BRAIN STRUCTURES RELATED TO VIBROTACTILE STIMULATION OF THE SOLE OF THE FOOT IN MAN: A FUNCTIONAL MAGNETIC RESONANCE IMAGING STUDY

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INTRODUCTION

Continuous evolution and progress of functional magnetic resonance imaging (fMRI) as well as its increasing popularity and spreading in clinical use as a highly sensitive diagnostic neuroimaging instrument suitable for the assessment of a large variety of neurological and neurosurgical indications makes additional research - in particular with respect to the investigation of its neurophysiological basics - necessary and an interesting subject to study.

Studies using active motor paradigms such as finger-to-thumb tapping or fist clenching [Golaszewski et al. 1998, Cao et al. 1998] are difficult to perform in case of impaired motor functions for example hemiparesis or hemiplegia. Sensory stimulation does not require the collaboration of the subject under examination. Sensory stimulation utilizing vibration has been performed in some studies [Fox et al. 1987, Seitz et al. 1992, Golaszewski et al. 2002a, Golaszewski et al. 2002b] and has shown that vibratory stimulation activates the sensory as well as the motor cortex.

The first aim of our study was to implement a vibratory stimulation device within the environment of the MR-scanner. We designed and implemented a moving magnet force call actuator system within the MR environment which operates within a range from 1 to 130 Hz and a vibration amplitude from 0.25 mm up to 4 mm and which does not interfere with the MR high frequency system or does not cause susceptibility artifacts. The second aim was to map in detail cerebral structures that exhibited changes of the BOLD response dur-

ing application of the newly implemented vibration device to the sole of the foot using a stimulus frequency of 50 Hz and a displacement of 1 mm. Therefore, a proper vibrotactile stimulus was developed and the elicited brain activation pattern was analyzed with regard to the applicability in clinical functional diagnosis of patients with neurological deficits.

MATERIALS AND METHODS

Ten healthy, male volunteers with dominance of the right foot without any history of neurological, psychiatric or internal disorders participated in this study. A complete experimental run consisted of two fMRI measurements. In the first run, subjects were asked to perform foot-tapping (on/off motor paradigm, FTP) with the right foot with a self-paced frequency of about 2 Hz. The second fMRI measurement using the 50 Hz vibrations paradigm (VPD) was carried out, keeping the indenter of the vibrator attached to the sole of the right foot above the basic joint of digit I of the foot with a contact force of 0.05 N to the skin surface. The contact area of the skin surface and the indenter was circular and exactly 0.5 cm^2. The Moving Magnet Actuator System (MMAS) set up to work in the MRI environment consists of one or two intender-vibrators (Fig.1, 2) mounted on adjustable stands (Type SG-MU, Tekusa Inc.), a control box (analog, power electronics and AD/DA-converters), a master and a slave-PC. The stimulator was tested to elicit tonic vibration reflexes in the right flexor hallucis longus (detected by surface EMG) and to evoke cortical responses from the sole of the right foot. To elicit tonic vibration reflexes (deep muscle receptors) relative high indentation forces (> 20 N) at rather low vibration frequencies (30 – 60 Hz) were necessary. To evoke contra- and ipsilateral responses in the sensorimotor cortex rather low indentation forces at high vibration frequencies gave the best result.
All experiments were performed on a 1.5 Tesla whole body scanner (Magnetom VISION, Siemens, Germany) with an echo-planar capable gradient system and a circular polarized head coil. For fMRI, we employed T2* weighted single shot echo-planar sequences. Image analysis was performed offline on a workstation using Matlab and SPM99 (The Welcome Department of Cognitive Neurology, http://www.fil.ion.bpmf.ac.uk.). A design matrix was defined comprising contrasts testing for significant activations during foot tapping and during vibration.

RESULTS

FMRI group data for the FTP showed: 1. Brain activity contralateral to the tapping foot within the primary sensorimotor cortex within the precentral gyrus (GPrC) and the postcentral gyrus (GPoC, SM1, Brodmann Area BA 4, 3 and 2), 2. bilateral brain activity medially within the superior frontal gyrus within the supplementary motor cortex (GFs, SMA, BA 6).
The VPD led to the following cortical activation pattern within the group analysis of the ten subjects (Fig.3): 1. Bilaterally within the secondary somatosensory cortex located in the inferior parietal lobule of the secondary somatosensory cortex (LPi, BA 40), 2. contralaterally to the stimulated side within the primary sensorimotor cortex SM1 located in the pre- and postcentral gyrus (BA 4), 3. bilateral brain activation medially within the superior frontal gyrus within the supplementary motor cortex (GFs, SMA, BA 6) and 4. on the right hemisphere ipsilateral to the stimulated foot within the anterior cingulate gyrus (BA 32). Single subject analysis does not show constantly the brain activation pattern for the group.

DISCUSSION

This paper describes an fMRI compatible stimulator designed for mapping of the sole region. In order to elicit selective responses from different mechanoreceptor types, the stimulator was designed for independent control of indentation force, vibration amplitude and vibration frequency. This precisely controllable stimulator, based on a moving-magnet, covers a wide application range in neurophysiological testing. As the stimulator works without electrical commutation it is well suited for the MR environment to obtain lower limb cortical representations. Using a vibration paradigm of 50 Hz and 1 mm displacement amplitude leads to activation not only in the sensory cortex but also causes activation in the motor cortex via the tonic vibratory reflex. These results hold promise that the VPD can be employed for functional diagnosis in patients unable to perform an active motor paradigm.

With the new vibration device we could show cortical activations during fMRI in sensory as well as in motor cortical areas. Within the somatosensory cortex we especially observed brain activation in area 3a which can be explained by the fact that area 3a receives input from deep and propriozeptive receptors [Moore et al. 2000, Iwamura et al. 1993, Ibanez et al. 1989, Maldjian et al. 1999, Recanzone et al. 1992]. In our results, the fMRI response in the primary motor cortex is of major interest because the vibrotactile stimulus is a somatosensory stimulus, which does not require the collaboration of the subject under examination. In our series all volunteers showed contralateral SM1 activation during the foot-tapping paradigm. The activation contralateral within the SM1 could be found by group analysis of the VPD, but was not so robust in single subject analysis of the VPD. This is in agreement with a previous study about somatosensory evoked potentials, which showed a broader tuning function during vibration of the sole of the foot in comparison to the hand [Tobimatsu et al. 2000]. The cortical activation of motor areas during VPD is presumably based on the simultaneous stimulation of cutaneous receptors and muscle spindles, which requires sufficient displacement amplitudes and vibration frequencies.

In the present study the contralateral SM1 area is not so constantly seen as the bilateral SII response, which can be explained with a study from Tommerdahl [Tommerdahl et al., 1999a und 1999b]. He could show in cats, which have a similar architecture of the somatosensory cortex as human beings, that a vibrotactile stimulus with 25 Hz could constantly activate the contralateral SI and bilaterally SII. With higher frequencies, the contralateral SI response became shorter, followed by a longer lasting deactivation. At the other hand, the bilateral SII response increased with increasing frequency of the vibrotactile stimulus.

Preliminary results with a frequency of 25 Hz could already show a more robust cortical response within the contralateral SM1 area of the foot with the lower frequency than with the higher frequency of 50 Hz in concordance with the results of Tommerdahl. Thus, the vibration parameters (vibration frequency, vibration amplitude, modulation frequency) should be chosen according to the diagnostic information one expects. Therefore, for probing the nature and function of SII a higher frequency beyond 50 Hz of a vibrotactile stimulus can provide a more sensitive assay than a lower frequency, whereas for the probing of SI a lower frequency should be chosen in the order of 25 Hz. In further studies it is planned to test the response characteristics of the cerebral cortex to a modulation of the frequency and the amplitude of the vibrotactile stimulus.

CONCLUSION

The described results are in concordance with the neurophysiological literature. The developed stimulus for vibrotactile stimulation of the sole of the foot elicits brain activity contralaterally within the SM1 area and bilaterally within the SII. Furthermore, bilateral brain activity could be detected within the supplementary motor cortex and ipsilaterally with the anterior cingulate gyrus. Thus, the applied vibrotactile stimulus elicits brain activity in main centers of the sensorimotor cortex, a fact, that holds promise for wide applicability functional diagnosis of the brain. Further studies are needed for the optimization of the vibration parameters for improving of the intra- und interindividual reproducibility of the results and to elaborate optimized vibration parameters for probing the nature and function of different brain regions of the sensorimotor cortex. The modulation of the vibration parameters should be an important step for the development of the vibrotactile stimulus in functional diagnosis of the brain because the primarily addressed peripheral receptors (Meissner's and Pacinian) are belonging to the class of the rapidly adapting receptors. These receptors respond to the detection of a specific stimulus with a maximum frequency of centrally transmitted action potentials but this frequency adapts very rapidly to lower rates with consecutive reduction of the rCBF within the specific brain regions and maybe below statistical significance within the corresponding brain map. Through a modulation of the parameters of the vibrotactile stimulus these receptors can be stimulated permanently and should therefore cause a constant cortical response within the somatosensory cortex. There could be several clinical applications for the fMRI vibration paradigm. VPD could be used to optimize vibration stimulus pattern presented to the brain for training propriozeption in mircogravity or during long immobilisation of patients to prevent muscle weakness and muscle atrophy in space disease respectively bedrest syndrome. Further applicability can be expected for the functional diagnosis in neurology especially for patients with stroke, brain trauma, spinal cord injury or the appalic syndrome.

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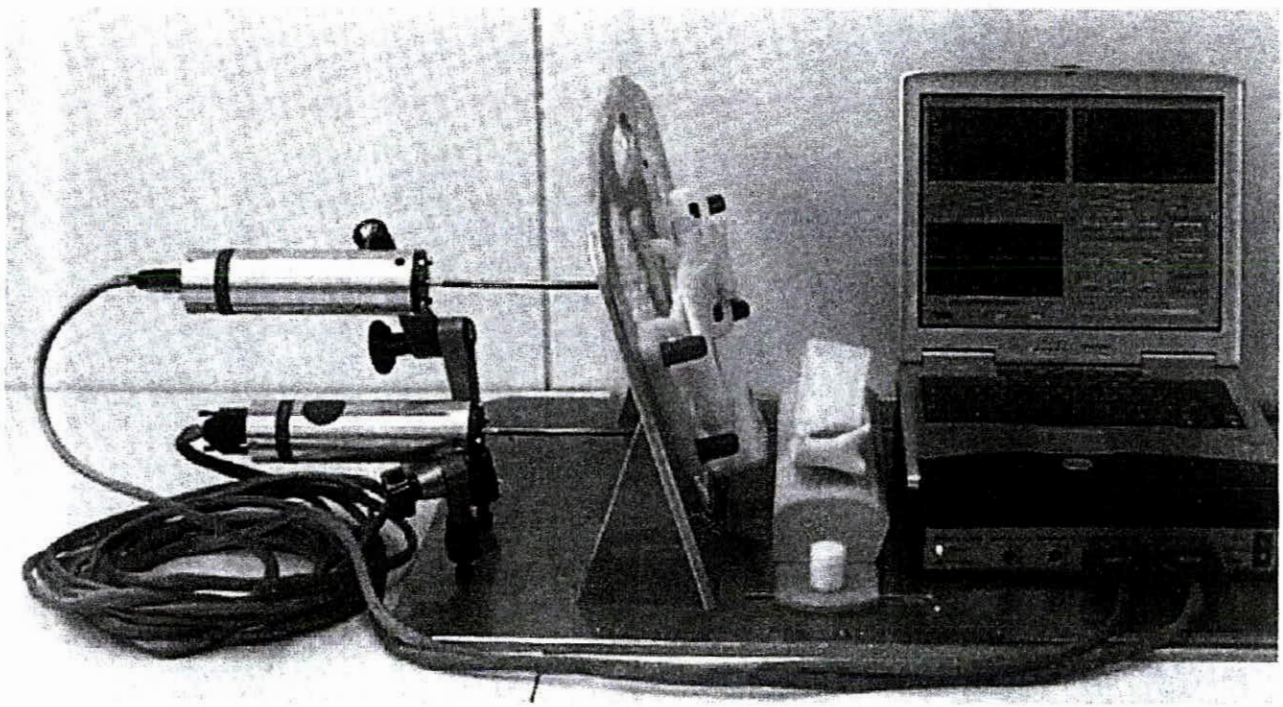

Fig. 1: Moving Magnet Actuator System (MMAS) consists of two intender-vibrators mounted on adjustable stands, a control box and a master and a slave-PC

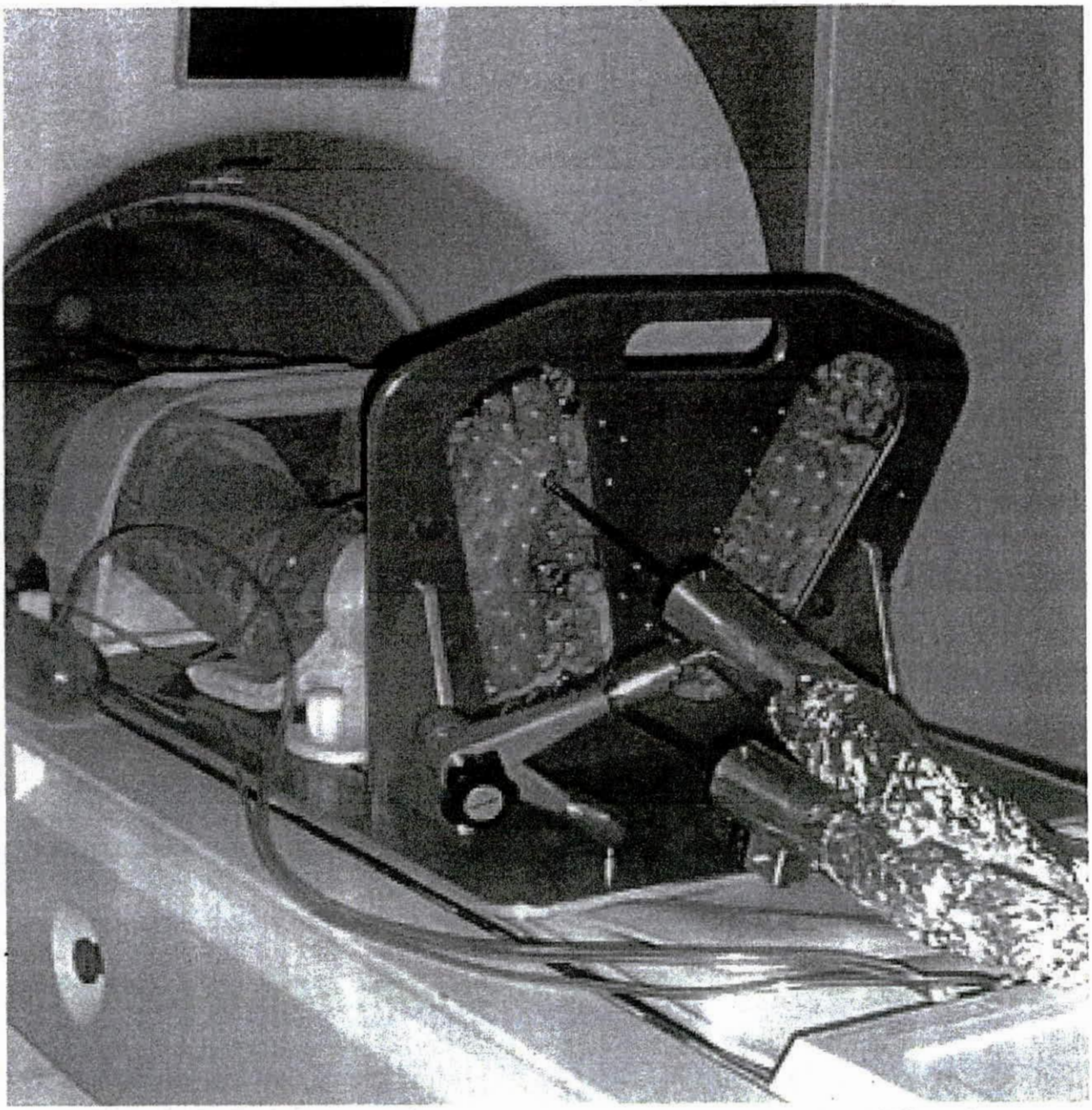

Fig. 2: Moving Magnet Actuator System (MMAS) set up to work in the MRI environment

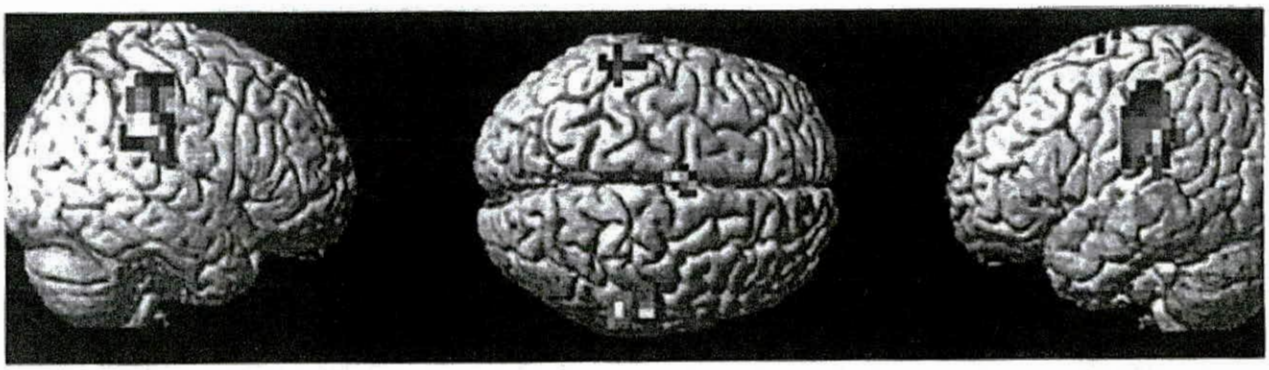

Fig. 3: 3D surface rendering of brain function during the vibration paradigm: Within group analyses in 10 subjects.

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von Ekaterina Kochueva (Herausgeber), Nick Kochuev (Herausgeber)

Andere Formate und Ausgaben ausblenden

	Preis	Neu ab	Gebraucht ab
Taschenbuch, November 2003	—	—	—