MEFII, movement evoked field II;
BP, Bereitschaftspotential; NS′, negative slope; ppMP, parietal peak motor potential;
fpMP, frontal peak motor potential.
MF and MEFI in MRMFs corresponds to ppMP and fpMP in MRCPs, respectively.

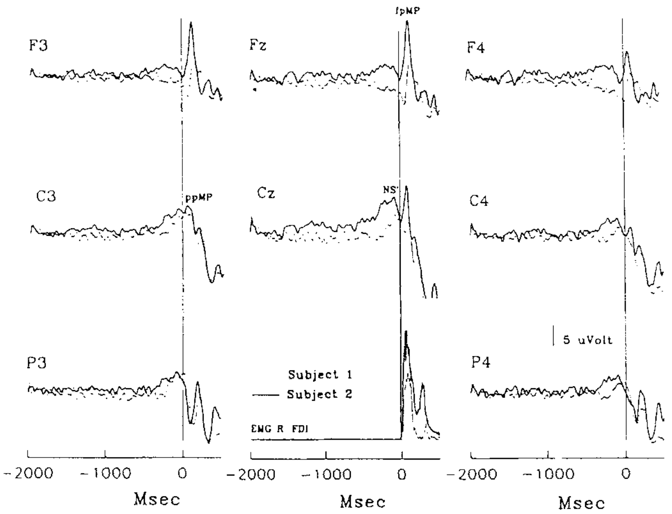

Figure 5. MRCPs from 8 representative electrode positions recorded against a linked-ears reference. Data of the two subjects are superimposed. Each average was generated from 120 artifact-free movements. The peaks of the NS′, ppMP and fpMP are identified. The latencies and amplitudes are shown in table I.

revealed the typical MRCP components as described in earlier studies (Shibasaki et al. 1980; Tarkka and Hallett 1990). Simultaneous recording of 7 channel MRCP with the MRMF and the later recording of 29 channel MRCPs showed quite reproducible waveforms at the corresponding electrodes with peak latencies that differed by less than a few msec. Figure 5 shows the representative waveforms from 8 electrode positions over both hemispheres and midline in the two subjects and identifies the MRCP components with the criteria established by Tarkka and Hallett (1990). Table I gives the peak latency and location of each MRCP component measured based on the 29 channel recording.

The topographic maps of those components are represented in sequence in the isocontour maps of magnetic fields and scalp electric potentials (figures 6 and 7).

The scalp distribution of the electric activity at the instant of -128 msec, which corresponds to the activity close to the beginning of the NS′ component of the MRCP or the early RF in magnetic recordings, showed a widespread surface negativity with maximum

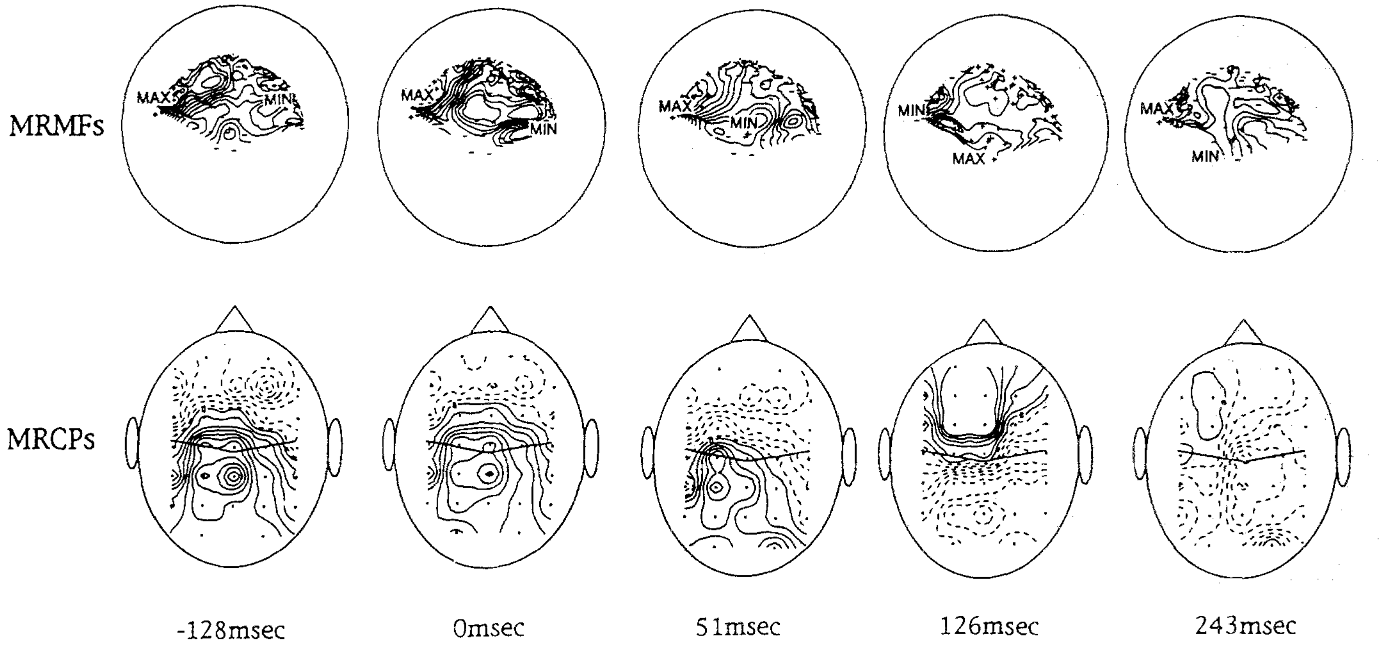

Figure 6. Isocontour maps of the MRMFs and MRCPs viewed from the top of the head in Subject I at the time instant of -128, 0, 51, 126 and 243 msec with respect to the EMG onset, respectively. In MRMF maps, field distributions are shown in 12 grades between maxima and minima. Each contour line in MRCP maps represents a 1 μV step. Broken lines depict positivity and solid lines negativity.

amplitude over the vertex region (figures 6 and 7). At this instant, a low amplitude widespread bifrontal positivity was present in Subject I (figure 6), while the isocontour map of Subject II (figure 7) revealed no anterior positivity. In both subjects, isocontour lines of MRMFs showed a peak with steep slope over the contralateral

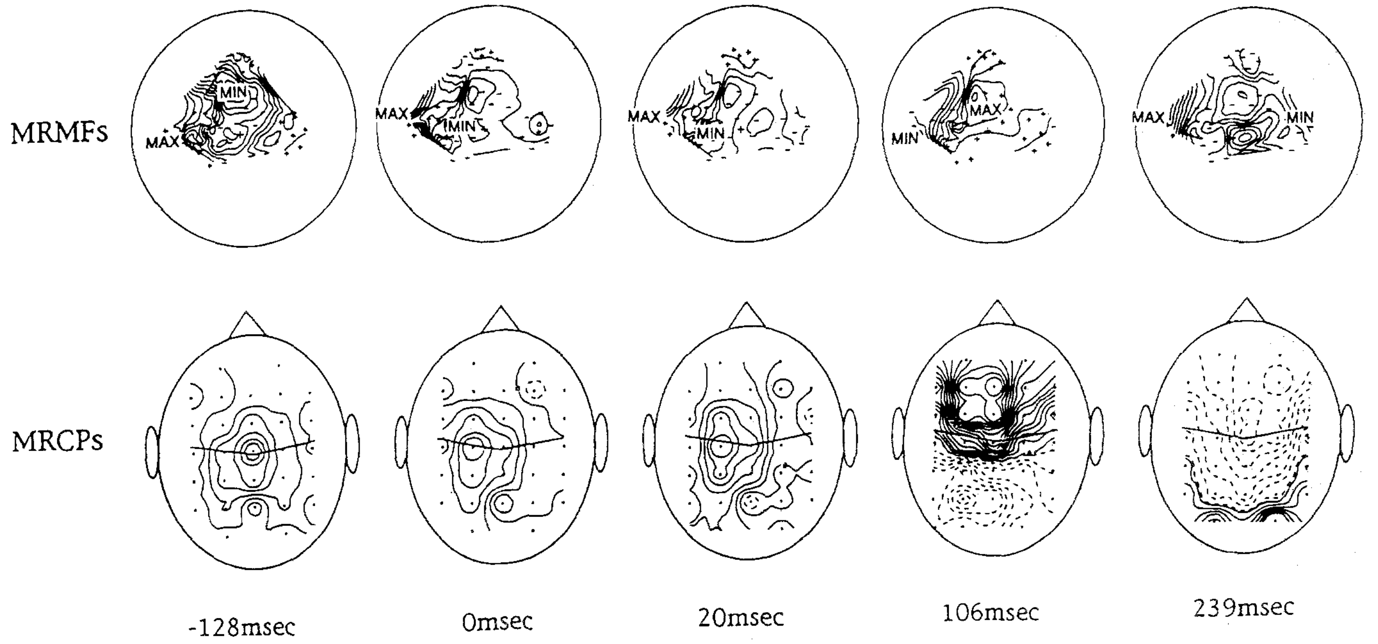

Figure 7. Isocontour maps of the MRMFs and MRCPs viewed from the top of the head in Subject II at the time instant of -128, 0, 20, 106, 239 msec, respectively. Mapping representations are the same as in figure 6.

Table II. Summary of MEG dipole localizations in two subjects.

Subject I					
Latency (msec)	-128	0	51	126	243
x(cm)	-1.13	-0.43	-1.61	-5.52	2.09
y(cm)	1.63	1.80	2.18	6.30	5.34
z(cm)	9.38	9.24	9.04	8.75	10.59
Psi(deg)	61.44	74.91	59.59	-161.6	118.80
Q(nA-m)	3.98	6.07	11.89	21.23	2.88
Rho(cm)	9.59	9.43	9.43	12.11	12.04
Final corr.	.721	.860	.917	.908	.729
Subject II					
Latency (msec)	-128	0	20	106	239
x(cm)	3.90	-2.07	-1.78	-0.18	2.95
y(cm)	7.61	3.48	1.83	2.67	-0.26
z(cm)	8.48	5.19	4.53	8.55	6.27
Psi(deg)	-171.53	13.99	11.75	-115.92	126.61
Q(nA-m)	1.30	43.86	87.11	26.61	25.84
Rho (cm)	12.04	6.59	5.20	8.96	6.94
Final corr.	.856	.943	.941	.933	.694

x, y, z: three Cartesian coordinates of dipole position: x: anteriorly positive, y: leftward positive, z: upward positive.

Psi: dipole orientation measured from the line connecting the center with the dipole position.

Q: size of dipole moment.

Rho: distance between the head origin and the dipole.

Final Corr.: correlation coefficient.

area, which was in contrast with the symmetrical distribution of MRCPs. At this time instant, MRMF showed a relatively widespread distribution as compared with the following peaks. At the time instant equivalent to the latency of the MF in MEG recordings (51 msec in Subject I and 20 msec in Subject II) and the parietal peak motor potential (ppMP) in electric recordings, the scalp activity was characterized by the lateralized surface negativity in electric recording and localized magnetic dipolar representation in the contralateral centro-parietal regions. The EEG activity at the time of MEFI which was also close to the time of the frontal peak motor potential (fpMP) (126 msec in Subject I and 106 msec in Subject II) showed a high amplitude frontal negativity and a posterior positivity with predominance over the midline and contralateral region. The MEFI showed almost the same magnetic field topography, though in an opposite field direction, as the MF with an orientation of the field maxima and minima almost perpendicular to the electrical field. The electrical activity at the time of the MEFII (243 msec in Subject I and 239 msec in Subject II) showed a widespread surface positivity. The magnetic field showed a relatively widespread distribution, although the polarity resembled that of MF.

We applied the source localization program with single dipole model in a single concentric spherical model on several MEG peaks. The positions of the suggested dipoles are expressed in Cartesian coordinates in table II. Correlation values, which gave us the significance of dipole localization, were not high and this would be one of the reasons for the discordance of the dipole position between subjects. Another reason would be the introduction of the assumption of a single dipole. Although the isocontour maps exhibit the existence of the largest dipole around the sensorimotor area at each time latency, additional generators might be playing various roles in each subject and in each time period.

Discussion

The present study demonstrated the presence of well defined waveform components in both magnetic and electric recordings associated with self-paced voluntary finger movements. Simultaneous multichannel recordings of EEG made it possible to compare directly the electromagnetic behavior. The RF was relatively low in amplitude as compared with other components of MRMF recorded in the present study or with the results published in previous reports (Cheyne and Weinberg 1989; Kristeva et al. 1991). This might be explained in part by the high-pass filter setting used in the present study. Nevertheless, the topographic characteristics of this component are well defined and agree with those previously described by others (Cheyne and Weinberg 1989; Kristeva et al. 1991; Chiarenza et al. 1991). The distribution of the magnetic activity over the scalp at the instant of -128 msec showed a maximum outward flux over the contralateral centro-temporal regions and a maximum inward flux over the midline and parasagittal areas, thus locating the source at an equidistant point between these two points over the contralateral central region (figures 6 and 7). The complexity of the magnetic field at this instant, which may be due in part to relatively low signal to noise ratio, suggests that other local fields may be also active simultaneously on the hemisphere ipsilateral to the movement. In contrast, the electric activity at this instant is dominated by a widespread surface negativity with maximum over the vertex region. The comparison between MEG and EEG at this instant provides a further insight into the nature, complexity and location of the underlying generator. It can be postulated from these results that more than one source might be active at this time instant. It appears also true that a significant contribution from radial dipole components may act at this moment as indicated by the widespread surface negativity on the EEG maps.

The present comparison of MEG and EEG recordings also provided a further evidence supporting the separation of the electrical motor potential (MP) component into distinct subcomponents. Based on the topographic and peak latency criteria, Shibasaki et al. (1980) and Tarkka and Hallett (1990) had identified an early peak in the MRCPs following the EMG onset referred to as N-10 component in Shibasaki's terminology or ppMP in Tarkka's nomenclature. The apparent discrepancy in latencies between these two reports arises from different methods to estimate the latencies. While in Shibasaki's nomenclature latencies were measured with respect to the EMG burst peak, the measurements in Tarkka's reports were made with respect to the EMG onset. This component reaches its maximum amplitude over the contralateral centro-parietal scalp regions with the peak occurring at 20 to 50 msec after the EMG onset. The following negative peak occurs over the frontal regions at a latency of approximately 100 msec after the EMG onset known as the N+50 (Shibasaki) or fpMP (Tarkka). These two peaks are often not so clearly separated, especially when a small number of recording sites or a longer time window is used. The close correspondence of the latencies between MF and ppMP and between MEFI and fpMP, respectively, and the opposite field direction on MEG recordings, further support the concept of two distinct events at these two instants following the EMG onset.

Tarkka and Hallett (1990) proposed that the ppMP represented the culmination of motor cortex firing to execute the movement. The topographic distribution of the ppMP over the contralateral centro-parietal electrodes agrees with the topographic distribution of the MF seen in the present and other studies. Furthermore, the previous dipole source analysis of MF (Kristeva et al. 1991; Chiarenza et al. 1991) has identified a strong equivalent source over the contralateral hand motor cortex at this instant. The reorganization in the electric scalp field configuration between the ppMP and the fpMP is paralleled by an inversion in the direction of the magnetic flux over the same time period giving rise to the MEFI. The dipole source analysis (Kristeva et al. 1991; Cheyne and Weinberg 1989; Chiarenza et al. 1991) suggests that the MEFI may originate primarily from activity in the post-central region and it is likely to represent sensory feedback information. Dipole modeling of the MRCPs (Toro et al. 1993) supports this idea but also suggests an additional contribution from structures in the vicinity of the supplementary motor area (SMA) to the activity at the time of the fpMP.

In the present study, the MEG, unlike EEG, showed more complex patterns and distributions of activities commonly with more than one distinct local field maximum and minimum, emphasizing the possibly simultaneous activation of multiple generator sources. This indeed has been supported by dipole modeling of the MRMF which has suggested that the magnetic activity at the times of the RF and MF is best modeled by at least one active source over the central region on each hemisphere. This feature is compatible with the results by subdural recording which showed activation of bilateral primary motor cortices and supplementary motor cortex preceding voluntary finger movement (Neshige et al. 1988; Ikeda et al. 1992). The "simplification" of the scalp EEG fields that most likely results from the conductive properties of the intervening tissues between the source and the electrodes may lead to the suggestion of overly simplistic solutions for the generators of the MRCPs. The use of a larger number of recording channels and special transformations (Gevins et al. 1990; Nunez and Pilgreen 1991), and also the use of head models which incorporate the conductive properties of the brain, skull and scalp may overcome some of these limitations (Scherg et al. 1989).

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