Functional Magnetic Resonance Imaging Based on An Inversion Recovery Method for Grey Matter Signal Suppression

Y. Shen[1], R. A. Kauppinen[1], R. Vidyasagar[1], Y-C. L. Ho[2], I. Zimine[2], E. T. Petersen[2], and X. Golay[2]

[1]School of Sport and Exercise Sciences, University of Birmingham, Birmingham, United Kingdom, [2]Department of Neuroradiology, National Neuroscience Institute, Singapore

Introduction

Inversion recovery technique has been recently exploited for functional magnetic imaging (fMRI) studies by nulling blood signal[1]. We investigate a new fMRI method by nulling grey matter (GM) signal instead of blood signal using the inversion recovery technique to explore cerebral blood volume (CBV) changes upon activation. The new method relies upon an inversion of GM signal using a spatially non-selective inversion with an inversion time (TI) matched to the GM T_1. In contrast to the blood nulling method, the functional signal change is positive and determined by increase in CBV during brain activation. In this study, we investigate the characteristics of the new GM nulling fMRI compared to both the blood nulling (VASO) and conventional BOLD fMRI to explore the advantages associated with this new fMRI method.

Methods and Materials

The functional signal change is defined by $\Delta S/S = (S_{gm}^{act} - S_{gm}^{rest})/S_{gm}^{rest} = S_{gm}^{act}/S_{gm}^{rest} - 1$. The ratio $S_{gm}^{act}/S_{gm}^{rest}$ determines the signal change in the measurement. The GM signal S_{gm}, including the contributions from extravascular GM tissue and microvascular blood, is represented by $(C_{gm} - CBV_{gm}\cdot C_{blood})\cdot M_{gm}(TR,TI)\cdot\exp(-TE/T_2^*_{gm}) + CBV_{gm}\cdot C_{blood}\cdot M_{blood}(TR,TI)\cdot\exp(-TE/T_2^*_{blood})$, where C_{gm} is the water density of GM, C_{blood} is the water density of blood, CBV_{gm} is the cerebral blood volume in units of ml blood/ml parenchyma, and $M_{gm}(TR,TI)$ and $M_{blood}(TR,TI)$ are the longitudinal magnetisation for GM and blood, respectively, after applying a spatially non-selective inversion pulse. In case of complete GM signal nulling with the applied inversion pulse, $M_{gm}(TR,TI)$ is zero. The signal S_{gm} becomes $CBV_{gm}\cdot C_{blood}\cdot M_{blood}(TR,TI)\cdot\exp(-TE/T_2^*_{blood})$. Assuming that C_{blood} does not change with stimulation, the functional signal change can be simplified to $\Delta S/S = [CBV_{gm}^{act}/CBV_{gm}^{rest}]\cdot[M_{blood}^{act}(TR,TI)/M_{blood}^{rest}(TR,TI)]\cdot[\exp(-TE/T_2^*_{blood}^{act})/\exp(-TE/T_2^*_{blood}^{rest})] - 1$. The first term in this equation represents a pure CBV change that is greater than 1 due to the increase of CBV upon stimulation. This term is scaled by the second and third term, which represents the blood magnetisation change and the blood T_2^* change respectively. Similarly, the functional signal change from the blood nulling can be written as $\Delta S/S = [(C_{gm} - CBV_{gm}^{act}\cdot C_{blood})/(C_{gm} - CBV_{gm}^{rest}\cdot C_{blood})]\cdot[M_{gm}^{act}(TR,TI)/M_{gm}^{rest}(TR,TI)]\cdot[\exp(-TE/T_2^*_{gm}^{act})/\exp(-TE/T_2^*_{gm}^{rest})] - 1$. The term which represents the CBV change in the blood nulling method is $[(C_{gm} - CBV_{gm}^{act}\cdot C_{blood})/(C_{gm} - CBV_{gm}^{rest}\cdot C_{blood})]$. Because there are two extra terms C_{gm} and C_{blood} in the formula for VASO, a pure determination of the CBV change is not feasible without estimating these values by additional measurements. In addition, this term is less than 1 due to the fact that the CBV increases moderately with activation, which is contrary to the case of GM nulling. Since TE > 0, the third term in both of GM nulling and VASO is greater than 1 due to the increase in T_2^* from activation. When the first term, which represents changes from increased CBV, in both of GM nulling and VASO, is scaled by this value, the effect is different. In the case of GM nulling, it will increase the signal change by promoting the CBV contribution, because the term is greater than 1. In the case of VASO, it will reduce the signal change due to CBV term increase, because the term is less than 1.

Brain activation studies were performed on a 3T MR scanner (Philips Medical System) using body coil transmission and SENSE head coil reception. Seven normal subjects (4 males, 3 females, age = 24 - 51) were scanned with prior informed written consent from each subject. Three types of scans (GM nulling, blood nulling and BOLD) were performed for each subject with: single shot GE-EPI, TR = 3 s, FA = 90°, FOV = 224 mm, matrix = 112x112, SENSE = 2.5, slice thickness = 5 mm, single slice, dual gradient-echoes with TE = 10 and 56 ms for both GM nulling and blood nulling, TE = 40 ms for BOLD, and TI = 703 and 889 ms for GM nulling and blood nulling respectively. Visual stimulation consisted of 45 s on and 45 s off in two cycles with B/W checkerboard flashing at 8 Hz. The total scanning time for each type of scan was 225 s with acquisition of 75 dynamic images. Analysis was carried out using FEAT (FMRI Expert Analysis Tool), part of FSL (http://www.fmrib.ox.ac.uk/fsl). A region of interest (ROI) covering the occipital lobe was applied in the process with use of FEAT. Signal time-courses data were determined by averaging over all activated voxels for each dynamic image. The first 3 time points in the time courses were not used in the determination of the mean baseline signal and were replaced by this mean baseline value when plotting the time-courses data. A routine under IDL 6.0 software (Research Systems Inc.) was used for the plot of time-courses data and the calculation of functional signal change.

Results and Discussion

Figure 1 shows the activation maps for GM nulling, blood nulling and BOLD and their correspondent time courses for a subject. The activated area is largest for BOLD, reflecting significant contribution from large veins. Smaller activated areas for GM nulling and blood nulling represent microvascular CBV responses during activation. The mean activated voxel numbers for 7 subjects are 611 ± 161, 354 ± 91 and 385 ± 154 for BOLD, GM nulling and blood nulling, respectively. A significantly higher response is demonstrated in the GM nulling fMRI relative to the blood nulling (Fig. 1, bottom panels). The average CNR (see definition[2]) from 7 subjects for GM nulling is 26.24 ± 3.92 vs. 7.7 ± 1.22 for blood nulling, showing an increase of more than 3.4-times in CNR. The mean functional signal change from 7 subjects for GM nulling is 5.23 ± 1.2%, compared with the changes of -1.73 ± 0.46% and 1.67 ± 0.33% for blood nulling and BOLD respectively. Using both TEs, the T_2^* effects can be removed for the GM nulling method by calculating the effective TE = 0 signal as shown in Fig. 2 by the red trace. This, however, is difficult to achieve for VASO because the functional signal change is significant reduced at a long TE[2]. The mean functional signal change after removing the T_2^* effects is 4.64 ± 1.33%. Some 5% signal change is much smaller than the normal CBV change of ~30% upon stimulation, illustrating the scaling effect from a change of blood magnetisation due to both the inversion preparation and blood flow effects[3].

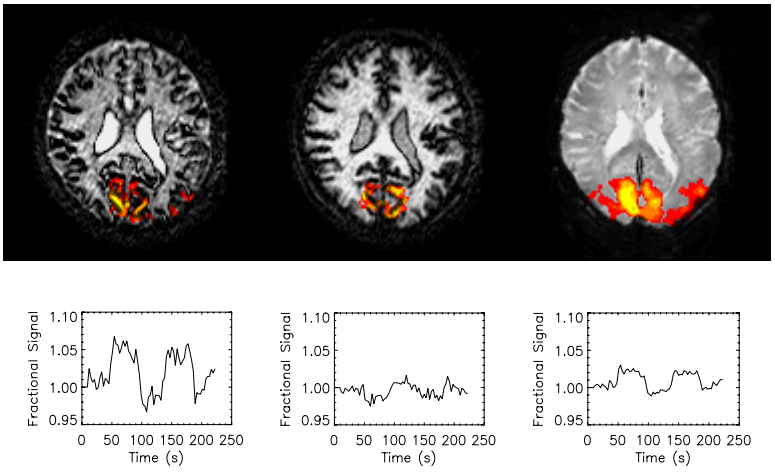

Figure 1. Activation maps for grey matter nulling, blood nulling and BOLD (top from left to right) and the correspondent time courses (bottom).

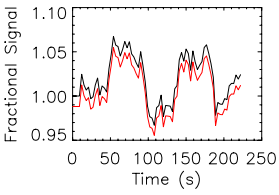

Figure 2. The responsive curve before (black) and after (red) removing the T_2^* effects for grey matter nulling fMRI.

Conclusion

We have established a new fMRI methodology by nulling GM signal using a spatially non-selective inversion recovery sequence. The method shows a higher signal change relative to blood nulling and BOLD fMRI methods. The CNR is significantly improved as compared with the blood nulling fMRI. The measured functional change is pure CBV change weighted by the changes of blood magnetisation and T_2^*. The T_2^* effects can be removed with multiple TE.

Reference

[1]Lu H, et al; Magn Reson Med 2003; 50:263-274. [2]Lu H, et al; Magn Reson Med 2005; 53:808-816. [3]Donahue MJ, et al; Proc. ISMRM 2006; 2769.