Magnetic Resonance Electrical Impedance Tomography (MREIT)

As Electromagnetic Tissue Property Imaging Modality

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Image Contrast

- Acoustic impedance
- Proton density and MR phenomena
- Oxygen and water diffusion
- Optical absorption, scattering, and emission
- X-ray attenuation
- $\gamma$-ray emission
Image Contrast

- Acoustic impedance
- Proton density and MR phenomena
- Oxygen and water diffusion
- Optical absorption, scattering, and emission
- X-ray attenuation
- $\gamma$-ray emission
- Electrical conductivity
- Electrical permittivity
- Magnetic susceptibility
- Neural activity
- Biochemistry

Electromagnetic Tissue Property

Electromagnetic Source
## Medical Imaging Modality

- Ultrasound
- MRI
- OCT
- X-ray
- PET

What are differences?

- Linear vs. nonlinear
- High vs. low sensitivity
- Well- vs. ill-posedness

- Source Imaging
- MRE
- MREIT
- EIT
- MAT-MI
- MIT
- MREPT
- QSM
- Microwave Tomography
- Terahertz Imaging
- DOT
Electromagnetic Tissue Property Imaging

- **Electrical Impedance Tomography (EIT)**
  - Admittivity (conductivity and permittivity) imaging
  - Frequency range: 10 Hz to 1 MHz
  - Difference imaging

- **Magnetic Induction Tomography (MIT)**

- **Microwave Tomography**

- **Magneto-Acoustic Tomography – Magnetic Induction (MAT-MI)**

- **MR Electrical Impedance Tomography (MREIT)**
  - Conductivity imaging
  - Frequency range: below 1 kHz
  - Static imaging

- **MR Electrical Property Tomography (MREPT)**
  - Admittivity (conductivity and permittivity) imaging
  - Frequency: Larmor frequency (128 MHz at 3 T)
  - Static imaging

- **Quantitative Susceptibility Mapping (QSM)**
**Conductivity and Resistance**

\[ \mathbf{E} = -\nabla u \quad \mathbf{F} = q\mathbf{E} \quad \mathbf{v}_d = \mu\mathbf{E} \quad \mathbf{J} = c\mathbf{v}_d \]

\[ \mathbf{J} = c\mu\mathbf{E} = \sigma\mathbf{E} = -\sigma\nabla u \]

\[ E = \frac{V}{L}, \quad J = \sigma E = \sigma \frac{V}{L}, \quad I = JS = \sigma \frac{V}{L}S \]

\[ V = \frac{1}{\sigma S} I = \rho \frac{L}{S} I = RI, \quad R = \frac{V}{I} = \frac{1}{\sigma S} \]
Permittivity and Capacitance

Immobile Polar Molecules

Polarization

\[ Q = CV = \varepsilon \frac{S}{L} V \]

\[ i(t) = \frac{dQ(t)}{dt} = C \frac{dv(t)}{dt} \]

\[ v(t) = V \sin(\omega t), \quad i(t) = V \omega C \cos(\omega t) \]

\[ V = V \angle 0, \quad I = V \omega C \angle 90^\circ, \quad Z = \frac{V}{I} = \frac{1}{j\omega C} \]
Cell and Bio-impedance

\[ i(t) = I_m \sin(\omega t) \quad \text{and} \quad v(t) = I_m Z \sin(\omega t + \theta) \]

\[ Z = R + jX = R_1 + \frac{1}{j\omega C_1} + \frac{1}{j\omega C_2} + R_2 \]

\[ Z = R + jX = Z \angle \theta \]

\[ R = Z \cos \theta, \quad X = Z \sin \theta \]
Cell Structures in Tissues

Extra-cellular Fluid

Intra-cellular Fluid

Cellular Membrane

\[ J(r, \omega) = \sigma(r, \omega)E(r, \omega) \]

\[ \sigma(r, \omega) = c(r)\mu(r, \omega) \]

- Ion Concentration
- Ion Mobility
Simple Case 1

Low Frequency Current

$\sigma(r, \omega) = c(r)\mu(r, \omega)$

High Frequency Current

Homogeneous Object

Macroscopic Conductivity Seen by the Current
Simple Case 2

\[ \sigma(r, \omega) = c(r) \mu(r, \omega) \]

- Low Frequency Current
- High Frequency Current

Insulating Membrane Filled with the Same Saline

Macroscopic Conductivity Seen by the Current
Simple Case 3

\[ \sigma(r, \omega) = c(r) \mu(r, \omega) \]

Low Frequency Current

Insulating Membrane with Holes Filled with the Same Saline

High Frequency Current

Macroscopic Conductivity Seen by the Current
**Simple Case 4**

\[ \sigma(r, \omega) = c(r)\mu(r, \omega) \]

- **Low Frequency Current**
  - Insulating Membrane with Holes Filled with the Same Saline

- **High Frequency Current**
  - Macroscopic Conductivity Seen by the Current
Simple Case 5

$\sigma(r, \omega) = c(r) \mu(r, \omega)$

Low Frequency Current

Solid Anomaly with Conductivity Contrast

Macroscopic Conductivity Seen by the Current
Admittivity of Biological Tissue

\[ \gamma(r, \omega) = \sigma(r, \omega) + j \omega \varepsilon(r, \omega) \]

- Molecular composition of cells
- Shape and direction of cells
- Density and structure of cells
- Intra- and extra-cellular fluids
- Concentration and mobility of ions
- Temperature
- Probing method including frequency and electrode configuration
Breast Tissues

Liver Tissues

Neural activity produces 1-5% local conductivity changes at low frequency.
Conductivity of Crab Nerve

From D. Holder and T. I. Oh
Functional & Pathological Changes

- Regional Lung Ventilation
- Perfusion
- Pulmonary Edema
- Cardiopulmonary Functions
- Hemorrhage
- Ischemia
- Stomach Emptying
- Visceral Fat
- Brain Functions
- Neural Activity
- Tumor
- Others
Probing by Injecting Current

\[
\begin{cases}
\nabla \cdot (\sigma(r) \nabla u(r)) = 0 \quad \text{in } \Omega \\
-\sigma(r) \nabla u(r) \cdot n = g \quad \text{on } \partial\Omega
\end{cases}
\]

\[J(r) = -\sigma(r) \nabla u(r) = \sigma(r) E(r)\]

\[B(r) = \frac{\mu_0}{4\pi} \int_{\Omega} \frac{J(r') \times (r - r')}{|r - r'|^3} \, dr'\]
Numerical Example using FEM

EIT and MREIT

EIT (Electrical Impedance Tomography)
- Admittivity imaging from 10 Hz to 1 MHz
- Boundary current-voltage measurement
- Time- or frequency-difference imaging
- Low spatial resolution
- High temporal resolution
- Functional imaging

MREIT (Magnetic Resonance EIT)
- Conductivity imaging below 1 kHz
- Internal magnetic flux density measurement
- Absolute or contrast imaging
- High spatial resolution
- Low temporal resolution
- Static and functional imaging
EIT

(Electrical Impedance Tomography)

\[ i_p(t) = I_m \sin(\omega t) \]

\[ v_q(t) = Z_{pq} I_m \sin(\omega t + \theta) \]

\[ \nabla \cdot (\gamma(\mathbf{r}) \nabla u(\mathbf{r})) = 0 \text{ in } \Omega \]

\[ -\gamma(\mathbf{r}) \nabla u(\mathbf{r}) \cdot \mathbf{n} = g \text{ on } \partial \Omega \]
Data Collection Protocol

(10^{-3}-10^{-4}A)

(10^{-4}-10^{-6}V)

Neighboring Method
Difference Imaging in EIT

The relation between voltage \( u \) and admittivity \( \gamma \) is nonlinear since

\[
\begin{align*}
\nabla \cdot (\gamma(r) \nabla u(r)) &= 0 \text{ in } \Omega \\
-\gamma(r) \nabla u(r) \cdot n &= g \text{ on } \partial \Omega.
\end{align*}
\]

- If admittivity changes as \( \gamma_2 = \gamma_1 + \delta \gamma \),
  boundary voltage changes accordingly as \( u_{\gamma_2} = u_{\gamma_1} + \delta u \).
- When \( \delta \gamma \) is small, \( \delta u = S_{\gamma} \delta \gamma \) by a linearization.
- A difference image is \( \delta \gamma = S_{\gamma}^\dagger \delta u \) by tSVD, for example.

<table>
<thead>
<tr>
<th>Time-difference (tdEIT)</th>
<th>Frequency-difference (fdEIT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( u_{T2} = u_{T1} + \delta u )</td>
<td>( u_{\omega 2} = u_{\omega 1} + \delta u )</td>
</tr>
<tr>
<td>( \gamma_{T2} = \gamma_{T1} + \delta \gamma )</td>
<td>( \gamma_{\omega 2} = \gamma_{\omega 1} + \delta \gamma )</td>
</tr>
</tbody>
</table>
EIT System

- **Current Source**
  - Digital waveform generation and DAC
  - Balanced current source using Howland circuit
  - Generalized impedance converter

- **Voltmeter**
  - Differential voltage amplifier and ADC
  - Digital phase-sensitive demodulation using FPGA
Imaging Experiments
Regional Lung Ventilation
Stomach Filling and Emptying

Filling

Emptying

0s 20s (Intake) 35s 45s 56s 1m 3s 1m 33s 1m 48s 1m 54s

15m 20m 22m 29s 25m 32m 30s 35m 50m 52m 29s
Applications of EIT

- Time-difference imaging
  - Pulmonary function
  - Cardiac function
  - Gastric emptying

- Frequency-difference imaging
  - Tumor
  - Ischemic Stoke
  - Hemorrhage
Dräger PulmoVista® 500

PulmoVista® 500 is an Electrical Impedance Tomograph which has been specially designed for use in clinical routine. Data is continuously displayed in the form of images, waveforms and parameters. Simply put, PulmoVista 500 lets you visualize the distribution of ventilation.
MREIT

(Magnetic Resonance Electrical Impedance Tomography)

High-resolution conductivity imaging using MRI

- Internal measurements
- Non-invasive measurements
- Non-contact measurements
- Spatial information encoded in measured data
Probing by Injecting Current

\[ \begin{align*}
\n\n\n\n\n\Delta \sigma(r) \nabla u(r) = 0 \quad \text{in } \Omega \\
-\sigma(r) \nabla u(r) \cdot n = g \quad \text{on } \partial \Omega \\

J(r) = -\sigma(r) \nabla u(r) = \sigma(r) E(r) \\
B(r) = \frac{\mu_0}{4\pi} \int_{\Omega} \frac{J(r') \times (r-r')}{|r-r'|^3} \, dr'
\end{align*} \]
Numerical Example using FEM

MRI for MREIT

\[ S^\pm (m, n) = \int \int e^{j(\delta(x, y) \pm j\gamma B_z(x, y) T_c e^{j(xm\Delta k_x + yn\Delta k_y)}} dx dy \]


Magnetic Flux Density \((B_z)\) Imaging

We use both positive and negative injection currents.

\[
S^\pm(m, n) = \int \int_{-\infty}^{\infty} M(x, y) e^{j\delta(x, y)} e^{\pm j\gamma B_z(x, y)T_c} e^{j(xm\Delta k_x + yn\Delta k_y)} \, dx \, dy
\]

\[
\mathcal{M}^\pm(x, y) = M(x, y) e^{j\delta(x, y)} e^{\pm j\gamma B_z(x, y)T_c}
\]

\[
\Psi(x, y) = \arg\left(\frac{\mathcal{M}^+(x, y)}{\mathcal{M}^-(x, y)}\right) = 2\gamma B_z(x, y)T_c
\]

\[
B_z(x, y) = \frac{\Psi(x, y)}{2\gamma T_c} = \frac{1}{2\gamma T_c} \arg\left(\frac{\mathcal{M}^+(x, y)}{\mathcal{M}^-(x, y)}\right)
\]
Agar Phantom

MRI parameters:

- TR/TE = 1400/60ms
- FOV = 200mm
- Matrix size = 128 × 128
- Slice thickness/Gap = 3/0mm
- Number of slices = 8
- Average = 2
- Current amplitude = 27mA
- Current pulse width = 24ms
- Voxel size(x,y,z) = 1.5625×1.5625×3mm³

Phantom:

- Solution : 2S/m (NaCl=12.5g/l, CuSO₄=2g/l)
- Object (agar) : 0.5S/m (NaCl=2g/l, CuSO₄=2g/l, Agar=15g/l)
Agar Phantom

MR Magnitude Image

Wrapped Phase Image
Homogeneous Domain: $B_z$

Horizontal Injection Current

Vertical Injection Current
Inhomogeneous Domain: $B_z$

Horizontal Injection Current  

Vertical Injection Current
**Harmonic $B_z$ Algorithm**

\[
\mu_0 J = \nabla \times B \quad J(r) = -\sigma(r) \nabla u(r) \quad \nabla^2 B = -\mu_0 \nabla \times \nabla \sigma \quad \nabla^2 B_z = \mu_0 \left( \frac{\partial \sigma}{\partial x}, \frac{\partial \sigma}{\partial y} \right) \cdot \left( \frac{\partial u}{\partial y}, -\frac{\partial u}{\partial x} \right)
\]

\[
\begin{bmatrix}
\frac{\partial \ln \sigma}{\partial x}(r) \\
\frac{\partial \ln \sigma}{\partial y}(r)
\end{bmatrix}
= \frac{1}{\mu_0} \left( A[\sigma_0](r) \right)^{-1}
\begin{bmatrix}
\nabla^2 B_{z,1}(r) \\
\nabla^2 B_{z,2}(r)
\end{bmatrix}
\]

where

\[
\begin{align*}
\nabla \cdot \left( \sigma_0 \nabla u_j[\sigma_0] \right) &= 0 \quad \text{in } \Omega \\
\int_{\varepsilon_j^+} \sigma_0 \frac{\partial u_j[\sigma_0]}{\partial n} \, ds &= -\int_{\varepsilon_j^-} \sigma_0 \frac{\partial u_j[\sigma_0]}{\partial n} \, ds \\
\nabla u_j[\sigma_0] \times n |_{\varepsilon_j^+ \cup \varepsilon_j^-} &= 0, \\
\sigma_0 \frac{\partial u_j[\sigma_0]}{\partial n} &= 0 \quad \text{on } \partial \Omega \setminus \varepsilon_j^+ \cup \varepsilon_j^-
\end{align*}
\]

and

\[
A[\sigma_0](r) =
\begin{bmatrix}
\sigma_0 \frac{\partial u_1[\sigma_0]}{\partial y}(r) & -\sigma_0 \frac{\partial u_1[\sigma_0]}{\partial x}(r) \\
\sigma_0 \frac{\partial u_2[\sigma_0]}{\partial y}(r) & -\sigma_0 \frac{\partial u_2[\sigma_0]}{\partial x}(r)
\end{bmatrix}
\]
CoReHA

(Conductivity Reconstructor using Harmonic Algorithms)

Available from http://iirc.khu.ac.kr with manual and data sets
CoReHA

Coordinate Setup

Pre-processing

K-space Data

\[ M_j^+ \]

\[ M_j^- \]

\[ \angle \]

iFFT

Magnitude Image

Unwrap

Phase Image

\[ B_z \text{ Image} \]
CoReHA

Segmentation

Electrode Modeling

Meshing and Modeling

Harmonic Inpainting
Conductivity Image

Homogeneous Phantom
\((L^2\text{-error} = 3.2\%)\)

Agar Object Phantom
\((L^2\text{-error} \sim 5\%)\)
Swine Leg

MR Magnitude Image

$B_z$ Image for Horizontal Injection

$B_z$ Image for Vertical Injection

Tesla $\times 10^{-8}$
Swine Leg

MR Magnitude Image  Conductivity Image  Color-coded Conductivity Image
Swine Leg

MR Magnitude Image

Conductivity Image

Color-coded Conductivity Image
Postmortem Canine Head

MR Magnitude Image

$B_z$ Image for Horizontal Injection

$B_z$ Image for Vertical Injection

(Tesla) $\times 10^{-8}$
Postmortem Canine Head

MR Magnitude Image

Conductivity Image
Postmortem Canine Head

MR Magnitude Image

Conductivity Image

Color-coded Conductivity Image
In Vivo Canine Brain

MR Magnitude Image

Conductivity Image
Postmortem Canine Chest

MR Magnitude Image

$E_1^+$  $E_2^+$  $E_2^-$  $E_1^-$

$B_z$ Image for Horizontal Injection

$B_z$ Image for Vertical Injection
Postmortem Canine Chest

**MR Magnitude Image**

- Longissimus thoracis muscle
- Spinal cord
- Mediastinum
- Left ventricle
- Right ventricle
- Interventricular septum

**Conductivity Image**

- Body fluid in thoracic wall
- Body fluid accumulated in mediastinum

**Color-coded Conductivity Image**
Pneumonic Canine Chest

MR Magnitude Image

- Longissimus thoracis muscle
- Esophagus
- Mediatinum
- Right atrium
- Left ventricle
- Right ventricle
- Interventricular septum
- Spinal cord
- Trachea

Images:
- Pleural fluid in pleural cavity
- Body fluid accumulated in mediastinum
- Normal
- Normal
Pneumonic Canine Chest

- MR Magnitude Image
- Conductivity Image
- Color-coded Conductivity Image
Postmortem Canine Abdomen

MR Magnitude Image | Conductivity Image | Color-coded Conductivity Image

- Spinal cord
- Peritoneal cavity
- Stomach
- Kidney
- Liver
- Spleen
- Large & small intestine
Postmortem Canine Abdomen

- MR Magnitude Image
- Conductivity Image
- Color-coded Conductivity Image
Canine Kidney

MR Magnitude Image

Conductivity Image
Postmortem Canine Pelvis

MR Magnitude image
Conductivity Image
Color-coded Conductivity Image
Postmortem Canine Pelvis
Human Imaging
In Vivo Human Leg

MR Magnitude Image

$E_1^+$ $E_2^+$
$E_2^-$ $E_1^-$

$B_z$ Image for Horizontal Injection

$B_z$ Image for Vertical Injection

[ Tesla ] $\times 10^{-8}$

[ Tesla ] $\times 10^{-8}$
In Vivo Human Leg

- Tendon
- Tibia
- Interosseous membrane
- Fibula
- Tendon
- Tibial artery & vein
- Tibial nerve
- Calcaneal tendon

MR Magnitude Image

Conductivity Image
In Vivo Human Knee

MR Magnitude Image  \[ B_z \text{ Image for Horizontal Injection} \]

\[ B_z \text{ Image for Vertical Injection} \]
In Vivo Human Knee

MR Magnitude Image

Conductivity Image

Infrapatellar fat pad with synovial membrane
Medial femoral condyle
Lateral femoral condyle
Synovial capsule of knee joint
Patellar ligament
Articular cartilage
Cruciate ligament
Tibial nerve
Gastrocnemius
MREIT Images
Signal in MREIT

- Phase Accumulation, \( \Phi(r) = 2\gamma T_c B_z(r) \)
- Magnetic Flux Density, \( B_z \)
  - Imaging object
    - Shape and size
    - Conductivity distribution
  - Electrode configuration
  - Amplitude of injection current, \( I \)
- Current Injection Time, \( T_c \)
  - Limited by \( T_E \) and \( T_R \)
  - Current injection during RF?
  - Current injection during reading?
- Typical Values using Spin Echo Pulse Sequence
  \[
  \Phi = 2 \times 41.065 \times 10^6 \text{[rad/s/T]} \times 10^{-2} \text{[s]} \times 10^{-8} \text{[T]} = 0.0082 \text{[rad]} \approx 1^\circ
  \]
Limitation in Injection Current

- Patient auxiliary current (IEC 601-1): current flowing in the patient in normal use between any patient connection and all other patient connections and not intended to produce a physiological effect

  - 0 Hz – 0.1 Hz : 0.01 mA_{rms}
  - 0.1 Hz – 1 kHz : 0.1 mA_{rms}
  - 1 kHz – 100 kHz : 0.1 \times f \text{ (in kHz)} \ mA_{rms}
  - Above 100 kHz : 10 mA_{rms}
Limitation in Injection Current

☐ Therapeutic current (IEC 601-2-10) is defined as functional current from nerve or muscle stimulator

- 0 Hz – 0.1 Hz : 80 mA_{rms}
- 0.1 Hz – 400 Hz : 50 mA_{rms}
- 400 Hz – 1500 Hz : 80 mA_{rms}
- Above 1500 Hz : 100 mA_{rms}
- For pulse duration < 0.1 s, pulse energy < 0.3 J
- Pulse voltage < 500 V

☐ Diagnostic current in dentistry and ophthalmology (IEC 601-2-10)

- 10 mA_{rms}
Limitation in Injection Current

- Threshold to stimulate a nerve with 20 \mu m diameter (McRobbie and Foster, 1984)
  - 1 A/m² below 1 kHz
  - 2.5 mA through 5×5 cm² uniform current density electrode

(σ = 0.17 S/m)
Noise in MREIT

- Random Noise in MR Phase Image

- Noise Standard Deviation in $B_z$, $s_{B_z} = \frac{1}{\sqrt{2} \gamma T_c \Psi_M}$
  - Current injection time, $T_c$
  - Magnitude image SNR, $\Psi_M$

- Typical Values

$$s_{B_z} = \frac{1}{\sqrt{2 \times 41.065 \times 10^6 [\text{rad/s/T}] \times 10^{-2} [s] \times 500}} = 3.4 \text{ [nT]}$$

- Factors Affecting $s_{B_z}$
  - Performance of current source
  - Performance of MRI scanner including RF coils
  - Pulse sequence
  - MR imaging parameters
Applications

- Pathological changes related with conductivity
  - Brain tumor
  - Breast tumor
  - Prostate tumor

- Brain functions
  - Conductivity changes associated with neural activity
  - Conductivity changes related with brain injury, stroke, epilepsy, tumor, and others

- Provide conductivity values to source imaging problems in EEG, MEG, and ECG

- Planning and optimization of treatments using electromagnetic energy

- Applications in biology and chemistry
Breast Model

Hydrogel: 0.17 S/m  
Glandular Tissue: 0.023 S/m  
Subcutaneous Fat: 0.019 S/m  
Anomaly: 0.0023 S/m  

FOV: 135 mm  
Slice thickness: 4.2 mm  
Image size: 128 x 128  
Injected current: 0.7 or 1 mA  
Anomaly size: 15 mm
Breast Simulation

1 mA Injection

Magnitude

$B_z$ - Horizontal

$B_z$ - Vertical

Conductivity

0.7 mA Injection

Magnitude

$B_z$ - Horizontal

$B_z$ - Vertical

Conductivity
Head Model

- Height: 22.5 cm
- Length: 18.8 cm
- Width: 16.4 cm
- Electrode size: 64 cm² (8 × 8 cm²)
Head Model

- Number of degrees of freedom = 2,709,374
- Number of elements = 291,294
Head Model

Skin and electrodes (31,190 elements)

Skull (26,320 elements)

CSF (64,036 elements)

Anomaly (580 elements)

Ventricle (5,919 elements)

Brain (163,249 elements)
Simulation Settings

Conductivity
- Hydrogel = 0.17 S/m
- Skin = 0.17 S/m
- Skull = 0.02 S/m
- CSF = 0.91 S/m
- Ventricle = 2.00 S/m
- Brain = 0.09 S/m
- Anomaly = 0.0945 S/m (5% contrast)

Imaging Parameter
- FOV = 200 mm
- Slice thickness = 6.8 mm
- Image size = 128
- Current amplitude = 6.4 mA
- Electrode size = 64 cm²
- Anomaly size: 15 mm
Horizontal Injection Current

Magnetic flux density, $B_z$

Current density, $J_x$

Current density, $J_y$

Voltage, $u$
Vertical Injection Current

Magnetic flux density, $B_z$

Current density, $J_x$

Current density, $J_y$

Voltage, $u$
Without Noise

Without anomaly

With anomaly

Magnitude  \( B_z \) - Horizontal  \( B_z \) - Vertical  Conductivity  Conductivity
With Noise

Without anomaly

Magnitude  $B_z$ - Horizontal  $B_z$ - Vertical  Conductivity  Conductivity

With anomaly

Magnitude  $B_z$ - Horizontal  $B_z$ - Vertical  Conductivity  Conductivity
Directions

- Maximize signal and minimize noise
  - Optimize current source
  - Optimize electrode configuration
  - Optimize pulse sequence and imaging parameters
  - Increase current pulse width
  - Increase averaging (low temporal resolution)
  - Increase pixel size (low spatial resolution)
  - Improve RF coil
  - Use high-field high-performance MRI system

- Reduced FOV and ROI imaging

- Denoising techniques and hybrid algorithms

Reduce Imaging Current!
Multi-echo Pulse Sequence

Spin echo

ICNE

Multi-echo
b-SSFP Pulse Sequence

\[ E_1 = \exp\left(-\frac{TR}{T_1}\right), \quad E_2 = \exp\left(-\frac{TR}{T_2}\right) \]
\[ D = (1 - E_1 \cos \alpha)(1 - E_2 \cos \theta) - E_2 (E_1 - \cos \alpha) (E_2 - \cos \theta) \]
\[ M_x(\theta) = M_0 \left(1 - E_1\right) \sin \alpha \left(1 - E_2 \cos \theta\right) / D \]
\[ M_z(\theta) = M_0 \left(1 - E_1\right) \sin \alpha E_2 \sin \theta / D \]
\[ M(x,y) = \sqrt{M_x^2 + M_y^2} = \frac{M_0 \left(1 - E_1\right) \sin \alpha}{D} \sqrt{1 + E_2^2 - 2E_2 \cos \theta} \]
\[ S(m,n) = \int \int_{\infty} M(x,y) e^{j\Delta} e^{-j(m\Delta x + n\Delta y)} \, dx \, dy \]
High-sensitivity RF Coils


www.medical.siemens.com
New Techniques in MRI

• Scheffler K 2004 Fast frequency mapping with balanced SSFP: theory and application to proton-resonance frequency shift thermometry Magn. Reson. Med. 51 1205-11
• Candès E, Romberg J and Tao T 2006 Robust uncertainty principles: exact signal reconstruction from highly incomplete frequency information IEEE Trans. Inf. Theory 52 489-509
• Donoho D 2006 Compressed sensing IEEE Trans. Inf. Theory 52 1289-1306
Towards Neuro-imaging

- MRI-compatible EEG
- MRI-compatible EIT
- MREIT
  - Low-noise high-performance MRI system at 3 or 7 T
  - Uniform current density electrode, electrode configuration, and low-noise current source
  - Sensitivity enhancement by improvements in RF coil and pulse sequence
  - Fast imaging method
  - Denoising, image reconstruction, and anomaly detection algorithms
  - Functional imaging protocol and statistical image analysis
Outlook: Multi-modal Approach

Surface voltage (EEG)
- Endogenous
- Spontaneous or evoked
- $10^{-6} - 10^{-5}$ V

Surface voltage (EIT)
- Exogenous
- Spontaneous or evoked
- $10^{-4} - 10^{-3}$ V

Internal magnetic flux density (MREIT)
- Exogenous
- Spontaneous or evoked
- $10^{-10} - 10^{-8}$ T

Geometry and other information (MRI)
- Endogenous
- Spontaneous or evoked

MRI-MREIT-EIT-EEG
Multi-modal Neuro-imaging

- MR image
- Surface voltage map
- Magnetic flux density image
- Conductivity image
- Current density image
- Current source image
Collaborators at IIRC
Acknowledgement

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  - Ion Conduction Imaging Group

- Kyung Hee University

- Researchers at IIRC
  - Mathematicians
  - Engineers
  - Biologists and clinicians

- International Collaborators
Thank you for your attention.