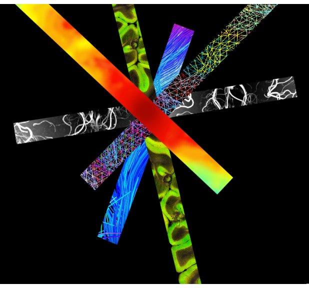
Beyond B_0 shimming: New applications of local ΔB_0 field control using multi-coil arrays

Jason Stockmann[1,2], Nicolas Arango[3], Thomas Witzel[1,2], Congyu Liao[1,2], Kawin Setsompop[1,2], Jacob White[3], Elfar Adalsteinsson[3], Lawrence L Wald[1,2]

[1] Athinoula A Martinos Center for Biomedical Imaging, Massachusetts General Hospital

[2] Department of Radiology, Harvard Medical School

[3] Department of Electrical Engineering and Computer Science, Massachusetts Institute of Technology



Athinoula A. Martinos Center For Biomedical Imaging

MASSACHUSETTS GENERAL HOSPITAL

HARVARD MEDICAL SCHOOL

Massachusetts Institute of Technology

Flexible spatial encoding

- Local multi-coil (MC) shim arrays with up to 48 channels have recently been proposed for improving B_0 homogeneity for brain MRI [1].
- Single or multi-turn loop arrays with just a few amps of current per channel can reduce the standard deviation of ΔB_0 (σ_{B0}) by 50% or more at both 3T [2,3] and 7T [4] using dynamic shim updating between slice acquisitions.
- In this work, we highlight new emerging applications that go beyond B_0 shimming and use MC arrays as tools for ***flexible spatial encoding***
- Key features of MC arrays that enable new spatial encoding applications:
  - *Local local, low-inductance coils can switch currents rapidly (<1ms)*
  - *High-channel count non-linear, non-orthogonal ΔB_0 basis allows fields to be tailored to curvilinear anatomy of interest (unlike linear gradients)*
- Local field control is useful even when the B_0 offsets are ~100 weaker than those produced by conventional gradients
- We illustrate flexible spatial encoding using a 3T integrated ΔB_0/Rx coil with parallel receive and B_0 field control capability

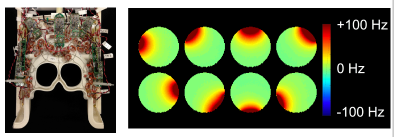


Fig. 1: Integrated ΔB_0/Rx coil with 32 loops each of which is used for RF receive and B_0 shimming. The same array is used for parallel imaging and for local field control. The loops are driven with low-voltage, low-cost current amplifiers [5]. Representative axial ΔB_0 field maps are shown at right.

Case #1: EPI distortion correction

- Problem: How can we enable low-distortion, high-resolution 1mm isotropic diffusion-weighted images using single-shot EPI?
- Solution: Use an integrated ΔB_0/Rx coil to provide *multiplicative improvements in geometric distortion* by enabling both *parallel imaging* and *local field control*:
  - *R=4* undersampling with GRAPPA reconstruction to increase single-shot resolution and reduce distortion
  - Approx. 2-fold reduction in distortion using slice-by-slice MC shim updating
  - Combined: *4×2 = 8-fold improvement*
- Slice-by-slice shimming performs better than whole-brain global shimming. *What about shimming two slices at once for Simultaneous Multislice acquisitions?*
- MB-2 shim performance is nearly identical to MB-1. Performance degrades for MB-3 and MB-4 [6].

Lessons learned: (1) Dynamically shim the GRAPPA and SMS autocalibration k-space scans. (2) Turn off slice-optimized MC shim during fat saturation pulse to avoid artifacts.

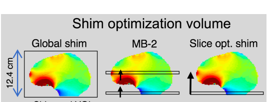


Fig. 3 *(right): SMS-2 dynamic shimming optimizes shim currents to shim two distant slices at the same time. SMS-2 shim performance is almost identical to single-slice optimized shimming.*

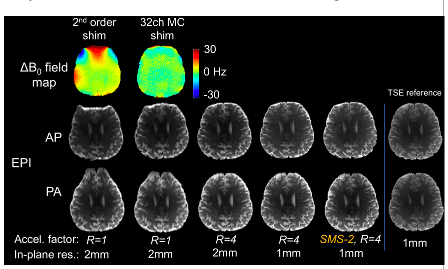


Fig. 2: MC shim array used for dynamic slice-optimized shimming in combination with R=4 undersampling to achieve 8-fold reduction in EPI distortion. Dynamic switching does not introduce any image artifacts. TE/TR=5100/77ms, echo spacing = 0.93ms

Case #2: Dynamic water-fat separation

- Problem: In chemical shift imaging spectroscopy, sidelobes of the encoding point spread function cause lipids from skull to contaminate metabolite spectra inside brain.
- Idea: Exploit spatial and spectral separation of lipids and brain metabolites in the head
- Solution: Improve lipid suppression in MR spectroscopy by playing a tailored B_0 field offset during fat suppression RF pulse; shift fat and water further apart spectrally [7]
- Use convex optimization to jointly optimize shim currents and transition frequency of fat sat. pulse. Maximize lipid suppression and minimize saturation of metabolites.

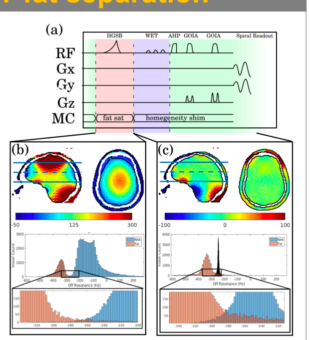


Fig. 4: (a) A spiral-readout CSI sequence with asymmetric HGSB lipid suppression pulse. (b) The MC field is tailored to spectrally separate the fat and water peaks over 4cm slab. The transition band of the HGSB pulse is shifted for optimal lipid suppression. (c) After the HGSB pulse, the MC field is switched to a B_0 homogeneity shim for the water suppression and excite/acquire modules of the sequence to improve metabolite linewidth.

Case #2: Dynamic water-fat separation (cont'd)

Fig. 5: Representative spectra for the ROI boxed in red. Improvements in CSI metabolite maps achieved with dynamic water-fat separation and B_0 homogeneity shimming. The proposed method dramatically reduces lipid contamination (green arrows) near the NAA peak. B_0 homogeneity shimming provides a modest improvement in metabolite linewidth (bigger gains are achieved in the frontal lobes).

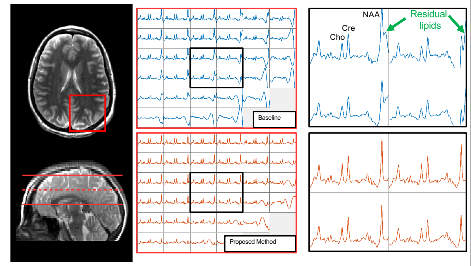
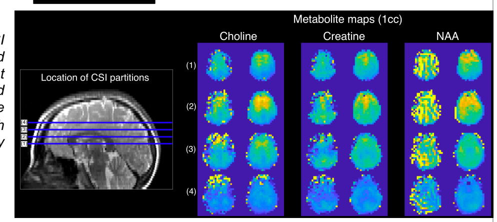


Fig. 6: Improvements in 1cc CSI metabolite maps for four acquired partitions. Dynamic water-fat separation reduces lipid contamination and increases the number of voxels in which metabolite levels can be accurately quantified.



Case #3: Zoomed 3D EPI for high-res fMRI

- Problem: Improve EPI spatial resolution without using a stronger gradient coil.
- Solution: Selectively excite a target region by playing a spatially-tailored B_0 offset during RF excitation. Reduce spatial encoding burden, thus allowing higher resolution without the need for saturation pulses (SAR penalty) or parallel imaging (g-factor noise penalty).
- First shown by DeGraaf *et al.* for 3D GRE in mice [8]. We extend the method to zoomed 3D EPI in humans for fMRI experiments.
- Application: High-resolution (1.25mm iso.) 3D EPI of occipital visual cortex for fMRI *with no parallel imaging*

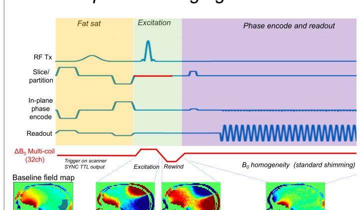


Fig. 7: In a 3D EPI sequence, the usual slab select linear gradient is set to zero and replaced with a switched MC field offset. The field polarity is then flipped to play a rephaser lobe. After excitation the MC field is set for B_0 homogeneity shimming.

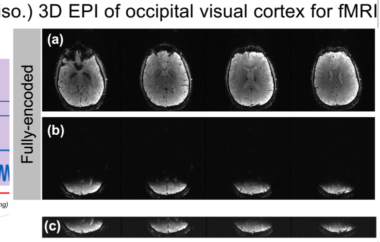


Fig. 8: Zoomed imaging results. (a) Fully-encoded 3D EPI with four shots per partition to achieve 1.25mm iso. Resolution. (b) Selectively excited, fully-encoded images. (c) Four-fold undersampled zoomed images reconstructed with no parallel imaging and no aliasing.

Fig. 9: Temporal SNR comparison for 1.25mm iso. 3D EPI with one shot per partition. Using zoomed EPI instead of R=4 undersampling provides a ~20% boost in tSNR over the region of interest. Outside this region, tSNR falls off in the transition region of the MC field offset, leading to a reduced flip angle. Improved RF excitation pulses with sharper transition bands would mitigate this problem in future work.

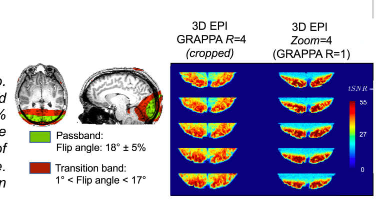
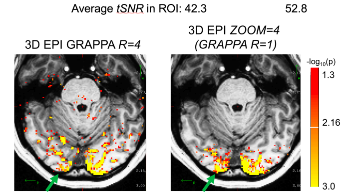


Fig. 10: Higher tSNR translates into a more robust BOLD response in the occipital visual cortex (green arrow) during a flashing checkerboard visual task.



Conclusion

- Use rapidly switchable local field control to play different nonlinear field offsets that are sequence-module specific, providing a new form of ***flexible spatial encoding*** for MRI.
- Example applications shown: Reduced EPI distortion, improved CSI lipid suppression, and zoomed 3D EPI.

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References: [1] Juchem C, JMR 2011. [2] Truong TK, NeuroImage 2014. [3] Stockmann JP, MRM 2016. [4] Stockmann JP, ISMRM 2017. [5] Arango N, ISMRM 2016. [6] Stockmann JP, NeuroImage 2017. [7] Arango N, ISMRM 2018. [8] Rudrapatna U, ISMRM 2016.