Electrical Conductivity Imaging and Its Applications

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http://iirc.khu.ac.kr
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Conductivity of Biological Tissue

Structure and Composition

- Molecular composition of cells
- Shape and direction of cells
- Density and structure of cells
- Contents of extra-cellular matrix
- Concentration and mobility of ions
- Concentration and mobility of charge-carrying molecules
- Amounts of intra- and extra-cellular fluids

Function and Pathology

- Neural activity
- Epilepsy
- Tumor
- Ischemic stoke
- Hemorrhage
- Apnea
- Respiration
- Cardiac function and hemodynamics
- Gastric emptying
- Abdominal bleeding
- Temperature
Volume Conduction of Injection Current
Volume Conduction of Injection Current
Volume Conduction of Injection Current
Conductivity Imaging Problem

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

Voltage

Conductivity

Injection Current

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

Current Density

Magnetic Flux Density

\[
B(r, t) = \frac{\mu_0}{4\pi} \int_{\Omega} \frac{J(r', t) \times (r - r')}{|r - r'|^3} \, dr'
\]
**EIT** (Electrical Impedance Tomography)

\[
\begin{align*}
\nabla \cdot (\sigma(r, t) \nabla u(r, t)) &= 0 \text{ in } \Omega \\
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\end{align*}
\]

- \( I_p = I_m < 0 \) : injection current
- \( Z_{pq} = Z_{pq} < \theta \) : transfer impedance
- \( V_q = Z_{pq} I_m < \theta \) : measured voltage

Transfer impedance \( Z_{pq} \) depends on:
- Electrode configuration
- Conductivity distribution
- Geometry (boundary shape and size)
EIT System

64-channel KHU Mark 1

Expandable 16-channel KHU Mark 2
EIT System

- Number of voltmeters: 8 - 64
- Number of current sources: 8 - 64
- Frequency range: 50Hz - 500kHz
- Flexible electrode configuration
- Maximum 100 frame/sec
- Automatic self-calibration
- Cascaded mode
- Event trigger mode
EIT Electrode and Belt (PVDF Nanofiber Web)

Electrode Belt

Inner Band

Outer Band
Smart Electrode and Belt

http://www.bmedical.com  http://www.alphatrace.at

http://www.alphatrace.at
EIT for Regional Lung Ventilation

MR Image  EIT Image  Normalized $\Delta Z$ in Lungs
EIT for Regional Lung Ventilation
EIT in ICU and OR

- Life-saving of 1.1 million patients per year
- Cost-saving of US$ 3000 – 10,000 per patient

http://www.swisstom.com
EIT for Upper Airway Apnea

Open

Closed

Open

Closed

Open
EIT for Abdominal Bleeding

- Inject blood between channel 1 and 16
- Injection speed: 180 ml/h
- Injection volume: 30 ml
- EIT belt at the end point of the ribs
- Operating frequency: 10 kHz
- Average: 16

Detection of conductivity changes after injecting 0.75ml (15 seconds)
Micro-EIT for Cell and Tissue Culture

Primary Injection

Secondary Injection

Secondary Injection

Voltage Distributions
Micro-EIT for Cell and Tissue Culture

Voltage Maps on Three Surfaces

Projection and Reconstruction Image
TAS (Trans-admittance Scanner)

- Apply voltage at hand-held electrode
- Measure exit currents through array of electrodes in the planar scan probe
- Display trans-admittance map
- Estimate location and size of anomalies
TAS (Trans-admittance Scanner)
TAS Image

Size = 6mm³

Depth = 10mm

Depth : 5mm  Depth : 10mm  Size : 4mm³  Size : 6mm³

Depth : 15mm  Depth : 20mm  Size : 8mm³  Size : 10mm³
TAM (Trans-admittance Mammography)
TAM Image

500Hz, Real

50kHz, Real

500kHz, Real

500Hz, Imaginary

50kHz, Imaginary

500kHz, Imaginary

Max

Min

Tissue A

Tissue B
Conductivity Imaging Problem

\[
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\]
MREIT (Magnetic Resonance Electrical Impedance Tomography)

\[ \mu_0 J = \nabla \times B \]

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

\[ \nabla^2 B = -\mu_0 \nabla \times \nabla \sigma \]

\[ \nabla^2 B_z = \mu_0 \left( \frac{\partial \sigma}{\partial x}, \frac{\partial \sigma}{\partial y} \right) \cdot \left( \frac{\partial u}{\partial y}, -\frac{\partial u}{\partial x} \right) \]
MREIT using MRI

3T (IIRC, KHU)  

9.4T (YU)  

3T (KHUH)
Magnetic Field Imaging using MRI

Horizontal Injection Current

\[ \nabla^2 B_z = 0 \]

\[ \mu_0 J = \nabla \times B \]

\[ J = -\sigma \nabla u \]

\[ \nabla^2 B = -\mu_0 \nabla u \times \nabla \sigma \]

Vertical Injection Current

\[ \nabla^2 B_z = 0 \]

\[ \nabla^2 B_z \neq 0 \]
MREIT Image

Canine Head

Canine Chest

Canine Abdomen

Canine Pelvis

Human Leg

Human Knee

Canine Head

1.4 mm

1.8 mm

2.2 mm

1.7 mm

1.4 mm

1.4 mm

1.4 mm

1.4 mm
MRI vs. Conductivity Image

Heart
- Left atrioventricular valve
- Left ventricle
- Ventricular septum
- Right atrioventricular valve
- Right ventricle

Kidney
- Cortex
- Medulla
- Renal pelvis
- Ureter

Prostate
- Urethral crest
- Central zone
- Fibrous connective tissue
- Peripheral zone

Heart Kidney Prostate
Animal Disease Model (Brain Abscess)

Before 6 hours 12 hours 18 hours 24 hours
Normal Edema Ring-shaped Membrane Necrosis
Treatment Planning (Electroporation)

\[ u \]
\[ [V] \]
\[ 1 \times 10^3 \]
\[ 0 \]

\[ |E| \]
\[ [V/m] \]
\[ 2 \times 10^5 \]
\[ 0 \]

\[ |J| \]
\[ [A/m^2] \]
\[ 5 \times 10^4 \]
\[ 0 \]
Treatment Monitoring (DBS)
Treatment Monitoring (tDCS)
Treatment Monitoring (RF Ablation)

(a) (b) (c) (d)
From Physiology to Pixel

- Physiology and pathology
- Clinical specialty
- Bioelectromagnetism
- Composition and molecular structure
- Ion concentration and mobility
- Extra- and intra-cellular fluids
- Cell membrane, shape, and density
- Tissue structure
- Maxwell’s equations
- Partial differential equation
- Volume conduction
- Point-wise conductivity
- Volume-wise or effective conductivity
- Apparent conductivity

- Human interface and electrode contact
- Electrode configuration
- Probing current (amplitude and frequency)
- Data collection protocol
- System development and calibration
- Electronics, SNR, CMRR, RE, and stability
- Numerical method and programming
- Modeling error
- Sensitivity and nonlinearity
- Linearization
- Reconstruction algorithm
- Post-processing method
Research Directions

• BIS and EIT
  • Regional ventilation and perfusion (with ventilator)
  • Cardiac function (with patient monitor)
  • Acute stroke type (ischemia or hemorrhage)
  • Upper air way apnea (for surgery plan)
  • Non-destructive testing and sensing (process tomography and pressure imaging)

• Micro-EIT
  • Cell culture (non-invasive, long-term, label-free, three-dimensional)
  • Tissue Culture (non-invasive, long-term, label-free, three-dimensional)

• TAS and TAM
  • Breast tumor

• MREIT
  • Tumor (early stage)
  • Electromagnetic therapy planning and monitoring (ablation, DBS, tDCS, electroporation)
  • Neural activity (direct functional neuroimaging)
EOD