First Order Induced Current Imaging and Electrical Properties Tomography in MRI

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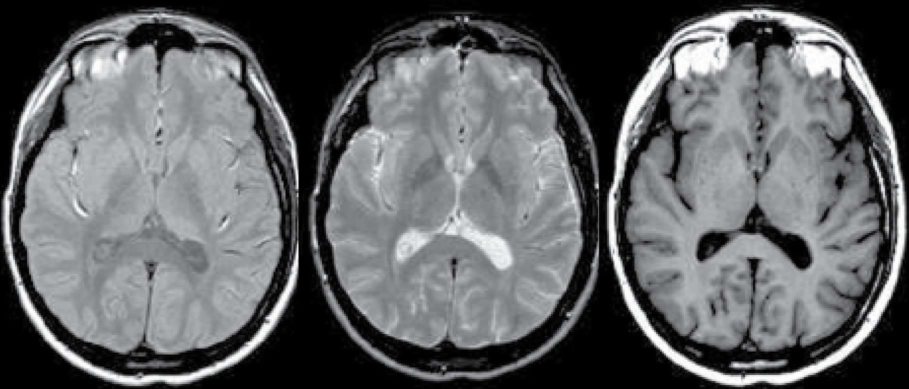
Outline

Introduction



Images of the human head with different forms of contrast: (left) a spin density-weighted image, (middle) a T_2-weighted image, and (right) a T_1-weighted image. Images taken from Brown, Cheng, Haacke, *et al.* [1]

Introduction

Qualitative imaging:

- Fast;
- Weighting is possible.

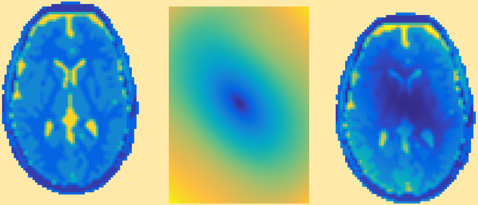
Quantitative imaging:

- Relaxation parameters;
- Proton density;
- Electrical properties;
- Spectroscopy;
- fMRI.

Introduction

Electrical properties and fields

- Electrical Properties
  - Conductivity (σ)
  - Permittivity (ε)
- Electric field ($\mathbf{E}$)
- Induced currents ($\mathbf{J}^{\mathrm{ind}}$)



Why do we want to know?

- Specific Absorption Rate (SAR)
- Oncology biomarkers[1]
- Stroke imaging

[1] K. K. Tha, U. Katscher, S. Yamaguchi, *et al.*, "Noninvasive electrical conductivity measurement by mri: A test of its validity and the electrical conductivity characteristics of glioma", *European radiology*, vol. 28, no. 1, pp. 348–355, 2018

Current imaging

Current imaging

Measured field[2]

$$\hat{B}_1^+ = \frac{\hat{B}_x + \mathrm{j}\hat{B}_y}{2}. \tag{1}$$

Maxwell's equations of the magnetic field

$$-\partial_x \hat{B}_y + \partial_y \hat{B}_x + \mu_0 \hat{J}_z^{\mathrm{ind}} = 0$$
$$-\partial_y \hat{B}_z + \partial_z \hat{B}_y + \mu_0 \hat{J}_x^{\mathrm{ind}} = 0$$
$$-\partial_z \hat{B}_x + \partial_x \hat{B}_z + \mu_0 \hat{J}_y^{\mathrm{ind}} = 0$$

[2] D. Hoult, "The principle of reciprocity in signal strength calculations-a mathematical guide", *Concepts in Magnetic Resonance Part A*, vol. 12, no. 4, pp. 173–187, 2000

Current imaging

Measured field[3]

$$\hat{B}_1^+ = \frac{\hat{B}_x + \mathrm{j}\hat{B}_y}{2}. \quad (1)$$

Maxwell's equations of the magnetic field in 2D[4]

$$-\partial_x \hat{B}_y + \partial_y \hat{B}_x + \mu_0 \hat{J}_z^{\text{ind}} = 0 \quad (2)$$

Combining measurement with Maxwell's equation

$$\frac{2(\partial_x + \mathrm{j}\partial_y)}{\mathrm{j}\mu_0}\hat{B}_1^+ = \hat{J}_z^{\text{ind}} \quad (3)$$

[3] D. Hoult, "The principle of reciprocity in signal strength calculations-a mathematical guide", *Concepts in Magnetic Resonance Part A*, vol. 12, no. 4, pp. 173–187, 2000

[4] B. Van Den Bergen, C. C. Stolk, J. B. van den Berg, *et al.*, "Ultra fast electromagnetic field computations for rf multi-transmit techniques in high field mri", *Physics in medicine and biology*, vol. 54, no. 5, p. 1253, 2009

Electrical Properties Tomography

Electrical Properties Tomography

Scattering formalism[5]

$$\hat{E}_z = \hat{E}_z^{\mathrm{inc}} + \hat{E}_z^{\mathrm{sc}} \tag{4}$$

Substitute known fields & currents

$$\hat{E}_z^{\mathrm{sc}} = G^{EJ}\left\{\hat{J}_z^{\mathsf{ind}}\right\} - G^{EE}\left\{\hat{E}_z\right\}$$

$$\hat{E}_z = \hat{E}_z^{\mathrm{inc}} + G^{EJ}\left\{\hat{J}_z^{\mathsf{ind}}\right\} - G^{EE}\left\{\hat{E}_z\right\}$$

$$\hat{E}_z + G^{EE}\left\{\hat{E}_z\right\} = \hat{E}_z^{\mathrm{inc}} + G^{EJ}\left\{\hat{J}_z^{\mathsf{ind}}\right\}$$

[5] A. T. de Hoop, *Handbook of radiation and scattering of waves, academic press*, 1995

Electrical Properties Tomography

Scattering formalism[6]

$$\hat{E}_z = \hat{E}_z^{\mathrm{inc}} + \hat{E}_z^{\mathrm{sc}} \tag{4}$$

Substitute known fields & currents

$$\hat{E}_z + G^{EE}\{\hat{E}_z\} = \hat{E}_z^{\mathrm{inc}} + G^{EJ}\{\hat{J}_z^{\mathsf{ind}}\} \tag{5}$$

This equation can be solved for $\hat{E}_z$ iteratively.

Induced current

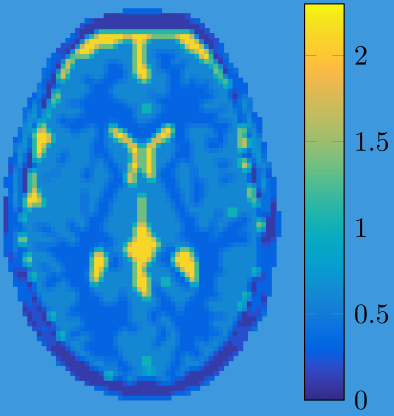
$$\hat{J}_z^{\mathsf{ind}} = (\sigma + \mathrm{j}\omega\varepsilon)\hat{E}_z \tag{6}$$

[6] A. T. de Hoop, *Handbook of radiation and scattering of waves, academic press*, 1995

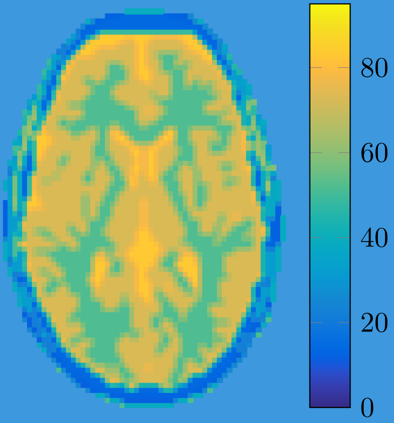
Results

Results

Simulation – Original properties



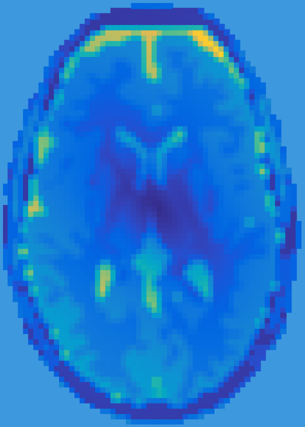
Original conductivity (σ)



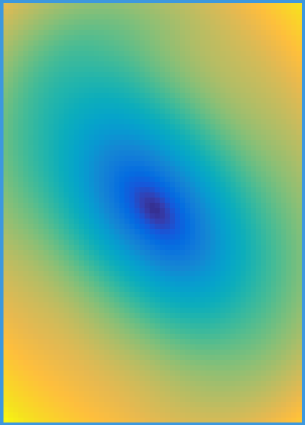
Original permittivity (ε)

Results

Simulation – Original fields / currents



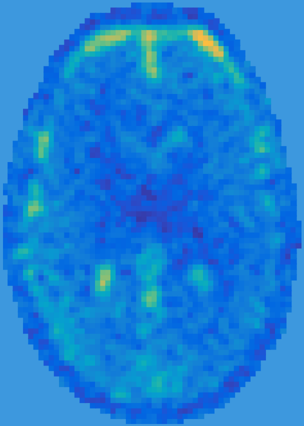
Original currents ($\hat{J}_z^{\text{ind}}$)



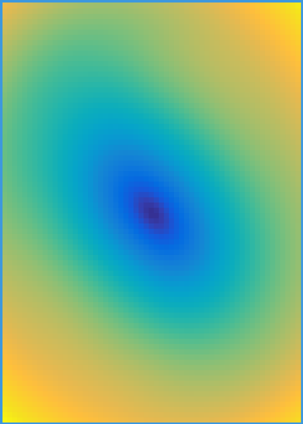
Original Electric field ($\hat{E}_z$)

Results

Simulation – Reconstructed fields / currents



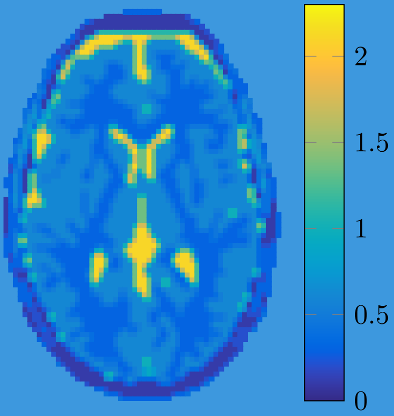
Reconstructed currents ($\hat{J}_z^{\text{ind}}$)



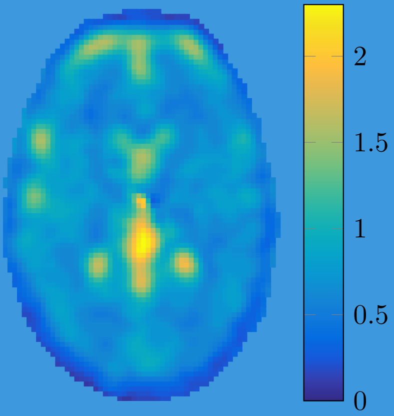
Reconstruced Electric field ($\hat{E}_z$)

Results

Simulation – Reconstructed electrical properties



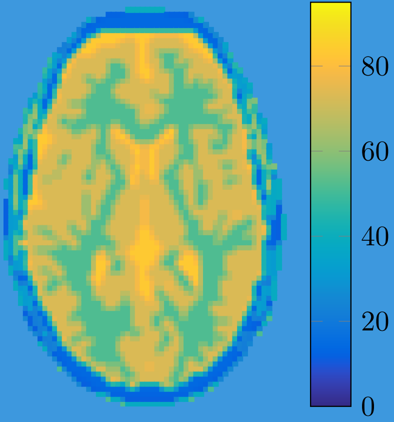
Original conductivity (σ)



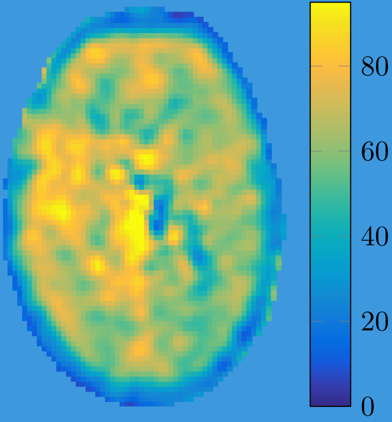
Reconstructed conductivity (σ)

Results

Simulation – Reconstructed electrical properties



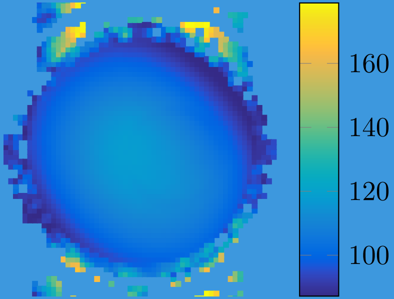
Original permittivity (ε)



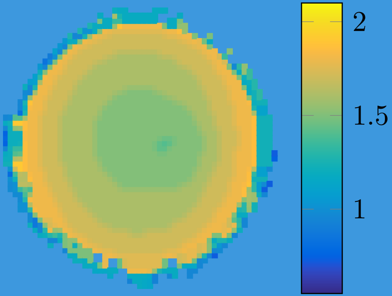
Reconstructed permittivity (ε)

Results

In-vivo



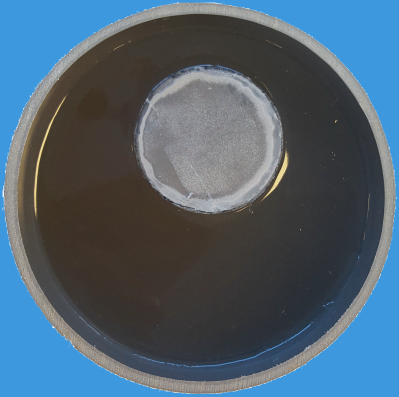
Measured field – Magnitude



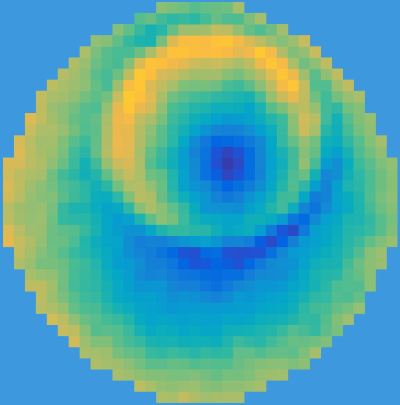
Measured field – Phase

Results

In-vivo



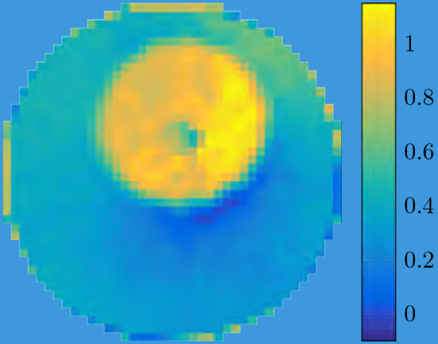
Original phantom



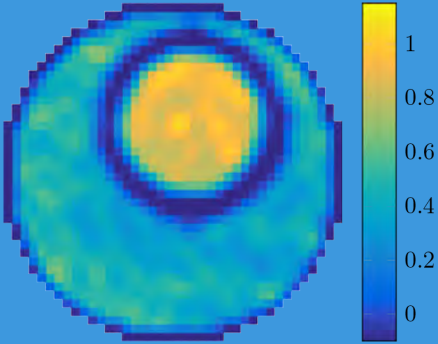
Reconstructed currents ($\hat{J}_z^{\mathrm{ind}}$)

Results

In-vivo



First Order EPT (σ)



Helmholtz EPT (σ)

Conclusions

Conclusions

1. Real time current imaging.
2. Robust to noise (in the presence of a sufficiently high E-field)
3. Accurate reconstruction of Electrical Properties
4. No boundary effects as seen in conventional methods.

Future work

- Expanding the method to three-dimensions;
- Investigating 2D assumption impact on reconstructions outside the centre of a birdcage with real measurements.

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I would like to thank my collaborators

- Dr.ir. Rob Remis,[7]
- Dr.ir. Nico van den Berg,[8]
- Dr.ir. Wyger Brink,[9]
- Dr.ir. Stefano Mandija,[7]
- ir. Peter Stijnman,[7]

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[7] Delft University of Technology – Circuits and Systems

[8] Utrecht University Medical Centre – Center for Image Sciences

[9] Leiden University Medical Centre – C.J. Gorter Centre for High Field MRI

Thank you for your attention

Any questions?

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References

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