MRI in the wild

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Novel Methods for Phytosequestration
ARPA-E Workshop
Chicago, 23 July 2015
“Wild” MRI?

High-field MRI instruments are of limited utility in widely deployable contexts.
“High-performance” ultra-low field MRI?

What would high-performance ULF MRI look like?
“High-performance” ultra-low field MRI?

What would high-performance ULF MRI look like?

MGH Connectome scanner: 24 MW
Los Angeles-class nuclear submarine
Ultra-low field MRI?

Field strength

- 0.001 T
- 0.01 T
- 0.0065 T
- 0.1 T
- 1 T
- 1.5 – 3 T
- 7 T

**6.5 mT**

Custom made Electromagnet + Gradients

**$200k test-bed system**

1.5 T – 3T

- Cost: ≈ $1 million / Tesla
- Weight: 7.3 tons
- Cooling: Liquid cryogens / Availability?
- Shielding: RF/magnetic
- Min. room size: 31m² ++
Ultra-low field MRI?

Acquisition time: seconds, minutes...

2D Gradient echo – 1 slice – acquired at ULF

Acq. time = 52 min / Voxel size = (3.9 x 7.8 x 15) mm$^3$
Fast acquisition strategy for ULF MRI

Balanced Steady State Free Precession (b-SSFP):
- Fast & efficient but demanding
- Refocused quantum control-based acquisition

State of the Art: non-cryogenic ULF MRI (6.5 mT)

Custom-fit single channel spiral head coil (276 kHz)

LANL 2015

6 min,

3.9 x 7.8 x 15 mm³
52 minutes, 2D GE

2 x 2.4 x 15 mm³ (5 slices)
67 min
3D MR fingerprinting *in vivo* at 6.5 mT

Stochastic Bloch trajectory-based imaging:

Optimized 20 point trajectory
3x3x10 mm³
NA: 1
Total acquisition time: **14min**

- Gray matter: $T_1 = 172\text{ms}$, $T_2 = 85\text{ms}$
- White matter: $T_1 = 127\text{ms}$, $T_2 = 76\text{ms}$
- Scalp: $T_1 = 91\text{ms}$, $T_2 = 69\text{ms}$

Quantitative image contrast!
Non-cryogenic ULF MRI (6.5 mT): Ultra-low field vs. high field in clinical TBI

3 T

6.5 mT

Traumatic skull cranioplasty w/ titanium mesh & MMA implant

High field: T2 FLAIR
ULF: 3D b-SSFP, 3x3x8.5 mm, 15 slices
NA=140, $\alpha=84^\circ$, Matrix: 64x75x15, 28 min.
What do we measure in MRI?

- Nuclear (Boltzmann) polarization: \( P \sim \frac{\mu B}{k_B T} \)
- Magnetization per unit volume: \( \rho \mu P \)

**Direct detection:**
- Liquids, *solids* (thermally polarized)
- ...& gases (non-Boltzmann “hyperpolarization”)
- Not just \( ^1H \)!
- \( ^3He, ^{129}Xe, ^{13}C, ^{23}Na, ^{29}Si ... \)

**Indirect detection:**
- Paramagnetic things (Gd) via nuclear relaxation
- Free radicals (Bohr magnetons) via polarization transfer (DNP)

*Physics*: Overhauser techniques transfer electron polarization into long-lived nuclear polarization
The Overhauser effect

Zeeman interaction

Scalar Dipolar Time dependent coupling

Rates depend on dynamics, $H_0$, & $|e^-$]

$H = g_S S \times H_0(0) + g_I I \times H_0(0) + g_S g_I 2^{8p/3} y(0) 2^S \times S(0) - 3^I \times r(0) S \times r(0) r^5 + I \times S r^3$
Hardware: free radical imaging at 6.5 mT

**NMR (276 kHz)**
- Johnson noise dominated
- Litz wire
  - BW=3KHz
  - Q=92

**EPR (141 MHz)**
- Modified A-G resonator
  - High ESR homogeneity
  - Suppressed E-field (SAR)

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(a) [Diagram of EPR and NMR setup]

(b) [Graph showing electric field distribution]

(c) [Graph showing magnetic field distribution]
High speed 3D free radical imaging

Images acquired at 6.5 mT: NMR: 276 kHz, ESR: 140 MHz, 2 mM TEMPO in H2O

b-SSFP based OMRI
Embedded ESR pulse
No additional sequence time
Dynamic *in vivo* OMRI

Proof of concept in healthy rat

OMRI

Central slice in rat head – axial view

- magnitude
- phase

Matrix: 128 x 35 x 11

Resolution: 1.7 x 2.2 x 4.2 mm³

1 full 3D OMRI scan (11 slices) = 10 s + 5 s pause

16 dynamic scans: 4 min total imaging time

**Carotid injection:** 1 mL in 2 min, 150 mM TEMPOL
Conclusions

- MRI is possible outside the scanner suite
  - Not limited to brain imaging!
  - Not limited to existing scanner footprint
  - Understand impact of time/resolution tradeoff
  - Next revolution in healthcare? Cost!

Eg. highly optimized tradeoff between resolution, speed, specificity, cost?

- Free radical sensitive MRI is possible
  - Hyperpolarization via \textit{in vivo} DNP & high speed ULF MRI
  - Free radical tracer agents? Redox/metabolic processes?

High-speed, inexpensive “medium resolution” MRI in the wild:

How would you use a tool like this?