Cortical Depth-related Functional R2 and R2* Changes at 9.4 T

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ABSTRACT

To examine cortical depth-related signal changes of gradient-echo (GE) and spin-echo (SE) blood oxygenation level dependent (BOLD) fMRI signals, a well-established cat visual stimulation model was used at 9.4T. The stimulation-induced ΔR2' (= ΔR2* - ΔR2) is closely related with the basal susceptibility effects. The ratio of ΔR2* to ΔR2 is also closely related to basal susceptibility effects. The averaged ratio of ΔR2* to ΔR2 is 8.8 ± 1.7 (n = 4) on the surface of the cortex with large pial draining vessels and decreases to 1.9 ± 0.1 on the middle cortical areas with parenchymal microvessels.

INTRODUCTION

The GE BOLD signal is dependent on static inhomogeneous magnetic fields induced by deoxyhemoglobin, while the SE BOLD signal is dependent on irreversible dynamic diffusion-related averaging in inhomogeneous fields. At a higher magnetic field, it is expected that diffusion-related signal averaging is more sensitive due to steeper field gradients (1-3). The ratio of R_2* to R_2 changes is expected to decrease at smaller size vessels, and at higher magnetic fields if the small-size vessel contribution increases. Therefore, it is important to compare R_2 and R_2* changes and their spatial specificity for understanding signal sources of the BOLD signals. In this abstract, the functional R_2* to R_2 changes of the SE BOLD and GE BOLD signals were compared at 9.4T.

METHODS

Cats (n = 4) were intubated and ventilated under ~1.3% isoflurane. End-tidal CO_2 (3.0-3.8%) and temperature were maintained under normal conditions. The binocular visual stimuli consisted of high-contrast, drifting square-wave gratings (0.15 cycle/degree, 2 cycles/s) of vertical orientation (4-5). All NMR measurements were performed on a 9.4T/31cm MR system. For GE BOLD fMRI, TE = 10, 15, 20, and 25 ms, TR for a single image = 0.5 s, and effective TR = 2.0 s. For SE BOLD fMRI, the double-echo EPI sequence with adiabatic pulses (6) was used. The spin-echo BOLD imaging parameters were: TE = 30, 40, and 50 ms, TR for a single image = 2 s, and effective TR = 6 s. Cross-correlation coefficient (CCC) maps were obtained using a boxcar cross-correlation method with a typical CCC threshold of 0.3. After fMRI studies, 10 mg Fe/kg dextran-coated monocrystalline iron oxide nanoparticles (MION) was injected into the femoral vein to enhance relative static susceptibility differences. The activated ROI was composed of all activated pixels from GE BOLD fMRI with TE of 20 ms, and contained both tissue and large vessels. This ROI was subdivided, based on a basal susceptibility effect, which is directly related to vessel size and density. To determine relative susceptibility effects in active pixels, R2* changes induced by MION ($\Delta R2^*_{MION}$) were calculated on a pixel-by-pixel basis using T_2*-weighted images with 12 TE values. ROI-based baseline R_2 and R_2* and stimulation-induced ΔR2 or ΔR2* were also calculated.

RESULTS and DISCUSSION

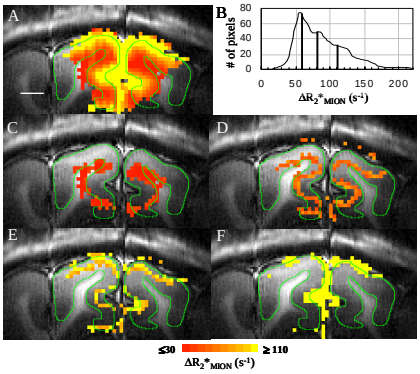

Fig. 1. Selection of ROIs based on basal susceptibility effects induced by MION.

In the absence of stimuli, contrast agents can highlight regional differences in the static susceptibility effect. Figure 1 shows the effect of administration of MION. All pixels that were activated in the GE BOLD fMRI were selected for calculation of $\Delta R2^*_{MION}$ values in Fig. 1A. The color bar shows the $\Delta R2^*_{MION}$ values. From the histogram of $\Delta R2^*_{MION}$ (Fig. 1B), boundaries of the four magnetic susceptibility regions were chosen (indicated by the vertical bars) such that each contained the same number of pixels, namely Lower (L), Middle, Upper (U), and (M), Surface (S) cortical regions. $\Delta R2^*_{MION}$ maps (Figs. 1C-F) show that the static susceptibility effect is highest at the surface of the cortex (Fig. 1F), and decreases with cortical depth.

Figure 2 shows basal R2 and R2* values (circles and squares in Fig. 2A) and stimulation-induced R2 and R2* changes (Fig. 2B) in the four previously-segmented susceptibility regions. L corresponds to active pixels from Fig. 1C, M from Fig. 1D, U from Fig. 1E, and S from Fig. 1F. From baseline R2 and R2* (Fig. 2A), an apparent transverse relaxation rate induced by local susceptibility effect (R2') can be calculated as defined by R2* – R2. Functional ΔR2* is the highest at the surface of the cortex, and decreases as cortical depth increases (Fig. 2B). Unlike ΔR2*, functional ΔR2 is the lowest at the surface of the cortex. Stimulation-induced ΔR2' change (ΔR2* - ΔR2) is linearly correlated with basal R2' (R2 = 0.997) (squares in Fig. 2C). The highest R2' is from the cortical surface where the stimulation-induced ΔR2*/ΔR2 of 8.8 ± 1.7 is also the highest (circles in Fig. 2C). At the middle and lower cortical regions with parenchymal microvessels, ΔR2*/ΔR2 is the lowest, with a value of 1.9 ± 0.1. Our data demonstrate that ΔR2' and ΔR2*/ΔR2 is closely dependent on basal R2' effect, which is related to anatomical and vascular structures.

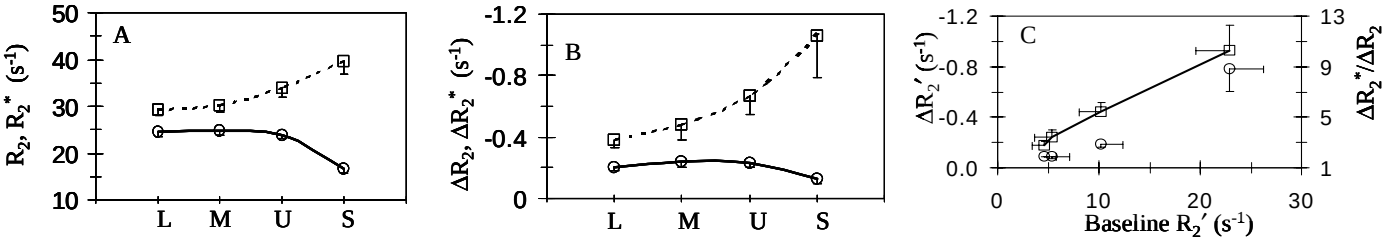

Fig. 2. Cortical depth-dependent baseline R2* and R2 (squares and circles in A) and stimulation induced R2* and R2 change (B). Relationship between baseline R2' and stimulation-induced R2' and ΔR2*/ΔR2.

Reference

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