Flexible spatial encoding strategies using rotating multipolar fields for unconventional MRI applications

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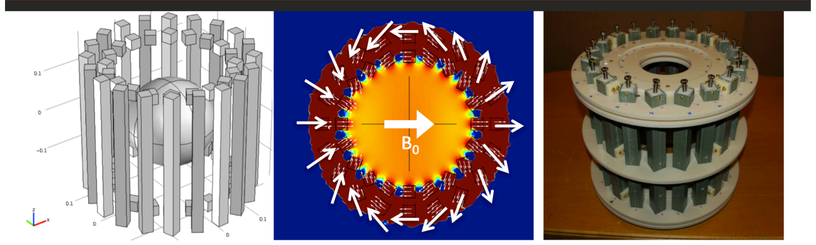
#2664

Imaging without switched gradients

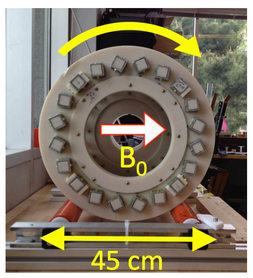
- ***Goal***: Portable MRI head scanner for sites with limited power/space for conventional magnets & gradients (See Oral #137 in "New Systems & Probes").
  - *Ambulance, neuro-ICU, sports arena, battlefield, etc.*
  - *Diagnose TBI, hemorrhagic stroke, and post-surgical bleeds.*
- Use Halbach array [1] of permanent magnets for B_0.
- "Poorly shimmed" B_0 used for spatial encoding by mechanically rotating magnet around the head.
- Refocus spins with a spin echo train (exploit long T_2 at low field).

  → ***No switched gradients are used*** ←
- Non-Fourier encoding requires generalized image recon via iterative matrix inversion.

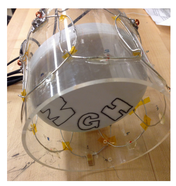
Imaging without switched gradients



- Halbach array generates 773 gauss field (3.29MHz) with ~30KHz variation over the 16cm FOV [2].
- Encode in transverse plane using rotating nonlinear B_0 field.
- Similar to ***quadrupolar PatLoc*** [3] with radial k-space trajectory.
- Use encircling array of surface coils to resolve aliasing caused by non-bijective encoding [3].



*B_0 points **transverse** to Halbach axis. Stepper motor rotates magnet around the sample to acquire projections.*



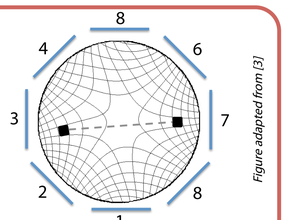
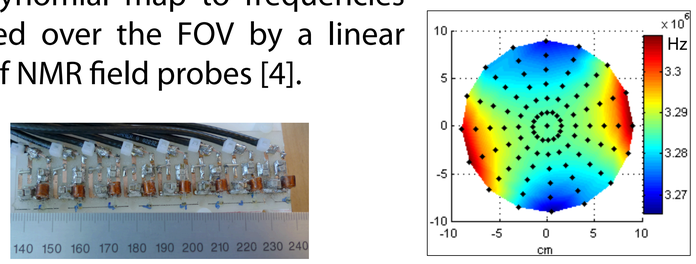


Figure adapted from [3]

TX solenoid coil (left) and RX 8ch surface coil array (center) with 2D phantom. Coil sensitivities break the symmetry of the multipolar B_0 field [3]. Coils 3 and 7 disambiguate signals from the two illustrated voxels.

Field calibration

- Fit polynomial map to frequencies acquired over the FOV by a linear array of NMR field probes [4].



- Use navigator probe to track drift during image acquisition.

Image reconstruction

- The continuous forward model is

$$E_{q,r}(r) = C_q(r)\exp\left(-iG(r)\,k(t)\right)$$

for the q^{th} coil sensitivity and the generalized encoding field, G, over all positions, r, in the 2D FOV.

- For one spin echo at a given rotation of the encoding field, the signal equation becomes

$$s_q(t) = \int_{FOV} C_q(r)\exp\left(-i2\pi\, G(\theta, r)\, t\right) m(r)dr$$

where m is the sample. In the discrete case,

$$s_{q,t} = \Sigma_r\, C_{q,r}\exp\left(-i2\pi\, G_{\theta,r}\ t\right)\ m_r = \Sigma_r\, E_{(q,\theta,t),r}\, m_r$$

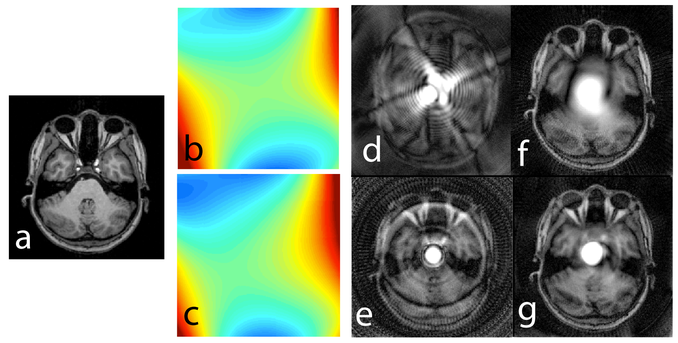
for encoding matrix with rows indexing the coil, rotation angle, and time point and columns indexing position.

- Use ***Kaczmarz method*** [5] for iterative matrix inversion to solve for m by stepping through all rows n of matrix E to update image estimate:

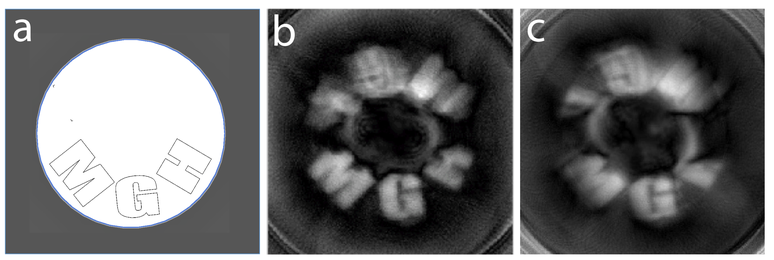
$$\hat{m}_{new} = \hat{m}_{old} + \lambda\frac{\overbrace{s_n - \langle E_n, \hat{m}_{old}\rangle}^{error}}{||E_n||^2}E_n^*, \qquad 1 < n < N_k N_C$$

- *Advantage over conjugate gradients* : Monitor convergence on fine time scale for tuning up the recon.
- Surface coil B_1^- varies depending on B_0 angle!
- Obtain approximate B_1^- using Biot-Savart Law. Difficult to calculate phase correctly.

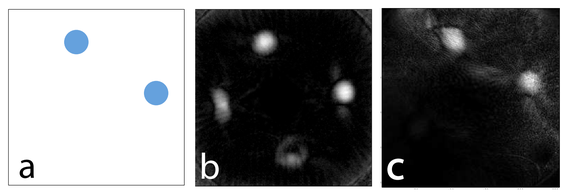
Preliminary results



Simulated reconstruction of reference object (a) comparing existing quadrupolar encoding field (b) and field with 2000 Hz/cm offset added (c) for single uniform coil (d,g) and 8ch RX array (f,g). A linear offset improves resolution in the center and reduces aliasing. 128 projections used.



Exp. proof of concept: CuS-doped phantom (a) imaged using uniform solenoid coil for RX (b) and birdcage-mode combination of surface coil signals (c). 91 proj. angles, 32 ave, 12 min.,16cm FOV, TR/TE=400/7ms.



Experimental two-ball phantom (a) imaged with solenoid RX shows expected aliasing (b). Aliasing is removed in parallel recon of 4-coil data (c).

Conclusion

- Generalized image reconstruction enables flexible MRI applications such as a portable scanner.
- ***Benefit: Replace expensive, bulky, heavy hardware with computationally-intensive software.***

Future work:
- Improve surface coil model to remove systematic error.
- Extend to multi-slice case using TRASE RF phase encoding [6] along Halbach axis.

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