Active $B_1$ Imaging Using Polar Decomposition RF-CDI

Weijing Ma, Nahla Elsaid, Dinghui Wang, Tim DeMonte, Adrian Nachman, Michael Joy

Department of Electrical and Computer Engineering
University of Toronto
Outline

- Background
- Methodology
  - Magnetic field measurement
  - Current density field calculation
- Experimental Validations
  - Active $B_1$ measurement and comparison with double-angle $B_1$ mapping
  - Phantom experiments with disturbance pulses
  - Phantom experiment with injected currents
- Conclusions and Discussions
Current Density Imaging (CDI) is a technique that non-invasively measures current densities in a volume using Magnetic Resonance Imaging (MRI).

- Current is applied externally.

- Low Frequency Source (5 - 100 Hz) - LFCDI
- Radio Frequency Source (64 MHz) - RFCDI
Current Density Imaging (CDI) is a technique that non-invasively measures current densities in a volume using Magnetic Resonance Imaging (MRI).

- Current is applied externally.
- Low Frequency Source (5 - 100 Hz) - LF-CDI
- Radio Frequency Source (64 MHz) - RF-CDI
Background: Polar Decomposition RF-CDI

- RF-CDI Methods:
  - Limitations of Rotary Echo RF-CDI
    - Magnitude of the injected current is restricted;
    - Inevitable systematic artifacts and high SAR.
  - Limitations of previous Polar Decomposition RF-CDI
    - Low SNR due to phase-wrapping and axis flips.
Flowchart: How PD-RFCDI works ...

Injected Current Density $J$ → Induced Magnetic Field $H$ → Changes in Local Magnetic Fields → Magnetization variations w.r.t. Position → Reconstructed Magnetic Field $H$ → Injected Current Density $J$ with $J = \nabla \times H$ → Encoded MRI Images
PD-RFCDI consists of two important reconstruction steps:

- Part 1: to measure the magnetic field from the rotation of magnetization measured by MRI;
- Part 2: to compute current density field from the measured magnetic field.
Flowchart: How PD-RFCDI works ...

Injected Current Density \( J \) → Induced Magnetic Field \( H \) → Changes in Local Magnetic Fields

- Magnetization variations \( w.r.t. \) Position

Reconstructed Magnetic Field \( H \) → Encoded MRI Images

Reconstructed \( J \) with \( J = \nabla \times H \)
How to measure the magnetic field from the rotation of magnetization?

- **Bloch’s Equation:**
  \[
  \frac{\partial \mathbf{M}}{\partial t} = \gamma \mathbf{M} \times (\mathbf{H}_L) - \frac{M_z - M_z^0}{T_1} \mathbf{z} - \frac{M_x}{T_2} \mathbf{x} - \frac{M_y}{T_2} \mathbf{y}
  \]

  - **Current-induced Magnetic Field Component**

- **Physical Interpretation:** Magnetization \(\mathbf{M}\) rotating about the rotation axis:
  - Magnitude of \(\mathbf{H}\) determines the rotation angle;
  - Orientation of \(\mathbf{H}\) determines the rotation axis.
How to measure the magnetic field from the rotation of \textbf{M}?

\textbf{Answer:} to measure the rotation angle and axis of \textbf{M}.

How to measure the rotation angle and axis of \textbf{M}?

\textbf{Answer:} three steps

1. Polar Decomposition;
2. Quaternion operation;
3. Dual-unwrapping.
How to measure the magnetic field from the rotation of $\mathbf{M}$?

- Answer: to measure the rotation angle and axis of $\mathbf{M}$.

How to measure the rotation angle and axis of $\mathbf{M}$?

- Answer: three steps
  1. Polar Decomposition;
  2. Quaternion operation;
  3. Dual-unwrapping.
Polar Decomposition: to extract rotation matrix from snapshots of the starting and ending positions of \( \mathbf{M} \).
Polar Decomposition: Rotation and Relaxation Decoupling

Top: The x and y components of $\mathbf{M}$ from the Maxwell-Bloch simulation.

Bottom: The x and y components of $\mathbf{M}$ after polar decomposition.

90% decrease in the discontinuity between the left and right halves after the polar decomposition.
How to measure the magnetic field from the rotation of $M$?

Answer: to measure the rotation angle and axis of $M$.

How to measure the rotation angle and axis of $M$?

Answer: three steps

1. Polar Decomposition;
2. Quaternion operation;
3. Dual-unwrapping.
Quatetion operation:
- Extracts rotation angle and rotation axis information from the rotation matrix.
- Introduces phase wraps and axis false-flips in regions where rotation angles reach multiples of $\pi$.

Dual-unwrapping:
- Unwraps the rotation angle and rotation axis that have been falsely interpreted in quaternion conversion.
Dual-unwrapping: Flood-fill algorithm

- Start from initial seed point A
- remove false flips and phase wraps in the neighborhood
- Find the next pixel with the highest quality value
- Set it to be the next seed point
- Probe the neighbourhood of the new seed point, remove false flips and phase wraps
Dual-unwrapping: simulations

Rotation angle

x y z components of rotation axis
**Flowchart: How PD-RFCDI works ...**

1. Injected Current Density $J$
2. Induced Magnetic Field $H$
3. Changes in Local Magnetic Fields
4. Magnetization variations w.r.t. Position
5. Encoded MRI Images
6. Reconstructed Magnetic Field $H$
7. Reconstructed $J$ with $J = \nabla \times H$
Current Density field $J$ is calculated by taking the curl of magnetic field $H$: $J = \nabla \times H$.

When single orientation assumption $\frac{\partial H_z}{\partial z} \parallel J_z$ is met, current densities can be computed through

$$J_z = j_z e^{j\varphi_z} = 2 \left[ \frac{\partial \tilde{H}_y^l}{\partial x} - \frac{\partial \tilde{H}_x^l}{\partial y} \right] + 2j \left[ \frac{\partial \tilde{H}_x^l}{\partial x} + \frac{\partial \tilde{H}_y^l}{\partial y} \right]$$

Conclusion: only the transverse magnetic field components are required to compute the longitudinal component of RF current density vectors.
Outline

 tá Background
 tá Methodology
 tá Magnetic field measurement
 tá Current density field calculation
 tá Experimental Validations
 tá $B_1$ measurement and comparison with double-angle $B_1$ mapping
 tá Phantom experiments with disturbance pulses
 tá Phantom experiment with injected currents
 tá Conclusions and Discussions
Validations: Double Angle vs. PD-RFCDI

- Double angle $B_1$ mapping method:
  - Conceptually simple
  - Straightforward implementation
  - One of the gold standards for active $B_1$ mapping

- Experiment settings:
  - A GE manufactured acrylic phantom was used.
  - GE bird cage head coil used as transmit/receive.
  - Flip angles $\alpha_1 = 20^\circ$ and $\alpha_2 = 40^\circ$
  - Excitation pulse of PD-RFCDI was calibrated to match the parameters in the double angle method.
Validations: PD-RFCDI v.s. Double Angle

Comparison of the measured flip angle using polar decomposition method (left) and the double angle mapping methods (right)
PD-RFCDI is able to measure the phase information of the active $B_1$ field
A hard 90 pulse was applied to the RF excitation coil to create a 90-degree tip angle.

The experiment was conducted on a GE manufactured acrylic phantom.
A disturbance pulse was applied to the gradient X coil to create a linearly increasing magnetic field along the x-axis.

Pulse duration was 8.2 ms and the relative pulse amplitude was 0.02.
Polar Decomposition RF-CDI with Injected Current

- Experiment settings

- RF pre-amplifier
  - RF excitation pulse
  - trigger signal

- MRI scan system
  - trigger signal
  - imaging pulses

- SSR control switch
  - Turn on/off

- RF current control box
  - trigger signal

- Saline filled phantom
  - injected current

- RF amplifier

- Matching network

- Feeding wires of the phantom
Phantom settings

- Three-chamber phantom;
- Copper electrodes covering only the inner two chambers;
- Center chamber filled with conductive saline;
- Outer two chambers filled with CuSO$_4$ doped water.
Current magnitude and phase vary from the inner to the outer chamber;
Consistent reconstruction results with comparison to the FDTD simulation.
Updated Flowchart: How RF-CDII works ...

1. Injected Current Density \( J \)
2. Induced Magnetic Field \( H \)
3. Changes in Local Magnetic Fields

Impedance distribution

- 180 rotation
- RF-CDII formula

Reconstructed \( J \) with \( J = \nabla \times H \)

Reconstructed Magnetic Field \( H \)

Magnetization variations w.r.t. Position

Encoded MRI Images
Conclusions and Discussions

In this work, we have:
- compared PD-RFCDI with the double angle B1 mapping method to confirm the validity of PD-RFCDI measurements.
- conducted the phantom experiments that showed PD-RFCDI is able to detect disturbances applied through RF and gradient coils;
- performed the phantom experiment with injected currents on a commercial scanner;
- proved that the new, improved PD-RFCDI is able to reconstruct currents of a much larger dynamic range.

Future work includes:
- to perform full vector PD-RFCDI experiment with 180 rotations;
- to implement RF impedance imaging algorithm (RF-CDII) with the measured RF current information.
References

• W. Ma, PhD thesis, Univ. of Toronto, 2010.
Acknowledgements

• Dr. Michael Joy, University of Toronto
• Dr. Adrian Nachman, University of Toronto
• Dr. Greig Scott, Stanford University
• Dr. Dinghui Wang, Center for Imaging Innovation at Barrow Neurological Institute
• Tim DeMonte, Field Metrica Inc.
• Nahla Elsaid, University of Toronto

Funding support
• Mitacs Elevate
• NSERC
• University of Toronto
For More Information on CDI, RFCDI, PD-RFCDI...

www.currentdensityimaging.org

- Software downloads;
- Reference papers;
- Projects overviews;
- Contact information.

Current Density Imaging

What is Current Density Imaging?

Current Density Imaging (CDI) is an imaging technique that measures electrical current density vectors in a volume of material/tissue which can be imaged using Magnetic Resonance Imaging (MRI). Measurements are performed by applying an external current to the material/tissue during an MRI acquisition. The magnetic fields produced by the applied current are mapped onto the phase images* of the MRI acquisition. The phase images are processed to compute the current density vectors. Performing CDI requires an MRI system, additional hardware, a modified pulse sequence (PSD) and data processing software.
Thanks for your attention!