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Somatotopic organization of human somatosensory cortex: a comparison of EEG, MEG and FMRI methods

D. Cheyne[1], L.E. Roberts[2],W Gaetz[2], D. Bosnyak[2], C. Nahmias[3], N. Christoforou[3] and H. Weinberg[1]

'Brain Behaviour Laboratory, Simon Fraser University, Burnaby, British Columbia; [2]Department of Psychology, McMaster University, Hamilton, British Columbia; and [3]Department of Nuclear Medicine, McMaster University, Hamilton, British Columbia, Canada

Abstract. *Background.* This study is an attempt to combine and compare EEG, MEG and functional magnetic resonance imaging (FMRI) methods to map the somatotopic organization of primary somatosensory cortex.

Methods. 32-channel EEG and 143-channel MEG recordings were acquired from two subjects during tactile stimulation of the fingertips. In addition, FMRI activation maps were produced during fingertip vibration and finger movements. Dipole analysis was used to calculate source location and confidence regions for the EEG and MEG responses which were compared to the FMRI activation maps.

Results. The 50 ms response in the averaged EEG and MEG data could be modeled as an equivalent current dipole in the postcentral gyrus with the expected somatotopic organization. 95% confidence regions indicated that sources for individual digits can be discriminated with sufficient signal-to-noise ratio.

Conclusions. The results indicated that the somatotopic organization of the somatosensory cortex can be successfully demonstrated using EEG and MEG responses to mechanical stimulation of individual digits. Initial fMRI results suggest that tactile stimulation does not produce robust responses, whereas passive stimulation produced clear activation patterns in the postcentral gyrus in close proximity to the dipole sources for tactile stimulation.,

Keywords: dipole source analysis, functional neuroimaging, rnechanoreceptors, somatotopy.

Introduction

One of the recent advances in human neuroscience has been the development of noninvasive functional imaging techniques which allow the precise localization of brain activity associated with simple sensory and motor processes. Many recent studies have attempted to combine these various methodologies, both for the purpose of cross-validation of different experimental techniques, and in order to obtain more information about human brain function than may be derived from any method alone. In order to achieve this goal, however, it is necessary to establish methods for the precise combination of these techniques and to test

Address for correspondence: Dr Douglas Cheyne, School of Kinesiology, Simon Fraser University, Burnaby, B.C., Canada V5A 1S6. Tel.: +1-604-941-8561. Fax: +1-604-941-8565.
E-mail: cheyne@sfu.ca

these methods using well-understood neurophysiological phenomena.

It has been shown in previous studies that evoked responses can be elicited by mechanical stimulation of the fingertips. In contrast to responses evoked by electrical stimulation, the earliest large response evoked by tactile stimulation occurs at a latency of about 50 ms, labeled the P50 and P50m in the EEG and MEG, respectively [1-3]. In theory, MEG and EEG measure orthogonal patterns of electric potential and magnetic flux at the scalp surface produced by simple current sources. The observed orthogonality of the respective topographies of the P50 response therefore makes this an ideal component for the comparison of EEG and MEG source modeling methods. In this study, we attempted to map the somatotopic organization of individual fingers in the postcentral gyrus using dipole source analysis applied separately to EEG and MEG evoked responses under similar stimulus conditions in the same subjects. In addition, we attempted to compare these electrophysiological responses to local blood oxygen level dependent (BOLD) changes as indexed by FMRI of the sensorimotor area during vibration of the fingertips, as well as active and passive movements of the same digits.

Methods

High-density EEG recordings were obtained from a grid of 19 electrodes overlying the left sensorimotor area, in addition to 13 distributed electrode sites using a 32-channel EEG system (NeuroScan, Inc.) in two subjects. In a separate recording session, whole-head MEG measurements were made using a 143-channel biomagnetometer system (CTF Systems, Inc.). Stimuli consisted of 5-ms duration pulses applied to the tips of the first, third and fifth digits of the right hand at an interstimulus interval of 750 ms, which produced a light tapping sensation. MEG recordings were obtained in an unshielded environment using software-constructed third-order gradients to reduce background environmental noise [4]. In addition, fMRI data were collected using a GE Signa 1.5T scanner and a spiral sequence (four spirals, TE/TR = 35/640 ms, flip angle = 45°, FOV = 18 cm, in-plane resolution 2.8 mm, matrix 128 x 128) during 3- and 18-Hz vibration of the fingertip as well as active and passive finger movements. Up to eight contiguous, 4-mm thick axial slices were imaged at a slightly oblique angle passing through the sensorimotor region of both hemispheres. For the vibration condition, 10 trials each consisting of 23 s stimulation and 23 s rest were collected for each finger, with fingers fixed in place to prevent movement between and during scans. For the active and passive movement conditions, 2-cm flexions of the digit at 4 Hz were produced either by the same probe used to stimulate the fingertip (passive movement condition) or by the subject (active movement condition) for 18 s followed by 18 s of rest. T maps were created by the subtraction of control (rest) conditions from the activation periods (vibration or movement) after correction for in-plane motion artifacts, and then projected onto two-dimensional fast inversion-recovery (FIR) structural images obtained for each activation slice. In addition, T1-weighted volumetric images were obtained from each subject for coordinate system matching and superposition of dipole sources on anatomical structure.

Single equivalent current dipole source locations were estimated for the P50m response using a spherical conductor model with corrections for nonradial field contributions and for software gradiometer formation. The sphere origin was based on the skull boundaries as shown in the structural MRI which was found to produce the lowest error *(cf.* [2]). EEG source analysis was achieved using a four-shell spherical model based on that of Stok [5] translated by the origin of the MEG sphere to obtain the dipole coordinates for MEG and EEG dipole fits to the same head-based coordinate system. In addition, Monte Carlo simulations were performed to obtain 95% confidence ellipsoid surfaces [6], using the average noise level of the prestimulus data which were projected onto the volumetric MRI images for each dipole source.

Results

Figure 1A shows representative waveforms for EEG and MEG responses to mechanical stimulation of the right thumb in one subject. The P50 and N70 responses can be seen clearly in the EEG data which correspond to a large field reversal at 50 ms in the MEG followed by a smaller reversal at 70 ms. As shown in Fig. 1B, both the EEG and MEG data show dipolar field reversals over the contralateral (left) central scalp at a latency of 50 ms (P50). These patterns were always dipolar with orthogonal orientations, suggesting a tangential anterior-posterior directed current source consistent with polarization of the wall of the postcentral gyrus. In contrast, a monopolar pattern was observed for the N70

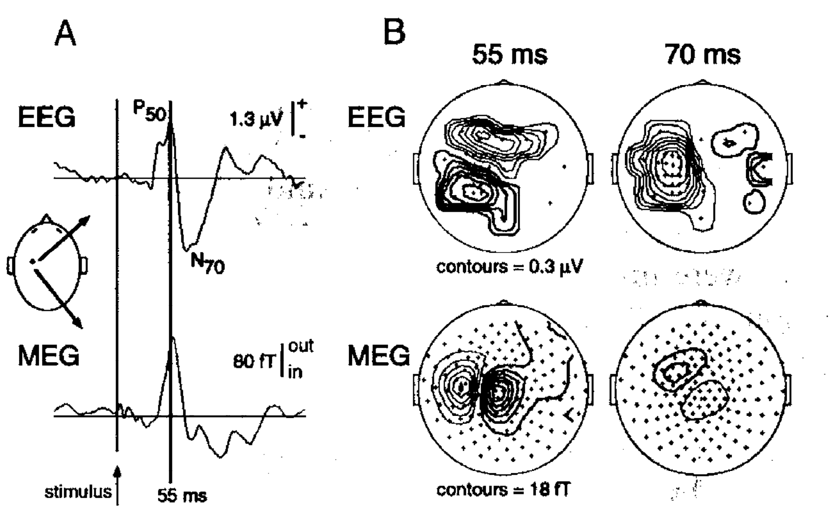

Fig. 1. **A:** EEG (top) and MEG (bottom) averaged responses for tactile stimulation in one subject, recorded over the left central scalp. Note the large response in both waveforms at approximately 55 ms. **B:** Vertex projection (nose upward) isocontour maps for EEG (top) and MEG (bottom) at 55 and 70 ms latencies. Thick contours indicate positive potential and ingoing flux, and thin contours indicate negative potential and outgoing flux.

with a weak or absent response in the MEG suggesting a predominantly radially oriented source.

Dipole locations showed similar locations for both the P50 and P50m with a somatotopic distribution along the postcentral gyrus for different digits as shown for the EEG sources in one subject in Fig. 2. Average separation between first and fifth digits for both MEG and EEG dipoles in both subjects was approximately 6 mm and 95% confidence regions calculated for each source indicated maximum localization errors ranging from 3 to 8 mm, these values being highly dependent on response amplitude which varied across subjects and different fingers. Thus, for cases where response amplitudes were sufficiently large, the 95% confidence regions of the sources for individual digits could be clearly separated. Discrepancies between dipole locations for MEG and EEG did not reflect an overall constant error in coordinate system translation, but rather variability of dipole location for each method alone.

For the analysis of the FMRI data, images for stimulation and rest (baseline) conditions were corrected for in-plane motion and then subtracted to produce T test maps for each finger condition. These images were projected onto the appropriate FIR anatomical image. In the subjects tested, no significant activation patterns were observed for 3- or 18-Hz finger vibration in the region of the postcentral gyrus. However, passive flexions of a single digit showed focal activation in the region of the hand area of postcentral gyrus (Fig. 3, right), whereas voluntary finger movements of the same digit showed increased activation in both pre- and postcentral cortex (Fig. 3, left).

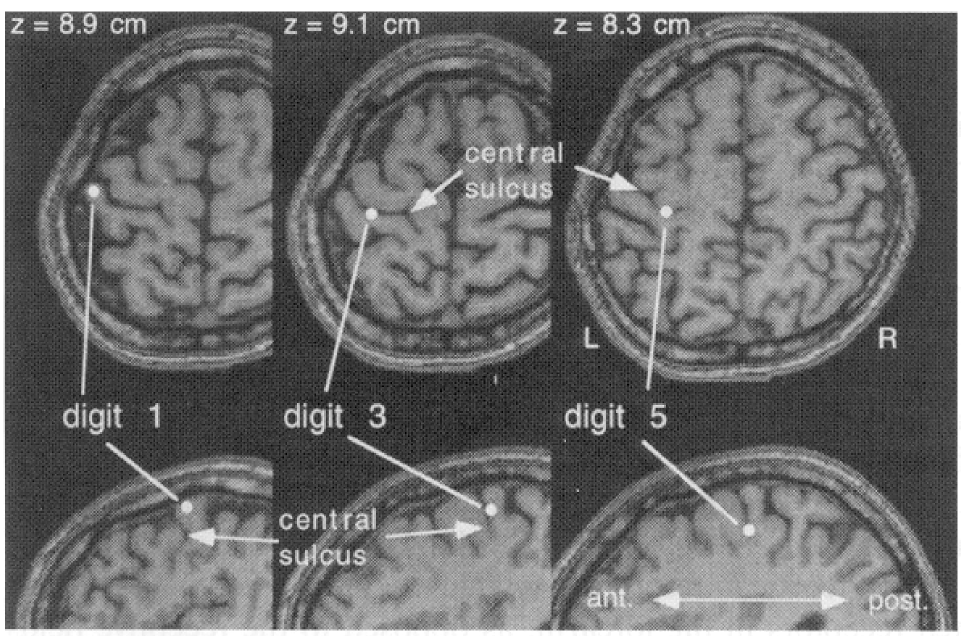

Fig. 2. Dipole source locations projected onto TI -weighted axial (upper) and sagittal (lower) MRI slices for the first, third and fifth digit stimulation conditions. Note that the source for digit 5 is medial but inferior to the source for digit 1.

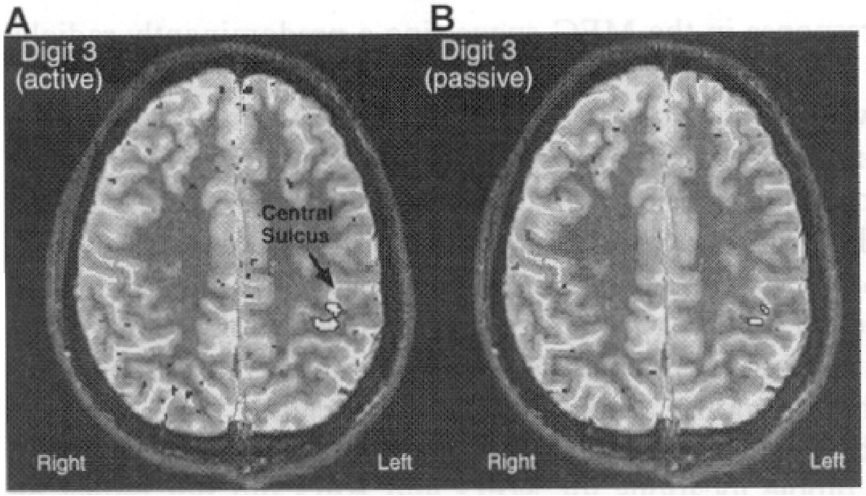

Fig. 3. T maps produced by subtraction of rest from activation conditions projected onto fast inversion recovery MRI slices for active third digit flexion (left panel) and passive third digit flexion (right panel) conditions in the same subject. Areas of significant activation are shown as white areas outlined in black and correspond to T values exceeding 6.0 (left panel) or 4.5 (right panel) where $P<0.001$.

Discussion

The results of this study indicated that the somatotopic organization of the somatosensory cortex can be successfully demonstrated using EEG and MEG responses to mechanical stimulation of individual digits. Overall separation for digits of the hand was about 6 mm which is consistent with the observations of Buchner et al. [7], who were able to model the N20-P20 evoked response to electrical digit stimulation as a tangential source in SI. In our study, source locations projected onto a region of the postcentral gyrus are immediately posterior to the hand region of the precentral gyrus as identified by anatomical landmarks [8]. Remaining discrepancies between EEG and MEG results may indicate separate sources of error for each method, such as head movement, errors in projection of electrode position and differences in sampling density (32 EEG vs. 143 MEG), or errors introduced by the use of a spherical conductor model. Further studies are required to identify and eliminate these remaining sources of error.

Our initial FMRI results indicated that tactile stimulation does not produce robust activation patterns in SI, making it difficult to compare metabolic changes to tactile stimulation with dipole source locations. Passive finger flexions most likely activate different neuronal populations in SI (i.e., neurons receiving proprioceptive input located in Brodmann's area 3a in comparison to those neurons receiving input from mechanoreceptors in area 3b). Thus, passive movement of the fingers may reflect cortical responses related to proprioceptive feedback from muscle stretch receptors in the forearm, as opposed to the receptive fields in the hand (*cf.* [9]). Nevertheless, the fMRI T maps indicated activation in the postcentral gyrus during passive finger flexions in close proximity to dipole sources for tactile stimulation. It is interesting that a similar region in the postcentral gyrus shows activation during active movements of the same finger. This is similar to the results reported by Gerloff et al. [10] and supports recent evidence that sensory feedback during voluntary movements involves input from muscle stretch receptors in the periphery to SI [11] which may also be elicited during passive finger movements. Whether these responses will also show somatotopic organization similar to that for tactile stimulation requires further study.

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