The Impact of Oblique Slicing and Shim Inclusions on Dynamically Shimmed Global Homogeneity

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Introduction Dynamic shim updating (DSU) provides significant global homogeneity improvement when compared to static, low-order spherical harmonic shimming. [1][2] Through spatially selective shim changes, DSU allows for global shimming in a local fashion. For spectroscopic applications, DSU is useful in multi-voxel spectroscopy. Within the imaging community, DSU is applicable to multi-slice imaging where it can be utilized in both oblique and non-oblique slicing protocols. DSU is particularly valuable to imaging applications requiring fast gradient echo acquisition strategies (fMRI, DTI), where extended k-space sampling times generate significant signal loss and geometric distortion in regions of high inhomogeneity.

It has been demonstrated that preferred oblique slicing geometries exist for optimal homogeneity over a single slice. [4] This angular dependence in single slice homogeneity suggests that DSU-utilized global homogeneity could also be dependent on slicing geometry. Coupled with this issue is question of improving global homogeneity through the inclusion of higher (>2) order shims in DSU. To formulate a response to these important issues in optimal application of DSU, global homogeneity was analyzed as a function of both oblique-slicing angle and order of shims included.

DSU utilization in imaging requires shim optimization over 2D planes. However, 3D spherical harmonic shim functions can degenerate when projected into 2D. This issue was previously circumvented for single-slice oblique shimming using linear projection methods over a 3D slab centered on the slice. [3] Here, we present the implementation of an alternative approach, whereby non-degenerate shim sets are chosen using functional degeneracy analysis over oblique imaging planes.

Methods DSU was implemented on a 4.0 T Magnex magnet interfaced to a Bruker Avance spectrometer. A Magnex whole-body gradient system housed pre-emphasized linear imaging gradients and all 2nd and 3rd order shim gradients. RF reception and transmission were carried out by a Bruker TEM coil. The DSU system was controlled by a custom built interface which stored and implemented shim changes on command from pulse programs with a minimum updating time of 10 ms. To maximize updating speed and minimize artifacts, a custom-built shim-change pre-emphasis system was also utilized.

Optimal shim settings were determined via χ^2 optimization of selected shim functions over magnetic field maps acquired with an asymmetric gradient-echo imaging sequence. Non-degenerate shim sets were determined through oblique-slicing degeneracy analysis. When slicing obliquely, degeneracies can be uncovered by projecting 3D shim functions onto the obliqued imaging planes. For a slice obliqued by angles θ and ϕ, the equation of a plane intersecting the gradient isocenter is given by $y\cos\theta\cos\phi - z\cos\phi\sin\theta + x\sin\phi = 0$, where θ is defined as the angle between the y and z planes. Using this relation, one variable can be removed from each shim function and a set of non-degenerate shims extracted from the 2D functional set.

In vivo magnetic field maps were acquired with 32 adjacent 0.2 cm thick slices, with 64x64 pixels over 25.6 x 25.6 cm, TE=13.6 ms, TR = 960 ms, and asymmetrizing delays of 0.0, 0.5, 1.5, and 5.0 ms. Maps were acquired with a static shim setting and coronal ($\theta = \phi = 0^o$) slicing orientation. The optimal static shim was determined using a 6.5 x 6.5 x 6.5 cm ROI centered on the rear of the corpus callosum. Single oblique (ϕ=0) slicing geometries for values of θ ranging from 0 to 175^o in 5^o increments were then simulated from these maps. Optimal settings for angle-specific non-degenerate shim sets were calculated using simulated maps over manually traced ROIs encompassing the entire brain. The resultant inhomogeneity was then determined by subtracting the optimum shim fields from the simulated maps on a slice-specific basis. Using these resultant field maps, global homogeneity was determined from the 80% width of histograms using all pixels within the whole-brain ROI. This process was repeated including a) up to 1st order, b) up to 2nd order, and c) up to 3rd order shims in the DSU optimization.

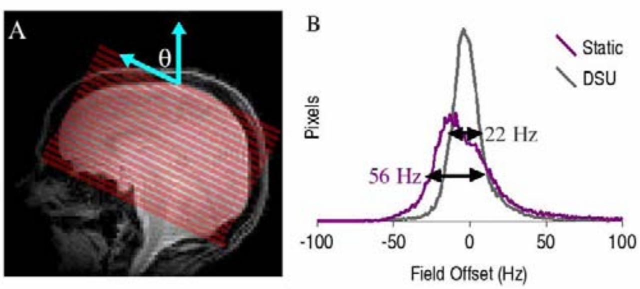

Figure 1: Experimental analysis of oblique DSU method. A) MRI showing slice geometry for θ = 65°, and B) global field offset histograms for static and 2nd order DSU shim settings

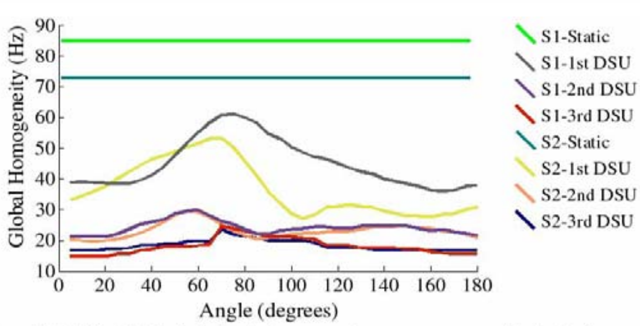

Figure 2: DSU global whole-brain homogeneity survey across shim inclusions and single-oblique angle for two subjects (S1 and S2) of similar head pitch.

Results and Discussion Figure 1 presents experimental verification of our oblique DSU procedure. As expected, the widths of global histograms show significant improvements (56 Hz to 22 Hz) with the implementation of DSU. To uncover this improvement's dependence on slicing geometry and shim inclusion, similar global homogeneity analysis was repeated using the simulated DSU-shimmed field maps.

As reported by Tyszka and Mamelak [5], B_0 inhomogeneity varies significantly with head pitch relative to the static field. It is thus imperative to analyze DSU-utilized global homogeneity within narrow head pitch ranges. Hence, an anatomic reference was used to register head pitch across subjects. Figure 2 presents a simulated survey of global homogeneity for one single-oblique strategy (axial-coronal). The oblique angle is measured relative to the coronal plane and data is presented for two subjects with head pitch within 2^o of one other. As expected, increasing shim inclusions reduce the variation of subject-specific homogeneity-slicing-angle trends. Significant global homogeneity for all slicing angles is gained in moving from static to 1st order DSU and similarly with the inclusion of 2nd order shims. However, it is clear that improvement with the inclusion of 3rd order shims is significantly reduced across all slicing angles, with a maximum improvement of 8 Hz at the 60^o slicing angle. Whole-brain global homogeneity improvement of 8 Hz will not likely have significant implications for any imaging applications. Similarly, while global homogeneity has a clear oblique angular dependence for 1st order DSU, the angular dependence for up to 2nd order DSU, shows significantly reduced variation. This dependence is similarly reduced for up to 3rd order DSU.

Conclusions The experimental and analytical results presented here demonstrate that DSU may be applied to arbitrary oblique slices with a substantial improvement in whole brain homogeneity over static shim settings. The inclusion of 2nd order shims in DSU substantially reduces the dependence of global homogeneity on oblique slicing angle. In all cases, greater fractional improvement may occur in individual slices, or specific regions within individual slices, than over the entire brain. Furthermore, image artifacts will have an independent angular dependence, depending on the orientation of the phase encode direction with respect to the inhomogeneity. A full interpretation of these effects will require specific impact investigations of shim inclusion and slicing-angle on signal loss and pixel shifts.

Acknowledgments and References

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[1] KM Koch, TM Nixon, S McIntyre, DL Rothman, RA de Graaf, Proc ISMRM (2004)
[2] RA de Graaf et al, Magn. Reson. Med. 49: 409 (2003)
[3] J. Shen, NMR in Biomed. 14: 177-183 (2001)
[4] J.M Tyszka and A.N. Mamelak, J. Magn. Reson. 159: 213-218 (2002)
[5] R Deichmann, A Gottfried, C Hutton, and R Turner. Neuroimage. 19: 430-441 (2003)