Quantitative Analysis of Brain Functional Hemodynamics with Time-Series T_1 Mapping

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Introduction. An advantage of direct measurement of the longitudinal relaxation time T_1 over T_1-weighted imaging is quantification. With a recently developed technique, we map the longitudinal relaxation time at a rate of 1.5 s per T_1 map during a motor–visual, blocked-design task. The general association of relaxation time change is blood flow. However, our results reveal that there is at least a stronger component that dominates in the observed change of T_1. Quantitative analysis suggests that oxygen relaxivity is likely responsible as discussed below, which could help further our understanding of functional hemodynamics and refine the experiment design for flow or diffusion related studies to deal with the motion-insensitive component.

Methods. *Time-series T_1 mapping.*—The T_1 mapping method is described in Refs. [1,2]. Briefly, the pulse train π-α_1-α_2-α_3-α_4 is executed repeatedly, where the four α RF pulses have a common flip angle 50° and are equally spaced by 750 ms. A spiral scan [3] follows each α RF pulse to sample the k-space (64×64-matrix equivalent). The signals of α_1 and α_2 are subtracted with those of α_3 and α_4, respectively, to produce a T_1 map. Subtraction of the signals of α_3 and α_4 with those of α_1 and α_2 of the next pulse train can also produce a T_1 map. Effectively, the mapping rate is 1.5 s per T_1 map. In this work, the slice thickness is 5 mm with 3-mm spacing between slices, field-of-view 20 cm, and T_E 4.7 ms. *fMRI paradigm.*—The functional task consists of 15-s on and 15-s off blocks and a total of 9.5 cycles. During the on-block, the subject is shown a flickering checkerboard and taps fingers. Two identical T_1 mapping scans and a conventional T_2^*-weighted scan (T_E = 40 ms and T_R = 3 s) are performed for each volunteer. *Statistics.*—The activation maps are constructed by correlating the time-series with a sinusoidal function [4]. The T_2^*-weighted activation map is used to identify the regions of interest. To determine the relaxation change between the activated and resting states, the Fourier transform of the time-series is computed for each voxel and a time-series is synthesized by using the components of the task frequency f_{task} and $3f_{task}$; then ΔR_1, or $-\Delta T_1/T_1^2$, is computed as two times of the root-mean-square of the synthesized time-series.

Results and Discussion. Three normal volunteers have participated. Figure 1 shows the activation map samples. The task induced ΔT_1 can be detected and is in agreement with T_2^*-weighted imaging. The average phase of the T_1 time-series relative to that of the T_2^*-weighted imaging is 178°; *i.e.*, T_1 decreases (R_1 increases) from the resting to the activated state. The observed ΔR_1 are given in Table I. For 1.5 T, the average ΔR_1^{obs} is 15.8×10^{-6}/ms. A generally accepted value for the activation induced change of the cerebral blood flow is 27 ml/100g/min [5], equivalent to $\Delta R_1^{flow} = 4.7\times10^{-6}$/ms, which is much smaller than our ΔR_1^{obs} and than 9.2×10^{-6}/ms estimated by an inversion-recovery method [6]. Recall that activation alters the oxygen level. Because the cerebral blood volume is only a small fraction of the brain, the hemoglobin's relaxation influence on the tissue and the MR signal should be negligible. Thus the focus is on the oxygen relaxivity. The R_1 value of distilled water as a function of the partial pressure of oxygen pO_2 at temperature 37 °C has recently been established for 1.5 T: $\Delta R_1^{oxy}/\Delta(pO_2) = 2.49\times10^{-7}$/ms/mmHg [7]. Oxygen is freely mobile in the tissue so its relaxivity to distilled water should be a good approximation for the tissue. Let $\Delta R_1^{oxy} = \Delta R_1^{obs} - \Delta R_1^{flow}$. Our ΔR_1^{oxy} corresponds to $\Delta(pO_2)$ = +45 mmHg. Assume the pO_2 is at equilibrium between the tissue and the blood. Because pO_2 of the tissue in the resting state is ~30 mmHg, our ΔR_1^{obs} represents pO_2 = ~75 mmHg in the blood in the activated state—a partial pressure at which the hemoglobin is highly saturated. It is very interesting because saturating the hemoglobin during the activated state is the contrast mechanism for T_2^*-based fMRI. In summary, our T_1 mapping results support that the cerebral blood flow as well as the hemoglobin saturation level increase during activation. The latter demonstrates the potential of fast T_1 mapping as oximetry.

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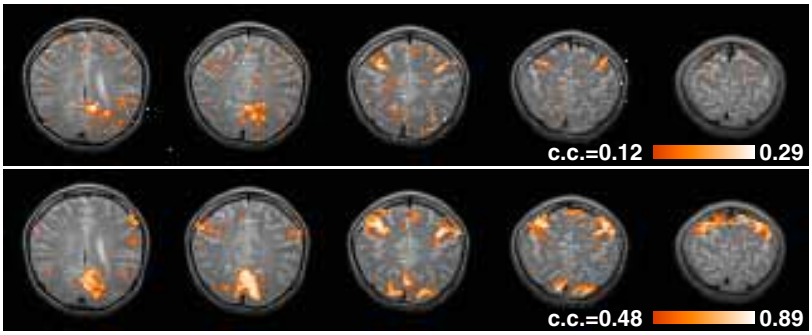

Figure 1 Activation maps constructed by direct T_1 mapping (top) and T_2^*-weighted imaging (bottom) at 3 T. The scan selected five oblique slices across the motor (upper portion) and visual (lower portion) areas. (c.c.: correlation coefficient)

Table I Average values of ΔR_1^{obs} and standard deviations ($\times10^{-6}$/ms) over the activated, qualified voxels in the motor and visual regions.

Subject	1.5 T	3 T
I	15.7 (3.8)	17.7 (4.9)
II	16.2 (4.0)	17.7 (4.4)
III	15.7 (6.6)	14.8 (3.9)

A voxel is qualified if it is deemed activated in the T_2^*-weighted and in the two T_1 mapping scans and if, for the two T_1 mapping scans, its time-series phase is consistent within 36° (i.e., 3 s) and the T_1^{obs} values agree within less than 3 % difference. No significant difference in ΔR_1^{obs} between results for 1.5 T and 3 T is found at this time.