High spatial resolution fMRI mapping of digit topography and the funneling illusion in SI cortex of the anesthetized squirrel monkey

G. H. Turner[1], L. M. Chen[2], R. M. Friedman[2], J. C. Gore[1], A. W. Roe[2], M. J. Avison[1]

[1]Institute of Imaging Science, Vanderbilt University, Nashville, TN, United States, [2]Psychology, Vanderbilt University, Nashville, TN, United States

Introduction

Intrinsic signal optical imaging can be used to map cortical activations with high spatial and temporal resolutions (2,3). However optical imaging is limited by the requirement that the cortical areas of interest must be accessible, and by the need for surgery to gain access. In contrast, fMRI is non-invasive and can detect signals from cortical and subcortical areas that are inaccessible to optical imaging, but with reduced spatial and temporal resolutions. At the higher field strengths now available for fMRI these limitations are less severe, but there have been few demonstrations that fMRI can reproduce the types of high resolution information obtainable from optical methods. In the present study we have used high field BOLD fMRI to map somatosensory cortex in anesthetized squirrel monkeys. As a test of the ability of high field fMRI to achieve high spatial resolution, we examined whether fMRI could map the neural correlates of the tactile funneling illusion in SI. The tactile funneling illusion is the perception of a single focal sensation at the center of simultaneously applied stimulation sites on the skin [1]; as if the stimuli from these sites are "funneled" to the central site, an illusory sensation at the central site is perceived even if no stimulus is applied to that site. Previously, intrinsic signal optical imaging studies revealed activation patterns in SI cortex of squirrel monkeys consistent with this percept [2, 3]: simultaneous stimulation of two adjacent digit tips (e.g. digits 3 and 4) produced a focal activation in between the topographic locations of either digit alone. This neural correlate could be observed only with submillimeter spatial resolution. A second goal was to examine whether two somatotopic maps in adjacent cortical areas within SI (Area 3b and Area 1) could be resolved. Since digit tip maps are reflected across the Area 3b/Area 1 border, resolving these adjacent maps also requires high spatial resolution. In this study, we have examined whether high field fMRI methods could reveal such activation patterns.

Methods

Squirrel monkeys were scanned on a Varian 9.4T narrow-bore scanner with a 3cm surface coil secured above the left SI. Animals were artificially ventilated on a mixture of N_2O and O_2 (70:30) and isoflurane anesthesia (.75-1% during functional scans). Heart rate, $ETCO_2$, spO_2, and temperature were monitored and maintained at normal physiological levels. T2*-weighted anatomic images were acquired using a fast gradient echo sequence (TR=200ms, TE=8ms, 40x40x2 mm, 256x256 matrix) on an oblique plane along the surface of the somatosensory cortex. Functional images were acquired along the same plane using a GE-EPI sequence (TR=1.5s, TE=16ms, 40x40x2 mm, 64x64 matrix). Tactile stimuli applied to individual digits consisted of rounded plastic probes (1 mm diameter) attached to a piezoelectric stimulator (30 ms pulses at 6 Hz in blocks of 30s on and 30s off). All procedures were approved by the Institutional Animal Care and Use Committee at Vanderbilt University.

The correlation to a reference waveform was calculated for each time-course and a threshold was set at $P<1X10^{-5}$. Spatial locations of activations for each individual digit and paired digits were compared. The degree of spatial shift in the activation location of two digit stimulation was calculated using a merging index (MI) [3]. The MI ranges from -1 (center of one digit) to zero (central point between two digits) to 1 (center of adjacent digit). The center of activation for the two-digit stimulation can shift toward the center of the MI scale ($|MI|<1$) or away from the center ($|MI|>1$).

Results and Discussion

Stimulation of individual digits (digit 3: D3, digit 4: D4) generated a somatotopic map consistent with previous optical imaging and electrophysiological studies. These consisted of focal activations of ~1 mm diameter in Area 3b of SI (see Fig 1). Distinct activations of adjacent digits (D3 and D4) separated by ~1 mm were clearly visible (compare Figs 1B and 1F). In some cases, a separate activation in Area 1 was resolvable (see Fig 1D and F). Furthermore, simultaneous stimulation of D3 and D4 (Fig 1D) produced a single mm-sized activation central to the locations of D3 alone (Fig 1B) and D4 alone (Fig 1F) stimulation. The spatial shift of the two-digit stimulation was resolved, with a merging index for this site of 0.53, in excellent agreement with that measured by optical imaging (MI = 0.54±0.13) [3].

These data confirm that high field fMRI can be used to resolve somatosensory activation with submillimeter accuracy in SI. Single digit topographic organization was resolvable both within single cortical areas and between two adjacent cortical areas (Area 3b and Area 1). Moreover, our fMRI images of the funneling illusion are in excellent agreement with recent optical imaging studies: simultaneous digit tip stimulation produces a submillimeter-sized activation shift. These results clearly demonstrate the capability of high field fMRI to visualize activation at the submilliter scale.

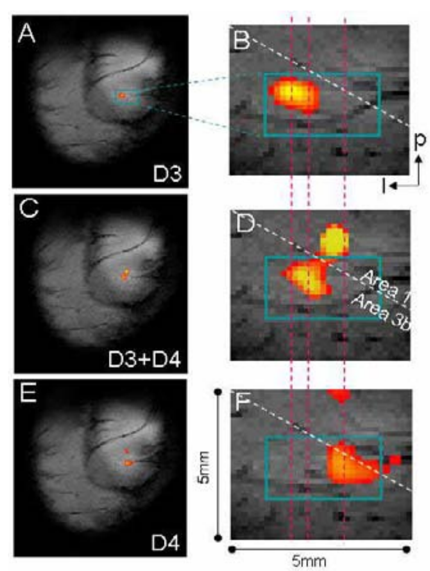

Figure 1. Functional maps of area SI during stimulation of digit D3 (A, B), digits D3+D4 (C, D), and digit D4 (E, F). B, D, F are expanded views of 5x5mm window over area 3b (blue outline in A shown expanded in B). Stimulation of individual digits and paired digits produce single focal activations in area 3b. D3+D4 activation (D) falls between D3 alone (B) and D4 alone (F) activations, with a MI=0.53 (activation centers indicated by red dashed lines).

References

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