High Resolution Functional Mapping of Primary Motor Cortex and Primary Somatosensory Cortex in Humans at 7 T

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Introduction: The primary motor cortex M1 and primary somatosensory cortex S1 have been intensively studied in human brain, using fMRI for nearly two decades [1]. At 3 Tesla and below, fMRI results already enable parcellation of the sensorimotor cortex in its main regions [2] and a rough somatotopic mapping of M1 [3] and S1 [4]. However, an unambiguous differentiation between M1 and S1 may already fail due to partial volume effects. A deeper look into the functional organization of the M1/S1 area, which covers the precentral and postcentral gyri, clearly requires functional imaging sequences with higher resolution. At 7 Tesla, isotropic resolution of 1 mm can be used for examining the M1/S1 complex [5]. Furthermore since M1 cortex is about 3 to 4 mm thick [6], voxels smaller than 1 mm might enable a functional parcellation of different cortex layers. Therefore, the goal of this study was to functionally differentiate between M1 and S1 and to detect activations dependent on the laminar position within primary motor cortex, by means of the high resolution functional mapping that is feasible at 7T. Our fMRI paradigm involved imagining finger movement, "classical" finger tapping, and movement of the fingers without touching the finger tips. The rationale behind the paradigm was twofold: Firstly, although input and output projections anatomically share the same layers within M1 [7], a functional layer differentiation might be possible due to different processing of imagining versus executing finger movements. A study showing laminar activation in primary visual cortex V1 was recently published by Polimeni et al [8]. Those results demonstrate the potential of fMRI for non-invasive detection of layer-specific function. However, the role of M1 in motor imagery is still under debate [9]. Secondly, finger tapping with touching the finger tips should show more activation in S1 than finger movement without touching.

Method: All experiments were performed on a 7 T whole-body MR scanner (MAGNETOM 7T, Siemens Healthcare, Erlangen, Germany) using a 24 channel phased array coil (Nova Medical Inc, Wilmington MA, USA). The study was carried out with ethical approval from the local university, and informed consent was obtained from the 10 subjects. In order to identify the M1/S1 area a whole-brain T_1-weighted data set was acquired prior to the functional experiment. For fMRI, 17 to 31 axial EPI slices (dependent on subject-specific SAR limit) were placed at the position of the "hand knob". In order to achieve an isotropic resolution of (0.75 mm)³ a combination of outer volume suppression and parallel imaging (iPAT = 3) was utilized [10]. The other sequence parameters were: TR = 3.3 s; TE = 25 ms; FA = 80°. Finally, a phase map was acquired (FLASH: TR = 1.06 s; TE = 17.3 ms; FA = 55°; voxel size: 0.3 x 0.3 x 0.75 mm³) exploiting the high contrast provided by this method, especially in the M1/S1 area [11]. For the fMRI experiment a stimulus paradigm consisting of 4 conditions was used: no finger movement (rest); no finger movement but imagining finger movement (imagining); "classical" finger tapping (tapping); movement of the fingers without touching the finger tips (movement). Each block consisted of 8 TR's and was repeated 15 times, respectively, resulting in 480 time steps. The LIPSIA software package was used for data analysis [12]. No spatial smoothing was applied. The activation maps were corrected for multiple comparisons using FDR with $p < 0.05$ and overlaid on the mean EPI image.

Results: Figure 1 shows an enlarged section of the acquired axial phase map containing the central sulcus. Voxel positions for fMRI time series determination are indicated (see Fig. 3). In Fig. 2 activation maps of the same subject as in Fig. 1 are shown. It can be seen that imagining the finger movement indisputably activates M1 (Fig. 2A). With actual finger movement (but without touching the finger tips) the activation of M1 is stronger and occupies a thicker proportion of the cortex (Fig. 2B). Only a few voxels in S1 are significantly activated. A similar amount of M1 cortex is activated while performing finger tapping with finger tip touching. However, as predicted, a larger proportion of S1 shows significant activation (Fig. 2C). Figure 3 shows the time course of the 4 conditions, averaged over the whole experiment, of 2 different voxels (position indicated in Fig. 1). The first voxel was located about halfway across the cortical layers. The time course suggests that this voxel is already activated during the pure imagination of finger movement. The voxel next to the pial surface becomes strongly activated only when the finger tapping is executed.

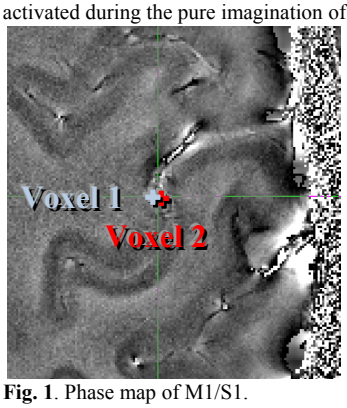

Fig. 1. Phase map of M1/S1.

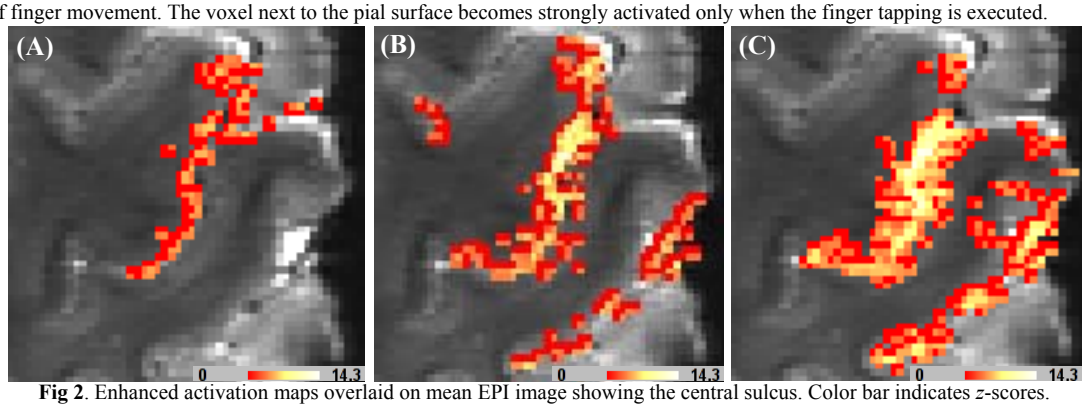

Fig 2. Enhanced activation maps overlaid on mean EPI image showing the central sulcus. Color bar indicates *z*-scores. **A**: Imagining (no finger movement) versus rest. **B**: Movement (no finger touching) versus rest. **C**: Tapping versus rest.

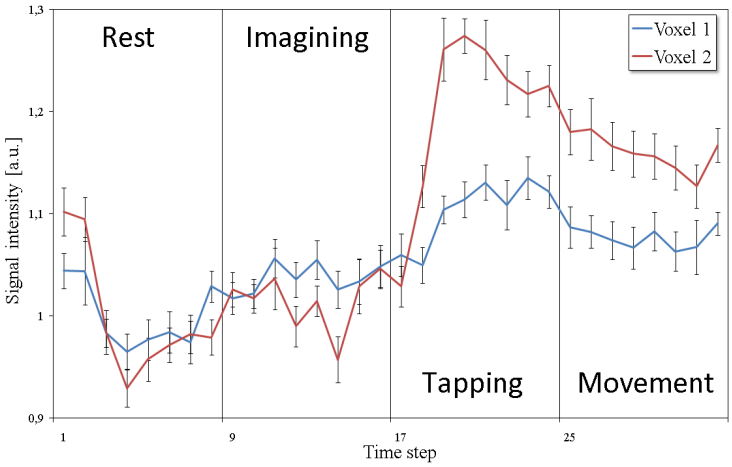

Fig 3. Time course of voxel 1 and 2 (Fig. 1) normalized to the baseline signal.

Discussion and Conclusion: The study demonstrates the feasibility of functional mapping of the M1/S1 complex in humans with isotropic voxels of (0.75 mm)³. The SNR required to perform fMRI at this resolution was provided by the high magnetic field strength of 7 T and the use of a high quality phased-array RF receive coil. Use of voxels in the sub-millimeter range dramatically decreases partial volume effects, and therefore enables a clearer functional differentiation between M1 and S1. Furthermore, activation dependent on the laminar position across M1 cortex was found with the approach described. The question, whether the behavior is caused by functional differences in the distinct laminae of M1 or by other reasons (e.g., vicinity of draining vein, see Fig. 1) needs to be addressed in further studies. However, our approach shows the feasibility of probing M1/S1 on an intra-cortical level.

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