Harvard-MIT Division of Health Sciences and Technology
HST.584J: Magnetic Resonance Analytic, Biochemical, and Imaging Techniques, Spring 2006
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Magnetic Particle Imaging*

A Parallel to MRI?

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*Gleich, B. and Weizenecker, J. Tomographic imaging using the nonlinear response of magnetic particles. *Nature*. **435**: 1214-1217 (2005).

What is Magnetic Particle Imaging (MPI)?

In the simplest terms – Imaging the magnetization of magnetic nanoparticles (MNPs)

- Spatially Resolved Magnetorelaxometry
  - Utilizes a SQUID gradiometer sensitive to 1st or 2nd spatial derivative of magnetic field
    - Romanus, E. *et al*. Magnetic nanoparticle relaxation measurement as a novel tool for *in vivo* diagnostics. *J. Magn. Magn. Mat.* **252**: 387-9 (2002).
- Imaging magnetization of MNPs using their nonlinear response to a modulated field
  - Spatial selection possible by taking advantage of saturation effects

Nonlinear Response of MNPs

Diagram removed for copyright reasons. See Young, H. D. *University Physics*. 8th ed. Addison-Wesley, Sec 29-8 (1992).

- Applies to ferromagnetic materials
- Nonlinear response occurs from zero-field values

Nonlinear Response to Modulated External Field

- Oscillating magnetic field applied to MNPs
- Produces a time varying response in magnetization [M(t)]
- M(t) is composed of a number of higher harmonics
- Addition of a time-invariant field produces constant M(t) and minimized harmonics

Graphs removed for copyright reasons.
See Figure 1 (page 1214) from Gleich, B., and J. Weizenecker.
"Tomographic Imaging using the Nonlinear Response of Magnetic Particles."
Nature 435 (2005): 1214-1217.

MPI Spatial Selection

Field-Free Point (FFP)

Diagram removed for copyright reasons.

See Figure 1 (page 1173) from Trabesinger, A. "Particular Magnetic Insights." *Nature* 435 (2005): 1173-4.

- Time-independent spatially varying field applied
- Most of object has magnetization saturated
- Regions around zero field strength respond nonlinearly
- Modulated signal [M(t)] in response to oscillating field occurs only in region of nonlinearity

Magnetic Contrast Agents in MPI vs MRI

Resovist – carboxydextran-coated superparamagnetic iron oxide (SPIO) particles (ferucarbotran)

MRI	MPI
• Liver-specific contrast agent • Magnetic susceptibility affects on protons • Decreases T_1, T_2, T_2^* • Diminished signal intensity in T_2 and T_2^* -weighted images	• Directly image the magnetization • Only areas with contrast agent highlighted • No biological signal • Improved SNR

See Blakeborough et al. "Hepatic lesion detection at MR imaging: a comparative study with four sequences." *Radiology* 203 (1997): 759-65.

Methods of MPI Image Acquisition

Two Fundamental Ways to Spatially Encode

Mechanical Movement

- Object physically moved around the FFP
- Low amplitude oscillating field
- Slow Scanning Speed
- Low SNR

Diagram removed for copyright reasons.
See Figure 2 (page 1215) from Gleich, B., and J. Weizenecker.
"Tomographic Imaging using the Nonlinear Response of Magnetic Particles."
Nature 435 (2005): 1214-1217.

Field-Induced Movement

- Apply 3 homogenous fields (drive fields) orthogonal to object
- FFP moved by adjusting drive fields
- High amplitude oscillating fields
- Fast encoding and high SNR

Compare MPI and MRI Spatial Encoding

“*Because the interaction may be regarded as a coupling of the two fields by the object, I propose that image formation by this technique be known as zeugmatography, from the Greek ζευγμα, ‘that which is used for joining*.”*

MRI	**MPI** (Theoretical)
• Static magnetic field for proton resonance • 3 gradient fields for spatial encoding: – 1 axial (Z) slice selection – 2 transverse (XY) encoding • Oscillating current applied to gradient field coils – At proton resonance • Gradient coils detect signal • Phased arrays possible • Large apparatus	• Static magnetic field for selecting nonlinear region (selection field) • 3 gradient fields for spatial encoding (drive fields) • Oscillating current applied to gradient field coils – Independent frequency selection • Separate recording coil(s) • Single side application • Small apparatus

*Lauterbur, P.C. Image formation by induced local interactions: examples employing nuclear magnetic resonance. *Nature.* **242**: 190-1 (1973).

MPI – Proof of Principle

Images removed for copyright reasons.
See Figure 3 (page 1215) from Gleich, B., and J. Weizenecker. "Tomographic Imaging using the Nonlinear Response of Magnetic Particles." *Nature* 435 (2005): 1214-1217.

Diagram of Maxwell coils and magnetic field lines removed for copyright reasons.

Imaging Resolution in MPI vs MRI

Encompasses Spatial Resolution and SNR

MRI

- Physically limited by movement of H_2O
- Practically limited by gradient slewing, measurement time and noise from instrumentation
- Determined by FOV and sampling frequency in transverse plane
- Determined by gradient slice selection in axial plane

$$pixel = \frac{FOV}{\#\, pixels} = \frac{1}{\gamma G_x f_s}$$

$$\Delta z = \frac{\Delta\omega}{\gamma G_z}$$

MPI (Theoretical)

- Limited by field strength at which MNPs produce significant harmonics
- Also, determined by gradient changes and measurement time ($\propto$ drive frequency)
- SNR is large: field intensity from MNPs

$$R = 2\frac{B_k}{G_s}$$

Graph removed for copyright reasons.

See Figure 4 (page 1216) from Gleich, B., and J. Weizenecker. "Tomographic Imaging using the Nonlinear Response of Magnetic Particles." *Nature* 435 (2005): 1214-1217

MPI Image Reconstruction

Drive field leads to contribution of neighboring points

Need to find the MNP response for each harmonic detected

$$V_n(\hat{y}) = \int G_n(\hat{r})C(\hat{x})d\hat{x}$$

$$\big\downarrow \ \textit{FT}$$

$$v_n(\hat{k}) = g_n(\hat{k})c(\hat{k})$$

Solve for g_n(k) by imaging known reference sample and dividing out c(k). Then perform FT to obtain response function.

How to Apply MPI to Medical Imaging

- Need to image larger volume (> 6mm X 6mm)
  - Determined by the FFP shift: $F = 2A / G_s$
- Need faster encoding time (<<18 min)
  - Determined by voxel volume (N^3) and drive field frequency (~ 25 kHz): $T = N^2 / f_1$
- Therefore, need larger drive fields and potentially higher frequencies
- Drive field amplitudes ~20mT and frequencies ~ 100kHz can be safely used in humans

MRI & MPI Head to Head

MRI	MPI
• Detects native signal from tissue	• Detects signal from administered agents
• **Many** multiple imaging techniques	• Will only image MNPs
• Can also utilize administered contrast agents	• High contrast with background
• SNR $\propto B_0$	• High Sensitivity and Resolution
• Body and instrument noise effects sensitivity	• Long RF wavelength (~1km) allows significant tissue penetration
• Equipment $$$$	• Potentially Cheaper Equipment
• Detectors small to prevent spin cross-talk	• Detectors can be much larger than the imaging volume
• Ever growing field	