Towards Parcellated Dynamic Shimming

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Introduction The need for a homogeneous magnetic field in magnetic resonance imaging is well established, especially at high static magnetic field strengths where susceptibility-induced image distortions and signal losses become excessively large. Dynamic shim updating [1], where the optimal set of shim currents is applied for each slice during a multi-slice acquisition has been shown to improve magnetic field homogeneity to a greater extent than conventional global field map based shimming [2]. Previous work showed by simulation that the magnetic field inhomogeneity can be further reduced if shimming is performed over a series of compact, cuboidal sub-volumes rather than planes [3]. The implementation of parcellated dynamic shimming poses significant challenges, and this work reports the progress made to date. Principally, this work describes corroboration of simulated results with experimental data obtained at 7T and demonstrates the efficacy of a fast, robust automatic field mapping and shim calculation routine.

Methods Maps of the magnetic field inhomogeneity, $\Delta B_z(\mathbf{r})$, are generally obtained by observing the difference in phase of image data obtained at different echo times. Such phase data contains “wraps” due to the lack of distinction between phases separated by a multiple of 2π, and therefore must be “unwrapped” to remove these discontinuities. Two unwrapped phase images may be subtracted from one another and appropriately scaled to yield a map of $\Delta B_z(\mathbf{r})$. There are 3 principal problems with this process; (i) it is insensitive to uniform ΔB_z offsets, (ii) it is computationally time consuming and (iii) it can be sensitive to errors and noise. Here, three single-echo, 3D gradient echo acquisitions with an echo-time difference of 0.3 ms permitting the resolution of a maximum $\Delta B_z(\mathbf{r})$ of 5.6 ppm at 7T were used. These scans each take 23 s and have an isotropic resolution of 2 mm with a 192 mm cubic field-of-view (FOV). The resulting data are exported for shim calculation in Matlab®. The phase data were temporally unwrapped across the three echoes. The magnitude data is skull-stripped using BET [4] and thresholded to generate a brain only mask for $\Delta B_z(\mathbf{r})$. Shim $B_z(\mathbf{r})$ maps are generated in the same FOV as the scans and collated into a matrix which is pseudo-inverted and multiplied by the measured $\Delta B_z(\mathbf{r})$ map to obtain the strengths of shims required to shim the brain region optimally [2]. These shim values were then transferred back to the scanner.

To provide a simple comparison between measured and simulated $\Delta B_z(\mathbf{r})$ data from the head of a healthy human subject we bisected the FOV in the *x*, *y*, and *z* direction to yield 8 parcels. Each was individually shimmed as described above with 0^{th} and 1^{st} order shim fields the field maps were acquired with these new shim settings. Parcellated shimming was additionally carried out on a 4 quadrant phantom containing agar gel, using 0^{th}, 1^{st} and 2^{nd} order shims with parcels formed from bisections in the *x* and *y* directions.

Results The speed of the shim calculation was measured overall to be less than 2 minutes in Matlab® R2007 on a 2.0 GHz Pentium 4 processor for the head data. Which comprises; ~25 s to read the image data from the scanner, ~58 s to unwrap the 3-echo 3D phase data, ~5 s to strip the skull from the magnitude image and ~3 s to fit the linear shims. Figure 1 shows the results of applying parcellated shimming to head data. It shows axial slices of the; a) magnitude, gradient echo data, e) $\Delta B_z(\mathbf{r})$ map with no shimming, masked by the skull stripped magnitude image, the shim field that optimally shims $\Delta B_z(\mathbf{r})$ with f) global shim and b) parcellated shim settings and the c) & g) theoretical and d) & h) measured $\Delta B_z(\mathbf{r})$ after parcellated and global shimming had been applied. Figure 2 displays histograms of $\Delta B_z(\mathbf{r})$ in the masked region for a) no shimming as well as b) global and c) parcellated shimming. The root-mean-square (RMS) $\Delta B_z(\mathbf{r})$ before shimming was measured to be 3.09 μT. Upon shim calculation, a residual RMS $\Delta B_z(\mathbf{r})$ of 1.59 and 2.42 μT is predicted for global and parcellated shimming, respectively. The $\Delta B_z(\mathbf{r})$ maps acquired after shimming give RMS measures of 1.67 and 2.49 μT. Figure 3 is histogram of the residual $\Delta B_z(\mathbf{r})$ before and after 1^{st} and 2^{nd} order, global and parcellated shimming of the 4-quadrant phantom., confirming experimentally the significant improvement in field homogeneity that can be achieved by parcellated shimming.

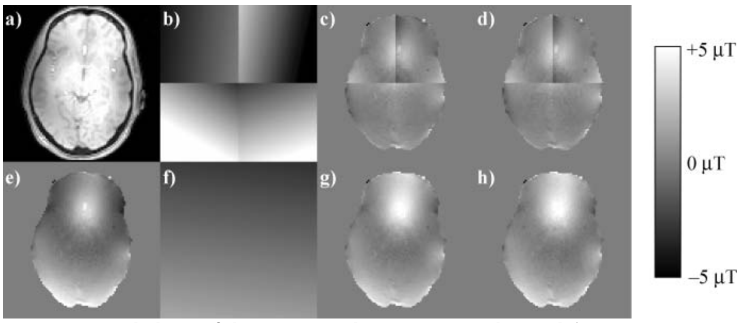

Figure 1. Axial slices of the a)magnitude image, e) unshimmed $\Delta B_z(\mathbf{r})$ map, optimal linear shim fields for b) parcellated and f) global, predicted residual $\Delta B_z(\mathbf{r})$ map for c) parcellated and g) global, and measured residual $\Delta B_z(\mathbf{r})$ map for d) parcellated and h)global shimming. A colour scale is provided for all the $\Delta B_z(\mathbf{r})$ maps.

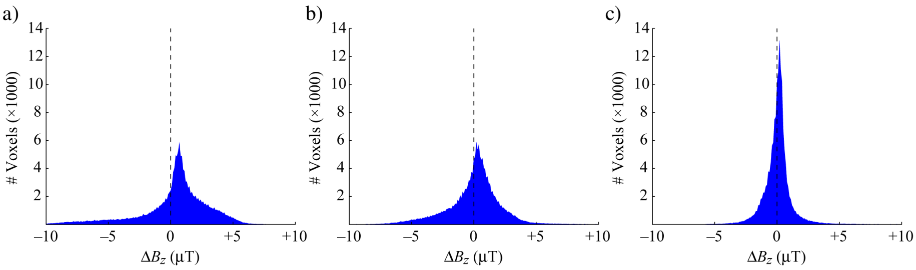

Figure 2. Histograms of the residual $\Delta B_z(\mathbf{r})$ distribution a) before and after b) global and c) parcellated shimming of the head corresponding to Fig. 1 a), d) and h) respectively.

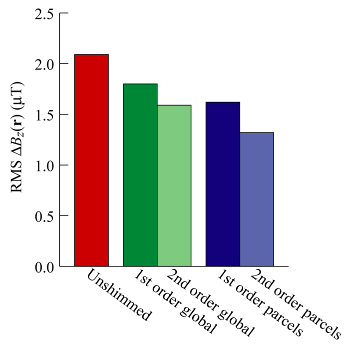

Figure 3.Histogram of the residual $\Delta B_z(\mathbf{r})$ before and after 1^{st} and 2^{nd} order, global and parcellated shimming.

Discussion The shim calculation code was completely unoptimised and runs in less than 2 minutes, which causes a tolerable increase in overall scan time. It should be possible to significantly reduce this time. The field mapping technique we have used here is fast, accurate and can detect uniform ΔB_z offsets, which subtracting 2 phase-unwrapped echoes cannot. Parcellated shimming was previously shown by simulation to be highly effective at reducing $\Delta B_z(\mathbf{r})$ by choosing the optimal shim settings for cuboidal regions of a 3D data set. This work has shown that there is very good agreement between the simulated shimming and the measured magnetic field once the optimal shim setting have been applied. The next steps towards the implementation of parcellated dynamic shimming are to use outer volume suppression and reduced acquisition in the phase-encoding direction with echo planar and echo volumar imaging (EPI, EVI[5]) to acquire image data with parcellated shim settings, and to be able to update the shim settings dynamically and automatically.

References **[1]** A. Blamire, D. Rothman and T. Nixon. *Magn Reson. Med.* **36**, 159-165 (1996). **[2]** M. Prammer, J. Haselgrove, M. Shinnar and J Leigh, *J. Magn Reson*, **77**, 40-52 (1988) **[3]** M. Poole and R. Bowtell *MAGMA* **submitted**. **[4]** S. Smith, *Human Brain Map.,* **17** 143-155 (2002). **[5]** P. Mansfield, A. M. Howseman and R. Ordidge, *J. Phys. E: Sci. Instrum.* **22**, 324-330 (1989).