Conductivity estimation of the human head in the low frequency domain using IC-MREIT with multi gradient echo sequences

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• Introduction
  Conductivity estimation of the human head in the low frequency domain

• Methodology
  Induced Current – Magnetic Resonance electrical impedance tomography (IC-MREIT) with multi gradient echo sequences

• Results

• Conclusions
Accurate electrical conductivity values of brain tissues

Important for the correct diagnosis and therapy of neurological diseases
- EEG source localization
- Mapping brain activity (MEG)
- Magnetic brain stimulation (TMS) [1]
- Etc.

Appropriate parameter to distinguish healthy from cancerous tissues

In the low-frequency domain

The electrical conductivity varies naturally with frequency

4 Cole-Cole model \[2\]

\[
\sigma(\omega) = -\omega \varepsilon_0 \Im [\varepsilon_\infty + \frac{\Delta \varepsilon_4}{1 + (j\omega \tau_4)^{1-\alpha_4}} + \frac{\sigma_i}{j\omega \varepsilon_0}]
\]

Low frequency range of interest (10 – 10^4 Hz)

Nevertheless often approximated by a constant value

Induced current - Magnetic Resonance Electrical Impedance Tomography (IC-MREIT) [3]

Currents are induced in the patients head by the gradient coils of the MR scanner (ECI gradient). The resulting internal magnetic flux densities cause variations of the phase image which is measured by the MR scanner and used to reconstruct the conductivity distribution of the patients head.

Principle of the MR imaging

Using IC-MREIT

- Water molecule
- Hydrogen proton
- MR signal
- Magnitude image
- Phase image

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Principle of the used gradient echo (GE) sequence

Using IC-MREIT

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Phase image

\[ \phi(r) = \int_{0}^{\text{TE}} \gamma_{g} B_{\text{total}}(r, t) \cdot dt \]  
with \( \gamma_{g} = 26.75 \cdot 10^{7} \text{ rad/sT} \) and TE the echo time

Without ECI gradient

The main uniform DC field \( B_{\text{DC}} \)

3 gradient fields \( B_{x} + B_{y} + B_{z} \) for spatial localization  

The RF field \( B_{\text{RF}} \) for excitation

With ECI gradient

An additional ECI gradient field \( B_{\text{ECI}} \)

\( B_{\text{total ECI}} = B_{\text{total}} + B_{\text{ECI}} + B_{s} \)  

Faraday: \( B_{p} \)

Faraday: \( B_{s} \)

Phase difference [4]

\[ \Delta \phi(r) = \int_{0}^{\text{TE}} \gamma_{g} B_{s}(r, t) \cdot dt \]

Using IC-MREIT


Using IC-MREIT

Measurement

- Time-varying magnetic field
- Voltage source $V_{ECI}$

- Induced currents $J_{induced}$
  - Calculated using the independent impedance method $ZJ_{induced} = V_{ECI}$

- Secondary magnetic field $B_s$
  - Calculated using Biot-Savart

- 'Measured' phase difference $\Delta \phi$

Simulation

- Time-varying magnetic field
- Voltage source $V_{ECI}$

- Induced currents $J_{induced}$
  - Calculated using the independent impedance method $ZJ_{induced} = V_{ECI}$ [5]

- Secondary magnetic field $B_s$
  - Calculated using Biot-Savart

- Simulated phase difference $\Delta \phi$

- Cost function
  - $\Delta \phi - \Delta \phi$

- Termination criteria satisfied?
  - Yes: Recovered conductivity values
  - No: Conductivity update

Initially 4 parameters / tissue

\[
\sigma(\omega) = -\omega \varepsilon_0 \Re \left[ \varepsilon_\infty + \frac{\Delta \varepsilon_4}{1 + (j\omega \tau_4)^{1-\alpha_4}} + \frac{\sigma_i}{j\omega \varepsilon_0} \right]
\]

\[\rightarrow \Delta \varepsilon_4, \tau_4, \alpha_4, \sigma_i\]

No good solutions for > 2 tissues [6]

By using multiple ECI gradients only 1 parameter / tissue

with conservation of the frequency dependence

Phase difference of a spherical head model segmented into the tissues skin, bone, gray and white matter
Non-linear least squares method

\[
\text{cost} = \frac{\| \Delta \varphi - \Delta \phi \|}{\| \Delta \varphi \|}
\]

ECI gradient \((T = 20 \text{ ms}, \tau = 0.1 \text{ ms and } A = 20 \text{ T/m})\)
Multi gradient echo sequences

Second ECI gradient \((T = 2\text{ ms}, \tau = 0.1\text{ ms} \text{ and } A = 20\text{ T/m})\)
Conductivity estimation is important for the correct diagnosis and therapy of neurological diseases.

These values vary naturally with the frequency (4 Cole-Cole model).

Induced Current - MR Electrical Impedance Tomography by using the phase difference (with ECI gradient - without ECI gradient).

By using multiple ECI gradients only 1 parameter / tissue with conservation of the frequency dependence.

Reconstructed conductivity in a spherical model with 4 tissues.

Further research on realistic head models with more tissues (e.g. CSF) and experimental validation with measured MR data.

Thanks for your attention!