Dielectric Shimming and EPT in MRI

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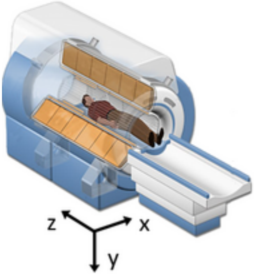
Introduction

Two RF research topics in high-field MRI

- Dielectric shimming (optimal pad design)
- Electrical Properties Tomography – EPT

Introduction

- Magnetic and RF fields in MRI



- The B_0 field: strong longitudinal static magnetic field (1.5T, 3T, 7T)
- Gradient fields: static magnetic fields used for slice selection
- RF field: transverse radiofrequency field used to flip the spins

Introduction

- The RF field is called the B_1 field
- Frequency of operation (Larmor frequency)

$$f = \gamma B_0$$

- γ is the gyromagnetic ratio ≈ 42.577 MHz/T (proton)
- Consequently,

$$\begin{aligned} f &= 64 \text{ MHz} && \text{at } 1.5\text{T} \\ f &= 128 \text{ MHz} && \text{at } 3\text{T} \\ f &= 300 \text{ MHz} && \text{at } 7\text{T} \end{aligned}$$

Introduction

- Time factor: $\exp(\mathrm{j}\omega t)$
- Decomposition of the vectorial B_1 phasor into circularly polarized fields:

$$\hat{B}_1 = \underbrace{\hat{B}_1^{\mathrm{rh}}(\mathbf{i}_x - \mathrm{j}\mathbf{i}_y)}_{\text{circ. pol.}} + \underbrace{\hat{B}_1^{\mathrm{lh}}(\mathbf{i}_x + \mathrm{j}\mathbf{i}_y)}_{\text{circ. pol.}}$$

- First term is right-handed with respect to the $\mathbf{i}_z$-direction
- Second term is left-handed with respect to the $\mathbf{i}_z$-direction

$$\hat{B}_1^{\mathrm{rh}} = \frac{\hat{B}_{1;x} + \mathrm{j}\hat{B}_{1;y}}{2} =: B_1^+ \qquad \hat{B}_1^{\mathrm{lh}} = \frac{\hat{B}_{1;x} - \mathrm{j}\hat{B}_{1;y}}{2}$$

Introduction

- The B_1^+ field essentially produces the MR image
- At sufficiently high frequencies, the dielectric composition of the body influences the B_1^+ field
- Interference effects – dielectric shimming
- Retrieval of dielectric properties of tissue – EPT

Dielectric shimming

In collaboration with the Gorter Center of the LUMC

Prof. A. Webb (LUMC), Dr. W. Brink (LUMC), Ir. J. van Gemert (PhD, TUD/LUMC)

- In high-field MRI ($\geq$ 3T) so-called signal voids may appear

- Possible solutions: active and passive shimming

Dielectric shimming

- Main objective: develop an efficient dielectric pad design tool
- Observations Part 1:
  - Background (body, coil, etc.) remains fixed when looking for an optimal pad
  - Pads are relatively small w.r.t. the background configuration

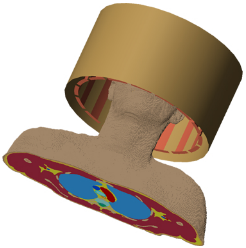
Dielectric shimming

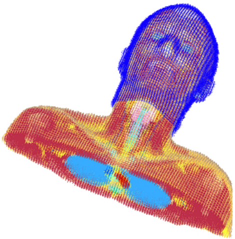
- Identify a domain where a pad can be possibly located = pad domain
- Make use of the linearity of Maxwell's equations
- and setup a scattering formalism

$$\text{total field} = \text{background field} + \text{scattered field}$$

Background field = field in fixed background (body+coil+...),
Scattered field = field due to the presence of a dielectric pad

Dielectric shimming





- In a formula

$$\mathbf{b}_1^+ = \mathbf{b}_1^{+;\text{no pad}} + \mathsf{G}^{B_1^+\mathsf{J}} \left[\mathsf{I}_P - X_{\text{pad}} \mathsf{G}^{\mathsf{EJ}} \right]^{-1} X_{\text{pad}} \mathbf{e}^{\text{no pad}}$$

- P = number of voxels belonging to the pad domain $\ll$ order of system

Dielectric shimming

- Scattering formalism is essentially the same as application of the Sherman-Morrison-Woodbury inversion formula from linear algebra
- Pad forms a small rank perturbation of the large system
- Computing B_1^+ fields using scattering formalism is significantly faster than solving full systems for each pad realization
- Speed up factor strongly depends on pad size
- J. van Gemert *et al.*, IEEE Transactions on Medical Imaging, 2017.

Dielectric shimming

- Observations Part 2
- Each voxel in the pad domain introduces a degree of freedom
- This many degrees of freedom is not necessary for designing pads in practice
- No optimization is included

Dielectric shimming

In collaboration with the Imaging Division of the UMC Utrecht

Dr. N. van den Berg, Dr. A. Sbrizzi, Ir. S. Mandija

- Given the B_1^+-field inside the body
- Determine the conductivity and permittivity tissue maps
- Determine the electric field strength

Electrical Properties Tomography

- Existing methods assume homogeneous media
- Differentiation operators act on the measured B_1^+-field

- We have proposed a new solution methodology
- No homogeneous model is assumed
- Integral operators instead of differential operators
- Method can determine the electric field strength as well
- Method is called CSI-EPT: CSI = Contrast Source Inversion

Electrical Properties Tomography

- CSI-EPT minimizes an objective function of the form

$$F(\mathbf{w}, \chi) = \left[F_{\text{data}}(\mathbf{w}) + F_{\text{object}}(\mathbf{w}, \chi)\right] F_{\text{TV}}(\chi)$$

- F_{data} data mismatch
- F_{object} mismatch in satisfying Maxwell's equations
- F_{TV} regularization term
- χ = dielectric contrast function
- $\mathbf{w} = \chi\mathbf{E}$ = contrast source

Electrical Properties Tomography

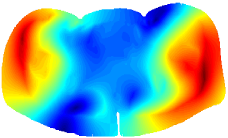
- Integral Green's tensor representations for the fields are used
- Method updates contrast source and contrast in an alternate fashion uisng CG-type updating formulas
    - Fix contrast, update contrast source
    - Fix new contrast source, update contrast

Electrical Properties Tomography

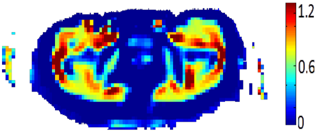
- In the midplane of the birdcage coil, the RF field is approximately 2D and E-polarized
- 2D implentation for midplane tissue reconstruction (3T)

Electrical Properties Tomography

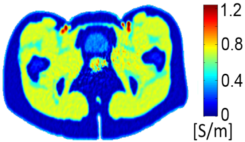
True conductivity profile
Slice through abdomen region
female body model



Input: B1+ field
Measured with an MRI scanner



Reconstruction standard EPT



Reconstruction CSI-EPT

Electrical Properties Tomography

- Recently, we have extended CSI-EPT to 3D
- Simplified inversion schemes have been/are being developed
- Real-time induced-current imaging