Composite Image Formation in Z-Shimmed Functional MR Imaging

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Introduction

A challenge in functional MRI is to develop imaging methods that are highly sensitive to the BOLD effect, with minimal sensitivity to macroscopic fields. Gradient echo EPI provides maximal sensitivity to susceptibility variations on all scales including microscopic (BOLD) and macroscopic susceptibility (static field inhomogeneities). Z-shimming compensates for the through-plane dephasing effects that arise in gradient echo images due to static field inhomogeneities. However, this approach reduces time efficiency, since multiple acquisitions are required to form a single composite image free of static field effects. To date, an analysis of the formation of composite images using multiple z-shim positive rates of activation detection, are considered, in addition to microscopic (BOLD) and macroscopic susceptibility (static field inhomogeneities). Z-shimming compensates for the through-plane presence of a field inhomogeneity gradient $G_z$ is given, by

$$M(z) = M(0)e^{-iG_z z_T}$$

The magnetization in the slice select direction, $M(z)$, in the presence of a field inhomogeneity gradient $G_z$ is given by $M(z) = M(0)e^{-iG_z z_T}$. The exponential term describes the phase dispersion across the slice that leads to signal loss. This phase may be re-wound with the appropriate compensation gradient offset, $G_z$, on the slice select rephase lobe for the z-gradient. If multiple images are collected each with a different gradient offset then each image will compensate for a different amount of phase dispersion. Multiple acquisitions are needed to form a single image compensated everywhere.

Time constraints limit the number of offsets that can be collected to 2 or 3. Adjacent acquisitions may be combined to form compensated composite images a number of ways. Two simple methods are maximum intensity projection (MIP) and the square root of the sum of squares (SSQ). The MIP approach is defined as

$$I_{\text{comp}} = \max\{G_{c1}, G_{c2}, G_{c3}, \ldots, G_{cN}\}$$

where $G_{c1}, G_{c2}, G_{c3}, \ldots, G_{cN}$ are the $N$ different compensated gradient echo images. A second approach is to take the square root of the sum of the squares (SSQ) images such that:

$$I_{\text{comp}} = \sqrt{G_{c1}^2 + G_{c2}^2 + G_{c3}^2 + \ldots + G_{cN}^2}$$

In an experiment, the different compensation gradients are cycled through with successive acquisitions such that in the first 3 acquisitions (called cycle A) for a given slice $G_{c1}(A)$, $G_{c2}(A)$ and $G_{c3}(A)$ are collected, and in the next three acquisitions (cycle B), $G_{c1}(B)$, $G_{c2}(B)$ and $G_{c3}(B)$ are collected. This continues until all of the images for a run are obtained. So far, we have assumed that the 3 images from cycle A are combined together to form a single composite image $I_{\text{comp}}(A)$, and the next 3 images are combined to form the 2nd composite $I_{\text{comp}}(B)$ etc. Spatial domain mixing (SDM) can be applied to this reconstruction approach. In SDM, a large number of composite images may be formed, by mixing the z-shimmed images obtained in different acquisitions. For example, using acquisitions (A) and (B) above, we could form images by:

$$I_{\text{comp}} = \sqrt{G(A)_{c1}^2 + G(A)_{c2}^2 + G(B)_{c3}^2}$$

and

$$I_{\text{comp}} = \sqrt{G(B)_{c1}^2 + G(A)_{c2}^2 + G(B)_{c3}^2}$$

With only two cycles, (A) and (B), the amount of SDM that can be applied is very limited. In a typical fMRI application many cycles are collected, and all of the images obtained under a specific condition can be mixed, yielding a very large number of images from a limited dataset.

Results and Discussion

Noise analysis reveals that the standard deviation of the noise is reduced by $\sqrt{N}$ in the MIP images and remains unchanged in SSQ and SDM. While the noise does not change in the SSQ or SDM approach the signal uniformity across an image can improve dramatically. The benefits of using this approach come, not from decreasing the noise, but from increasing the signal detected in regions of high field inhomogeneity.

The figure below illustrates the activation maps (complex scenes vs. fixation) obtained in the medial temporal lobes: a very difficult area for fMRI. The rows represent two adjacent slices and the columns processing strategies. Much stronger activation is observed in the z-shimmed image approaches along the inferior margin of the medial temporal lobe. In both slices strong activation is observed in the hippocampal formation including the posterior hippocampus and the fusiform gyrus. The activation in the right dorsolateral prefrontal cortex, a region with little field inhomogeneity, is constant across all approaches. With the SDM approach there is increased detectability in regions of high field inhomogeneity and no loss of activation in regions with little static field inhomogeneity.

Conclusions

Z-shimming provides an efficient solution to functional imaging in highly nonuniform fields. The more significant the spatial extent of the field inhomogeneity the more efficient the z-shimming approach becomes. The SDM approach yields excellent results in both regions of high field inhomogeneities, and in regions where little inhomogeneity is found.

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References: