Electrical Conductivity Imaging and Its Applications

Eung Je Woo

Impedance Imaging Research Center (IIRC)

Kyung Hee University

Korea

http://iirc.khu.ac.kr

http://www.ejwoo.com

Conductivity of Biological Tissue

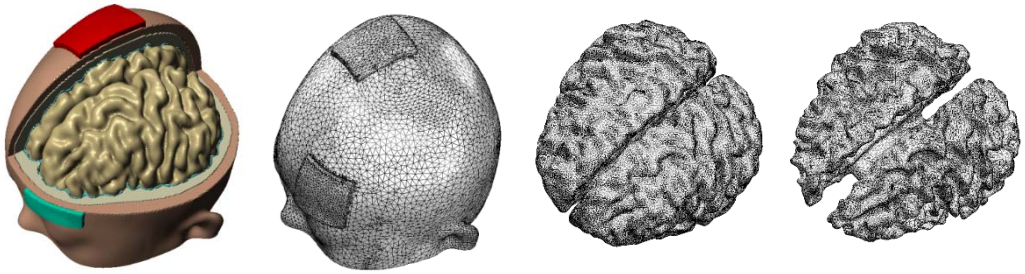
Structure and Composition

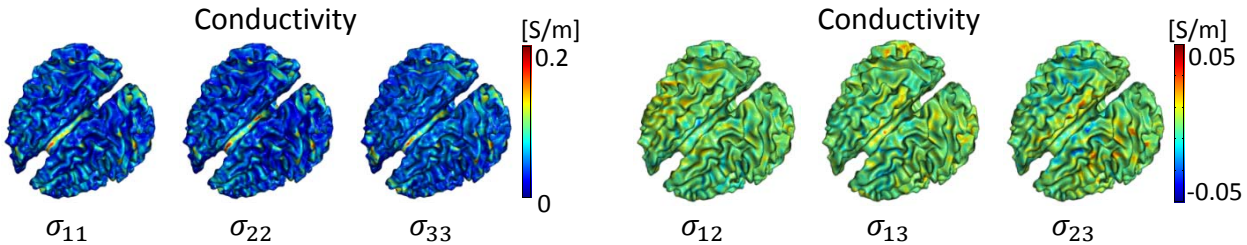
- Molecular composition of cells
- Shape and direction of cells
- Density and structure of cells
- Contents of extra-cellular matrix
- Concentration and mobility of ions
- Concentration and mobility of charge-carrying molecules
- Amounts of intra- and extra-cellular fluids

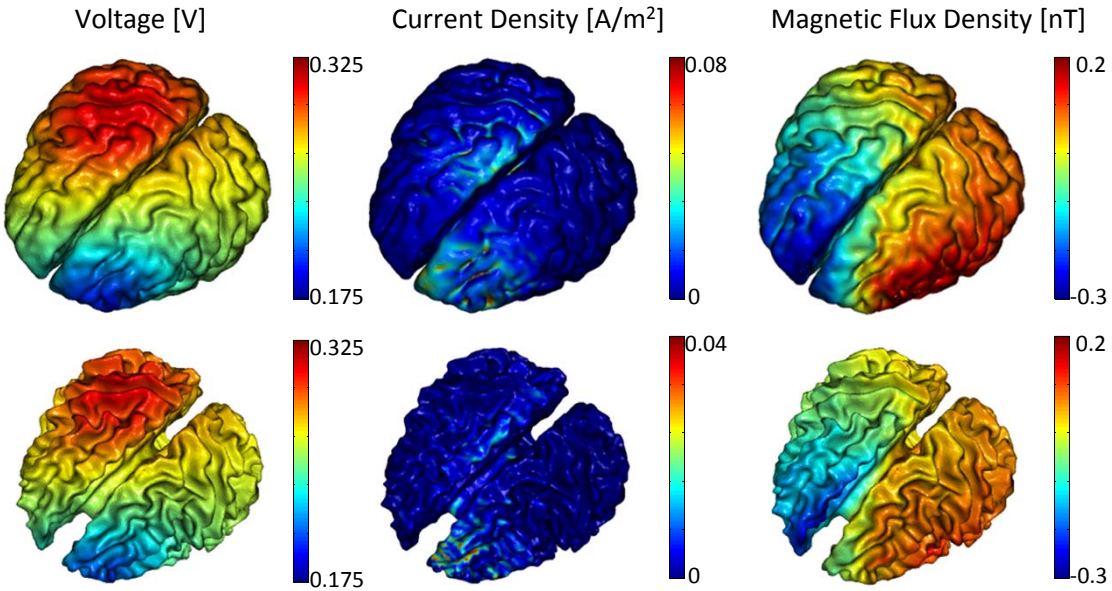
Function and Pathology

- Neural activity
- Epilepsy
- Tumor
- Ischemic stoke
- Hemorrhage
- Apnea
- Respiration
- Cardiac function and hemodynamics
- Gastric emptying
- Abdominal bleeding
- Temperature

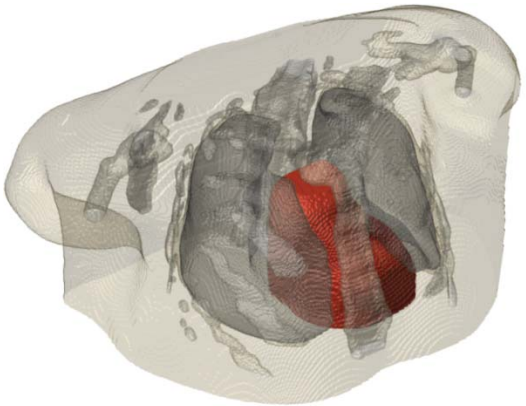
Volume Conduction of Injection Current

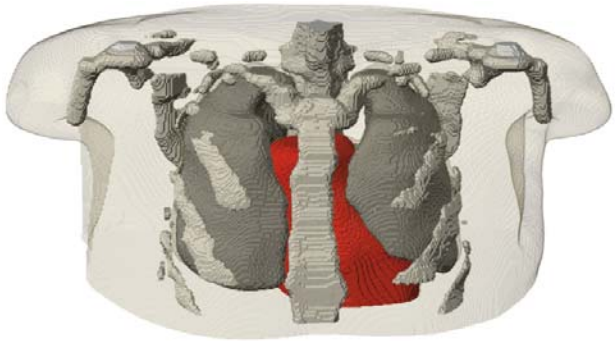


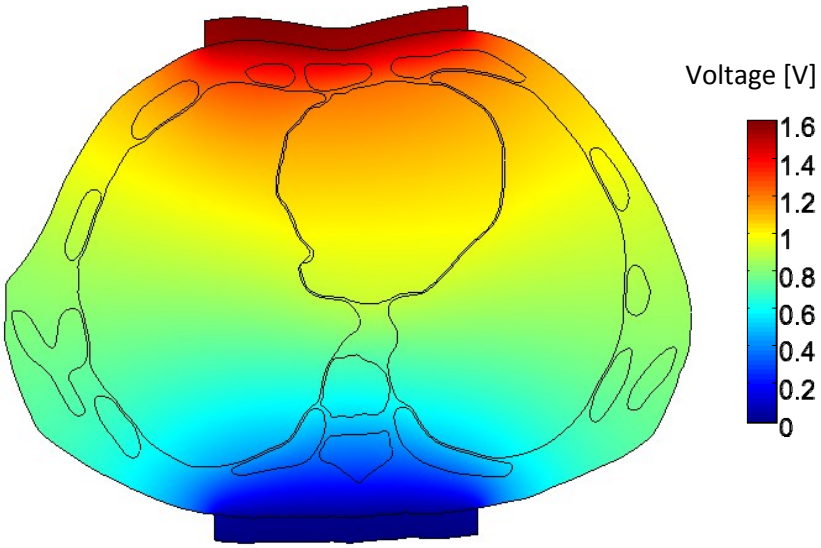




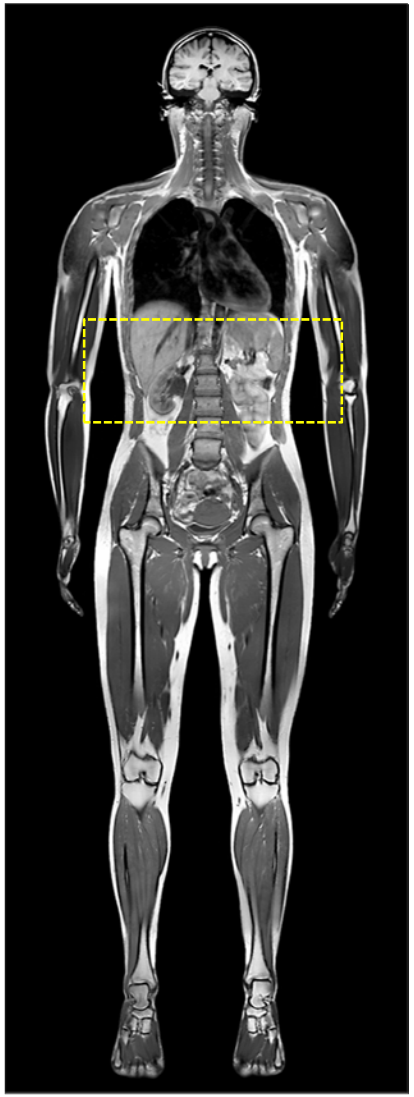
Volume Conduction of Injection Current

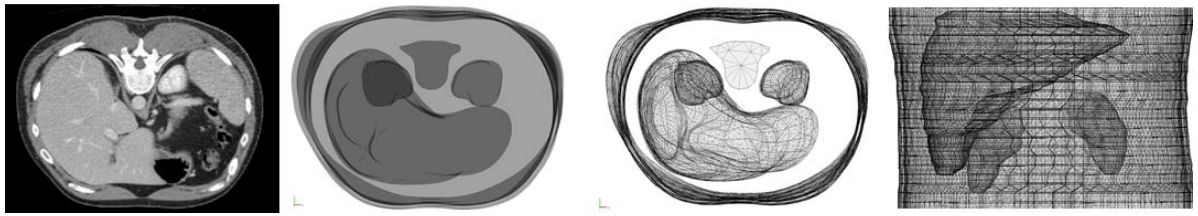


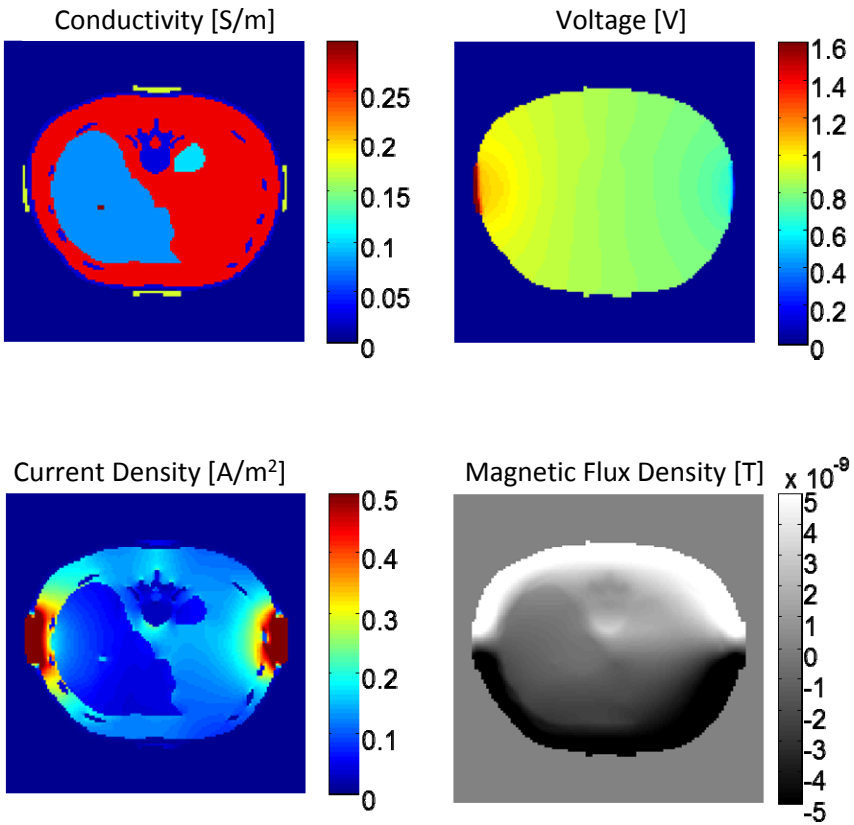




Volume Conduction of Injection Current







Conductivity Imaging Problem

Voltage

$$\begin{cases} \nabla \cdot \big(\sigma(\mathbf{r},t)\nabla u(\mathbf{r},t)\big) = 0 \text{ in } \Omega \\ -\sigma(\mathbf{r},t)\nabla u(\mathbf{r},t)\cdot \mathbf{n} = g \text{ on } \partial\Omega \end{cases}$$

Conductivity Injection Current

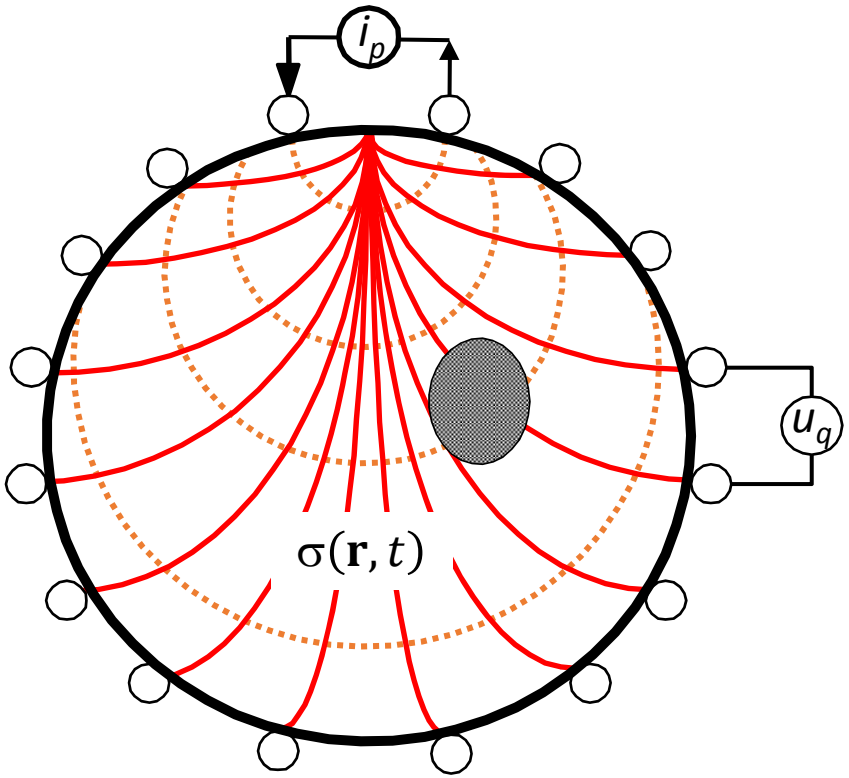
$$\mathbf{J}(\mathbf{r},t) = -\sigma(\mathbf{r},t)\nabla u(\mathbf{r},t)$$

Current Density

Magnetic Flux Density

$$\mathbf{B}(\mathbf{r},t) = \frac{\mu_0}{4\pi}\int_{\Omega} \frac{\mathbf{J}(\mathbf{r}',t)\times(\mathbf{r}-\mathbf{r}')}{|\mathbf{r}-\mathbf{r}'|^3}\,d\mathbf{r}'$$

EIT (Electrical Impedance Tomography)



$$\begin{cases} \nabla \cdot \big(\sigma(\mathbf{r}, t)\nabla u(\mathbf{r}, t)\big) = 0 \text{ in } \Omega \\ -\sigma(\mathbf{r}, t)\nabla u(\mathbf{r}, t) \cdot \mathbf{n} = g \text{ on } \partial\Omega \end{cases}$$

$I_p = I_m \angle 0$: injection current

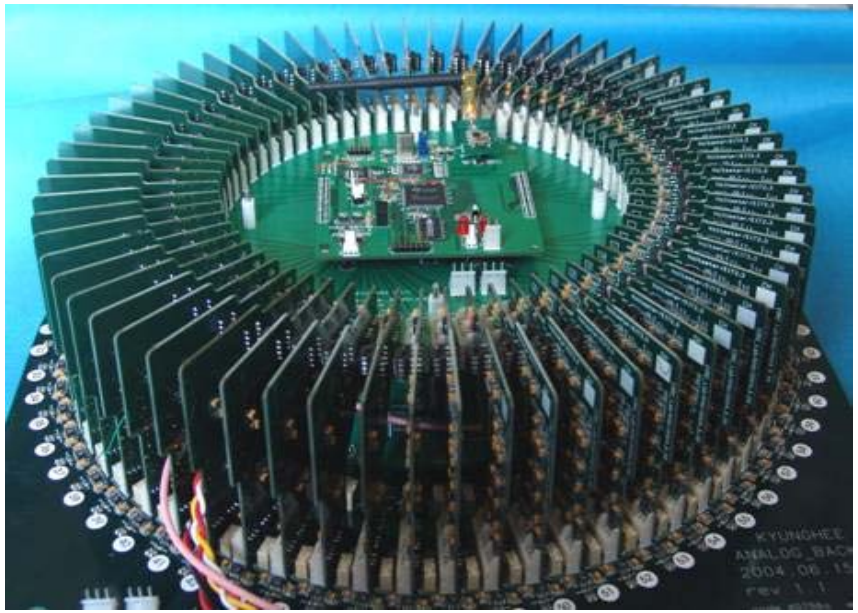
$Z_{pq} = Z_{pq} \angle \theta$: transfer impedance

$V_q = Z_{pq} I_m \angle \theta$: measured voltage

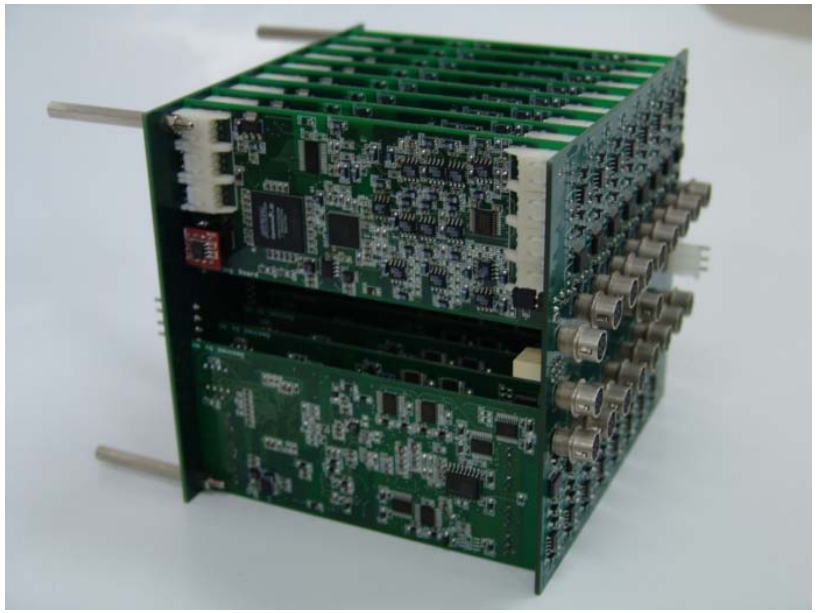
Transfer impedance $\mathbf{Z}_{pq}$ depends on

- Electrode configuration
- Conductivity distribution
- Geometry (boundary shape and size)

EIT System

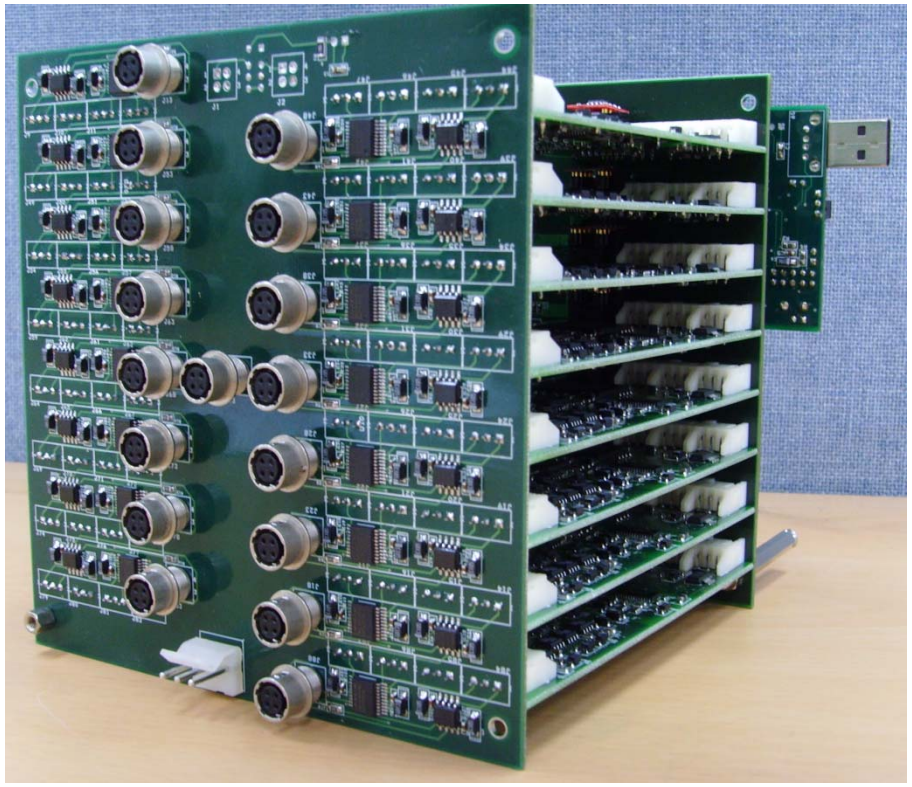


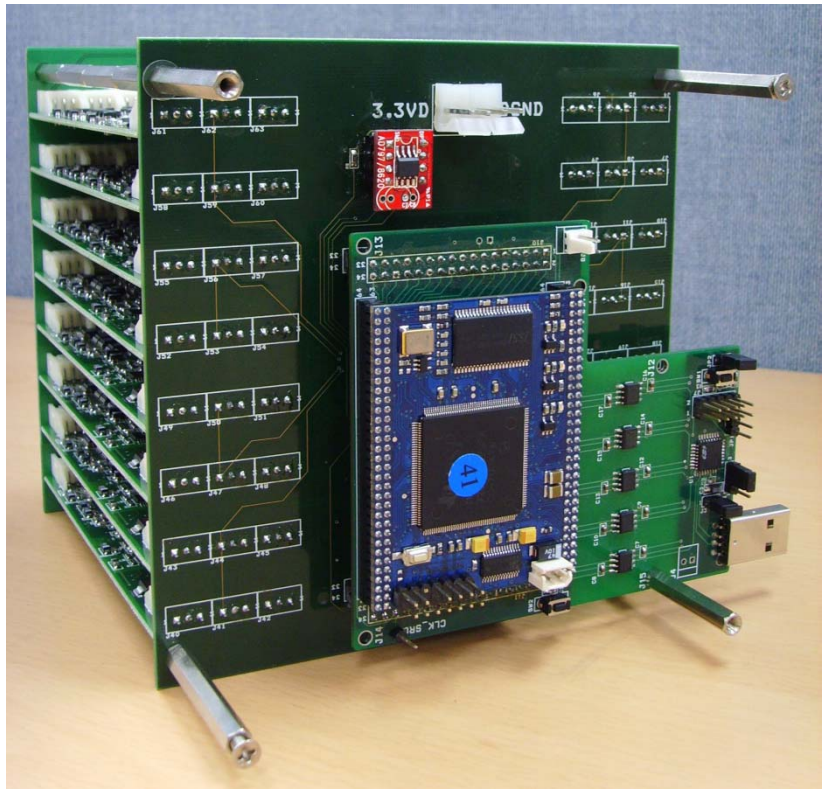
64-channel KHU Mark 1



Expandable 16-channel KHU Mark 2

EIT System

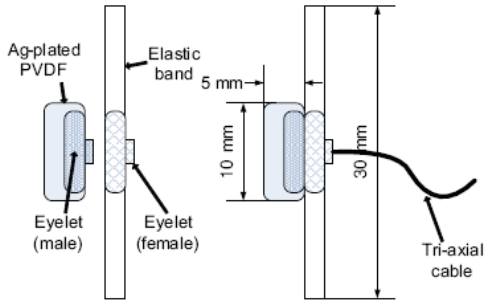


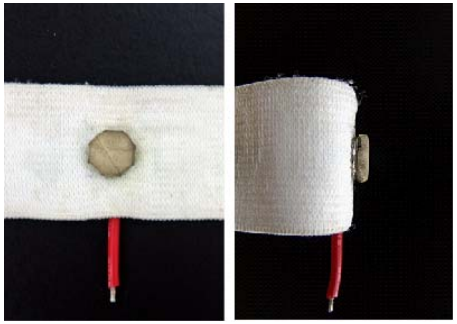


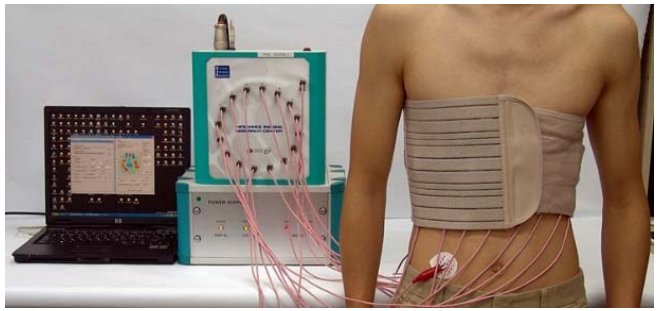
- Number of voltmeters : 8 - 64
- Number of current sources : 8 - 64
- Frequency range : 50Hz - 500kHz
- Flexible electrode configuration

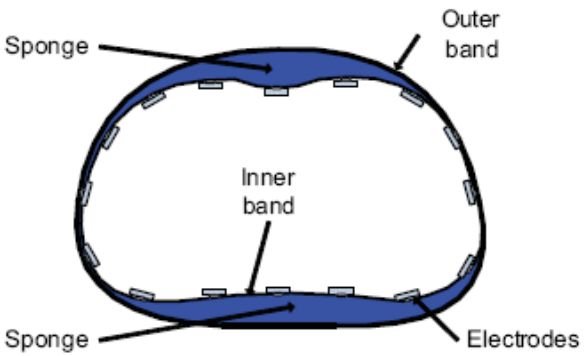
- Maximum 100 frame/sec
- Automatic self-calibration
- Cascaded mode
- Event trigger mode

EIT Electrode and Belt (PVDF Nanofiber Web)

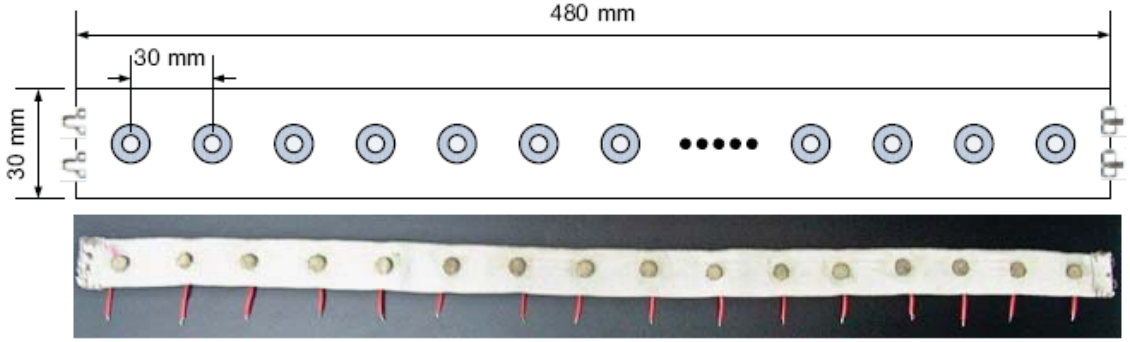




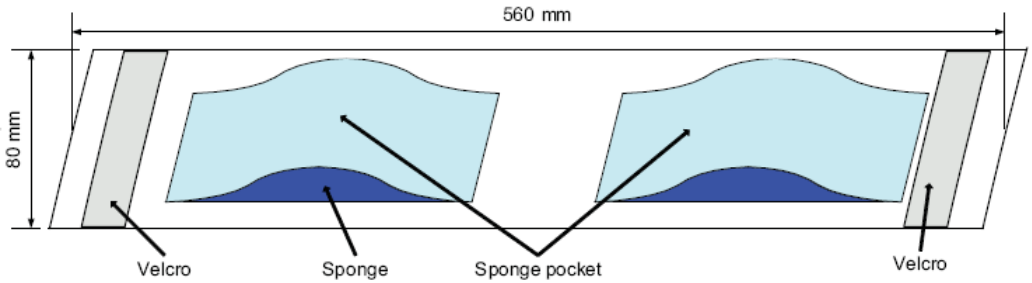




Electrode Belt



Inner Band



Outer Band

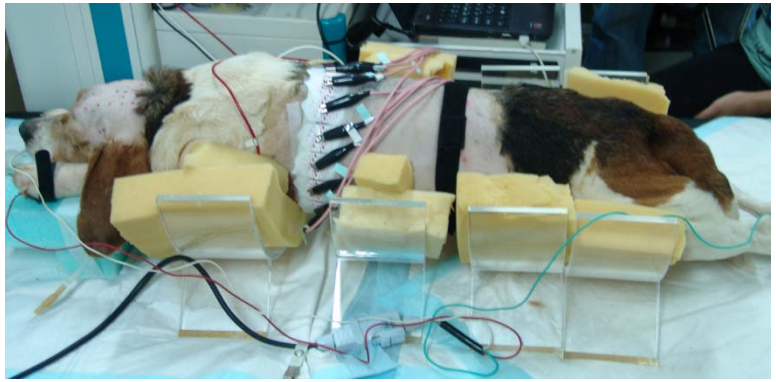
Smart Electrode and Belt

http://www.bmedical.com

http://www.alphatrace.at

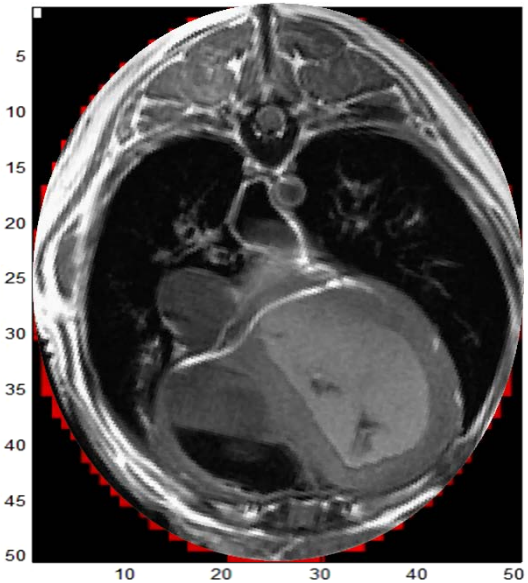
http://www.alphatrace.at

EIT for Regional Lung Ventilation

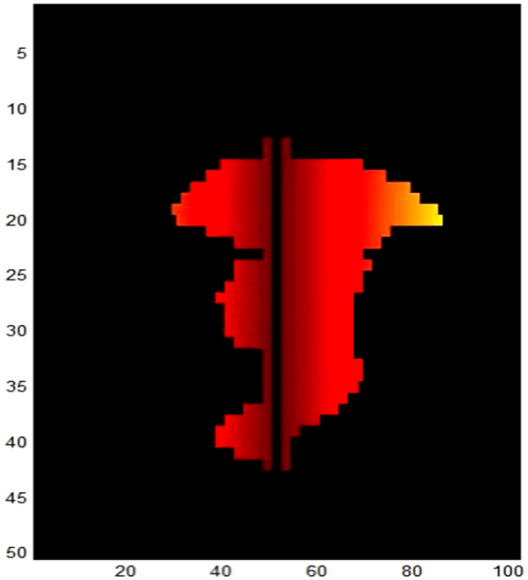


MR Image

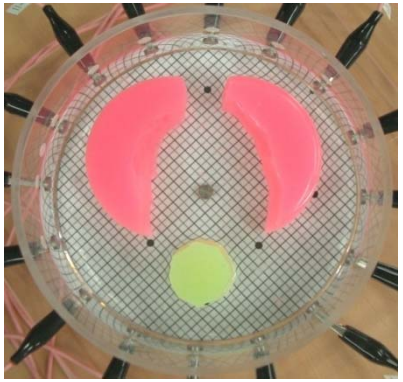
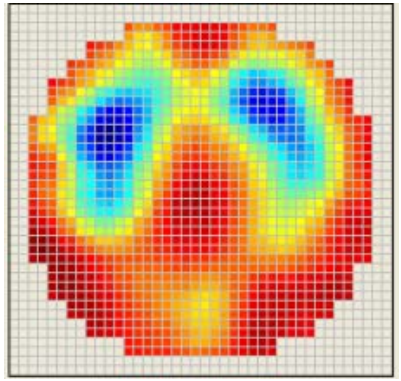
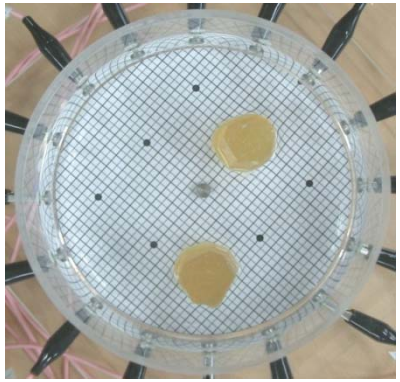
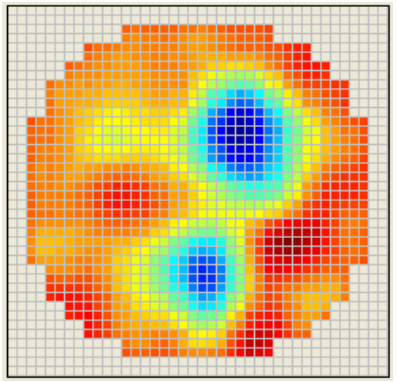
EIT Image

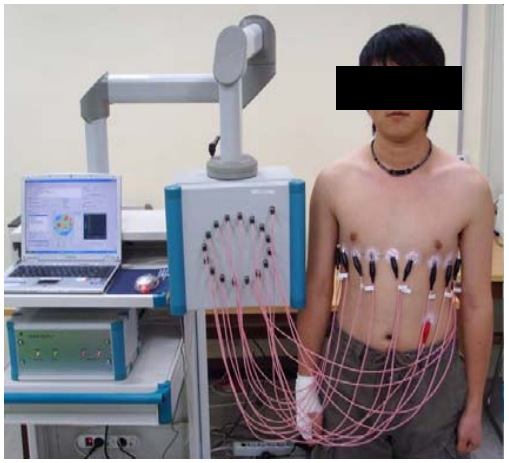
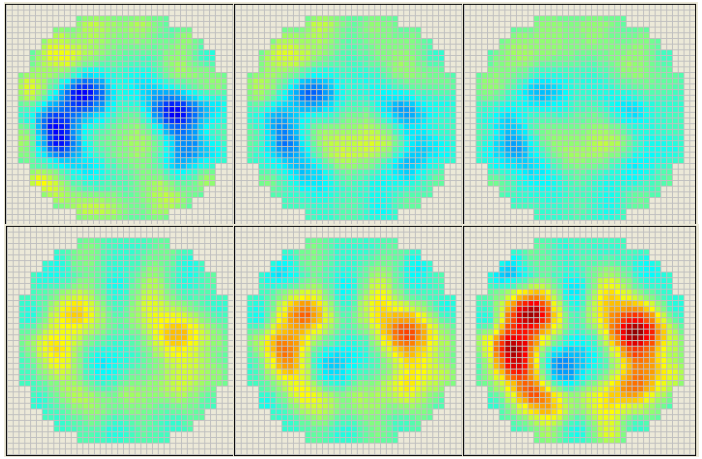
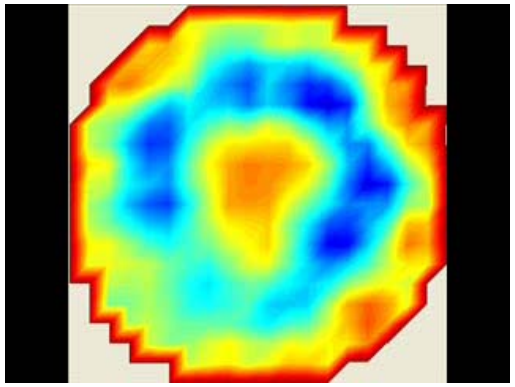


Normalized ΔZ in Lungs



EIT for Regional Lung Ventilation

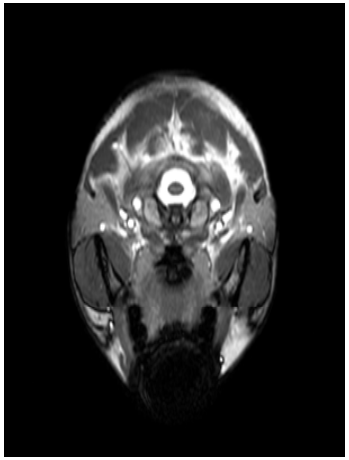
EIT in ICU and OR

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

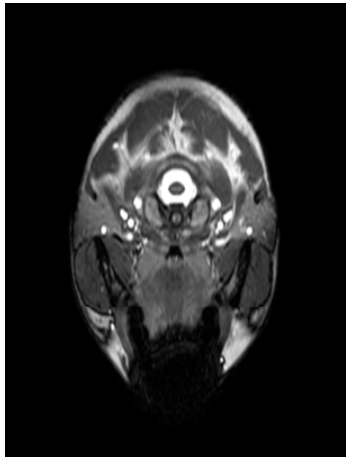
- Amato *et al.*, *New England Journal of Medicine*, 1998:338:347-54
- ARDS Network, *New England Journal of Medicine*, 2000:342:1301-8
- Rubenfeld *et al.*, *New England Journal of Medicine*, 2005:353:1685-93
- Wunsch *et al.*, *Critical Care Medicine*, 2010:38:1947-53

http://www.swisstom.com

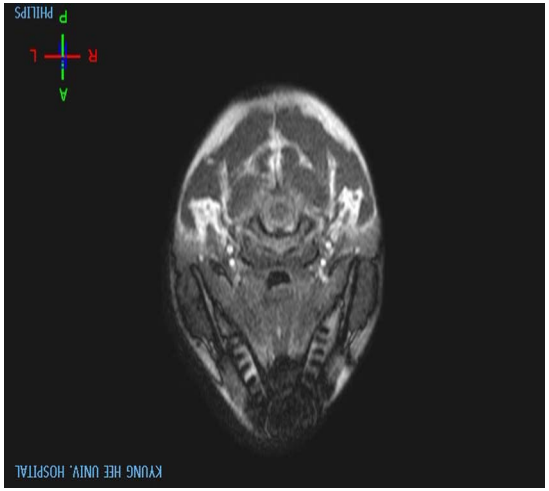
EIT for Upper Airway Apnea

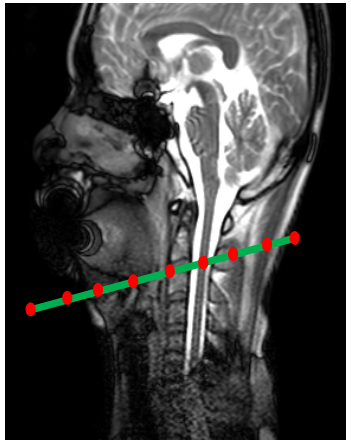


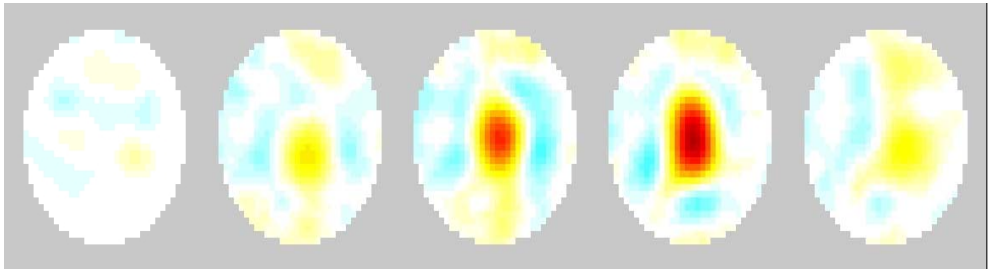
Open



Closed



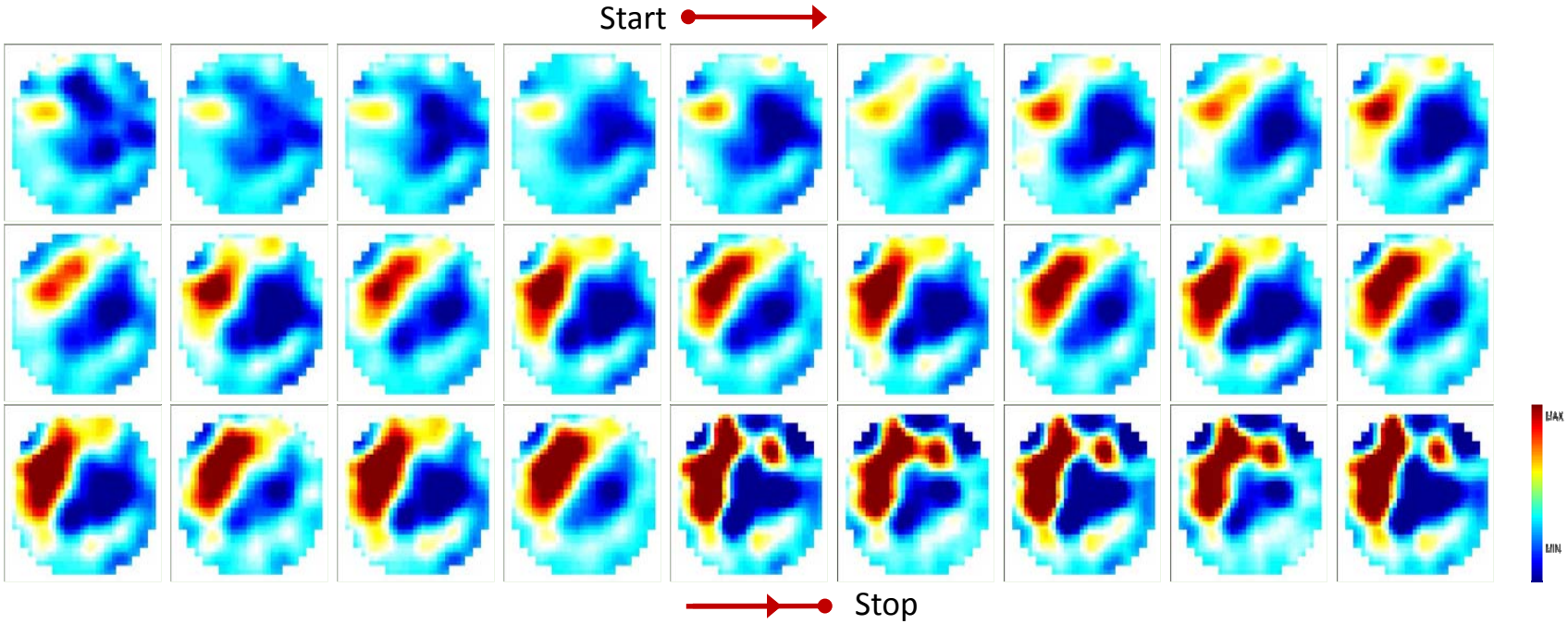




Open ⟷ Closed ⟷ Open

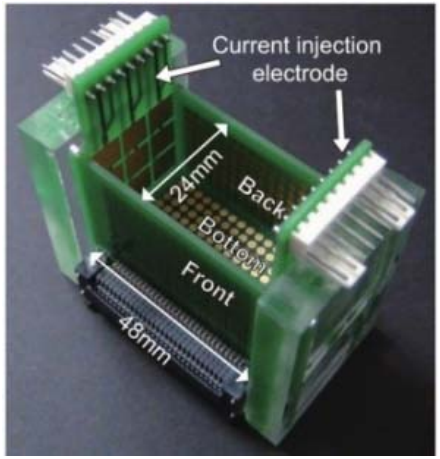
EIT for Abdominal Bleeding

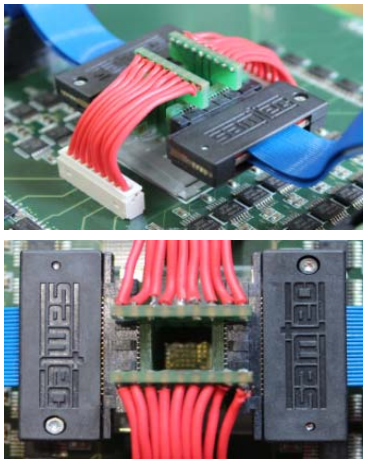
- Inject blood between channel 1 and 16
- Injection speed: 180 ml/h
- Injection volume: 30 ml
- EIT belt at the end point of the ribs
- Operating frequency: 10 kHz
- Average: 16



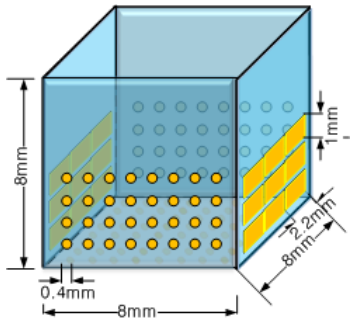
Detection of conductivity changes after injecting 0.75ml (15 seconds)

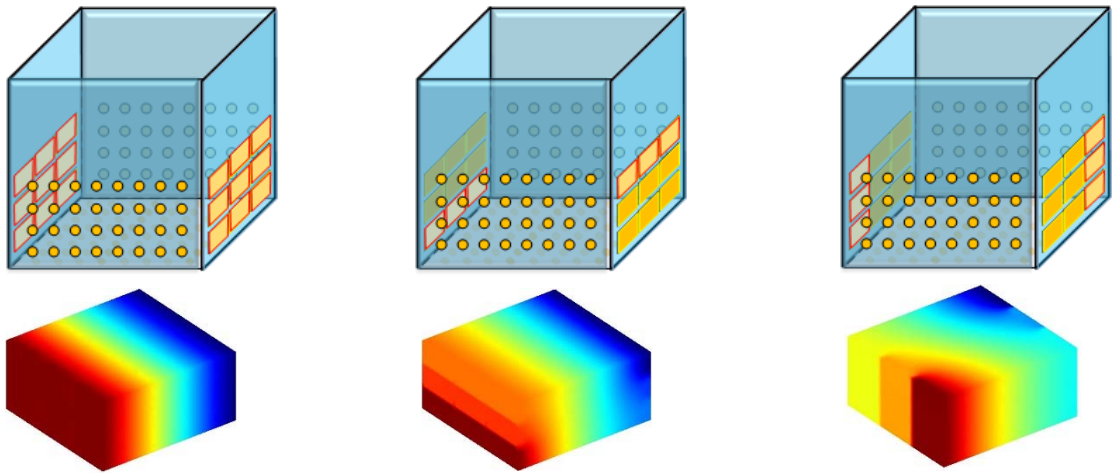
Micro-EIT for Cell and Tissue Culture





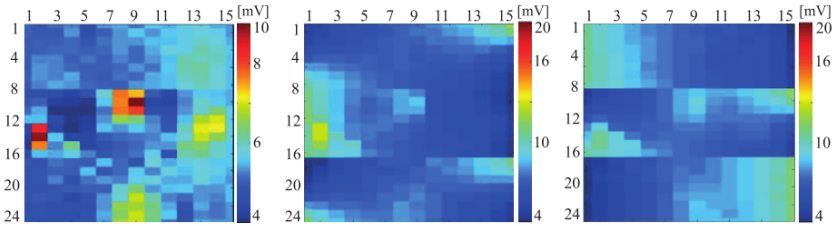
Primary Injection Secondary Injection Secondary Injection



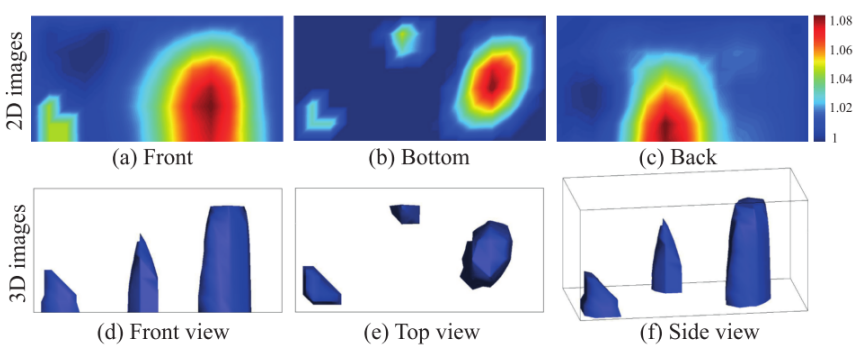


Voltage Distributions

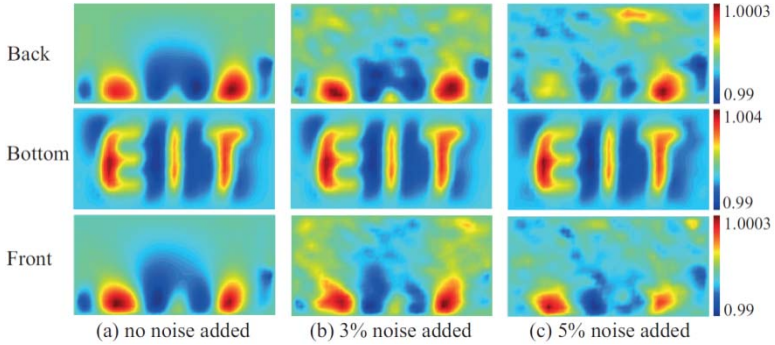
Micro-EIT for Cell and Tissue Culture

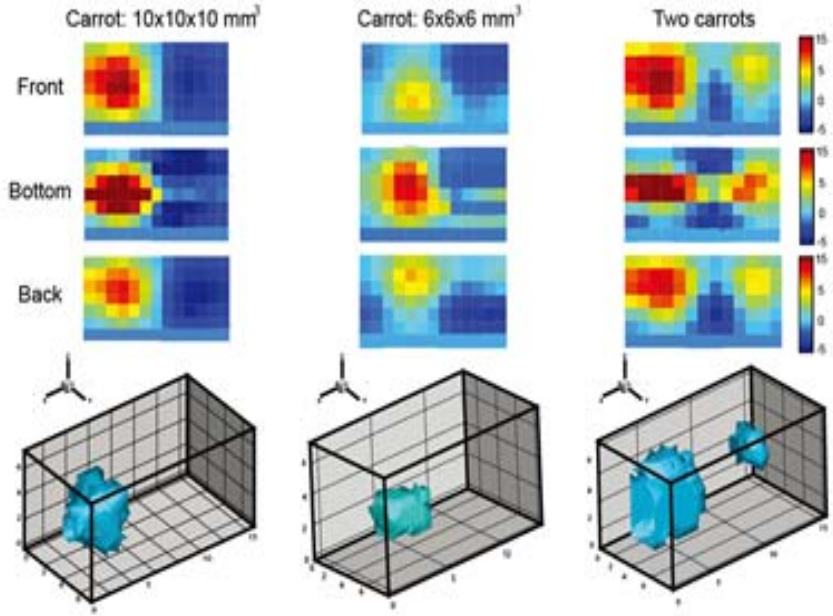


Voltage Maps on Three Surfaces

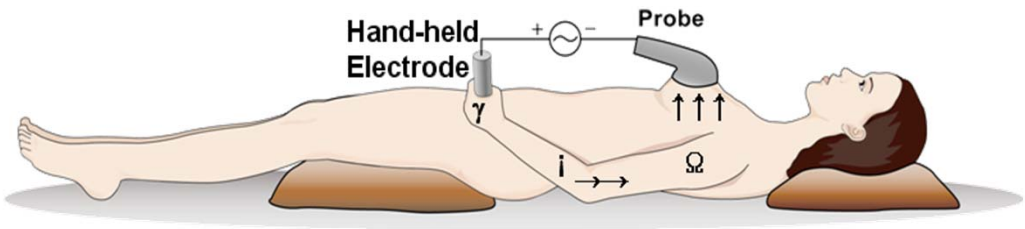


Projection and Reconstruction Image

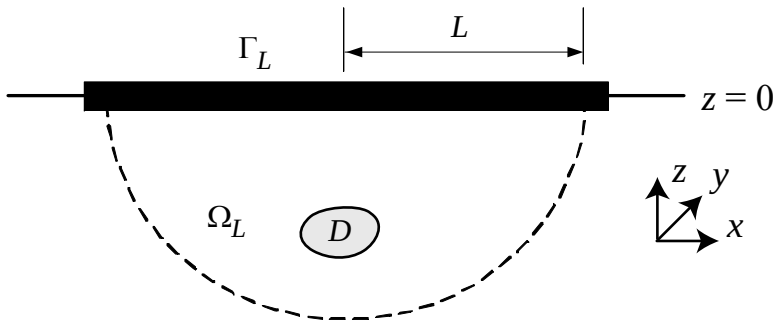




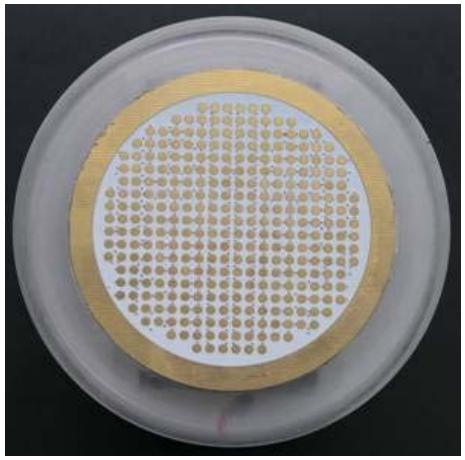
TAS (Trans-admittance Scanner)



- 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

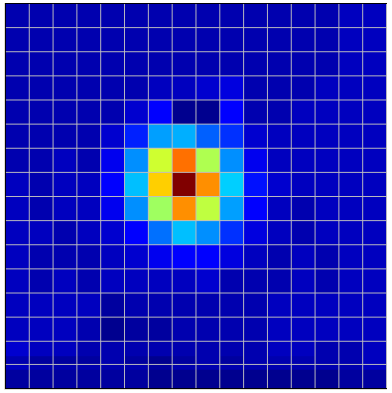


TAS (Trans-admittance Scanner)

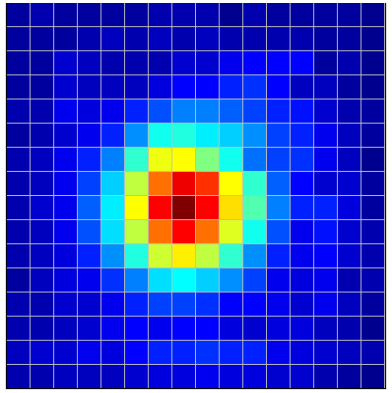


TAS Image

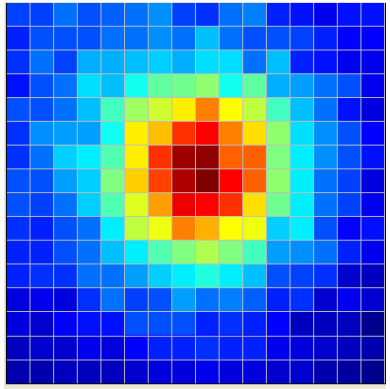
Size = 6mm^3



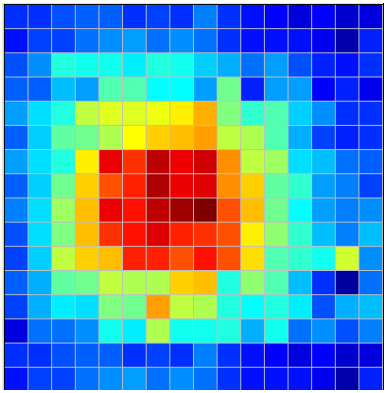
Depth : 5mm



Depth : 10mm

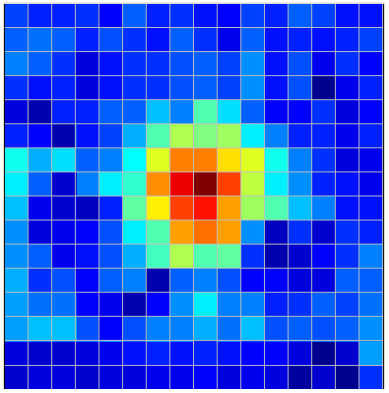


Depth : 15mm

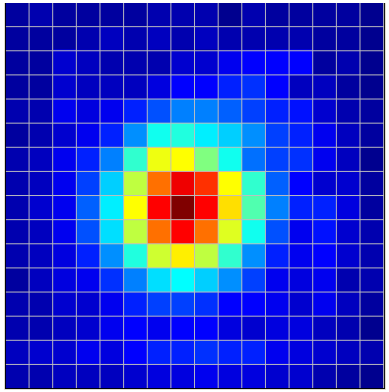


Depth : 20mm

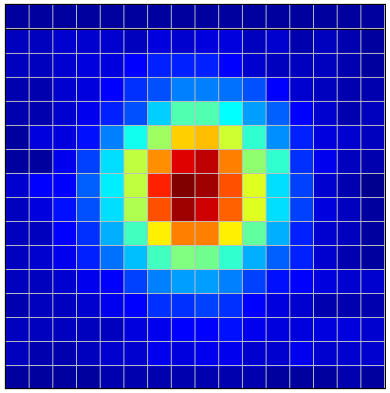
Depth = 10mm



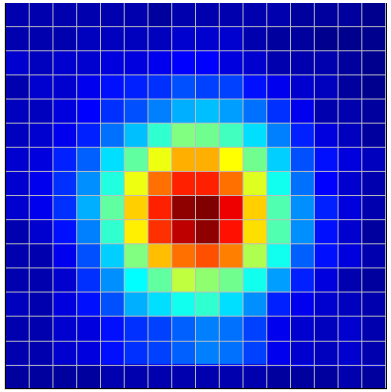
Size : 4mm^3



Size : 6mm^3

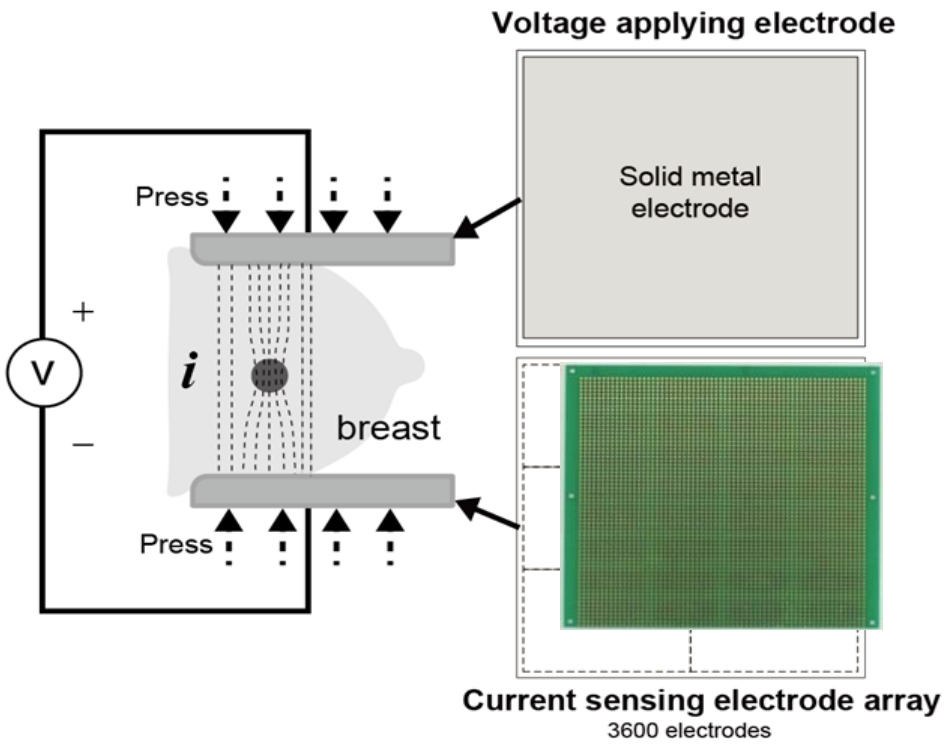


Size : 8mm^3

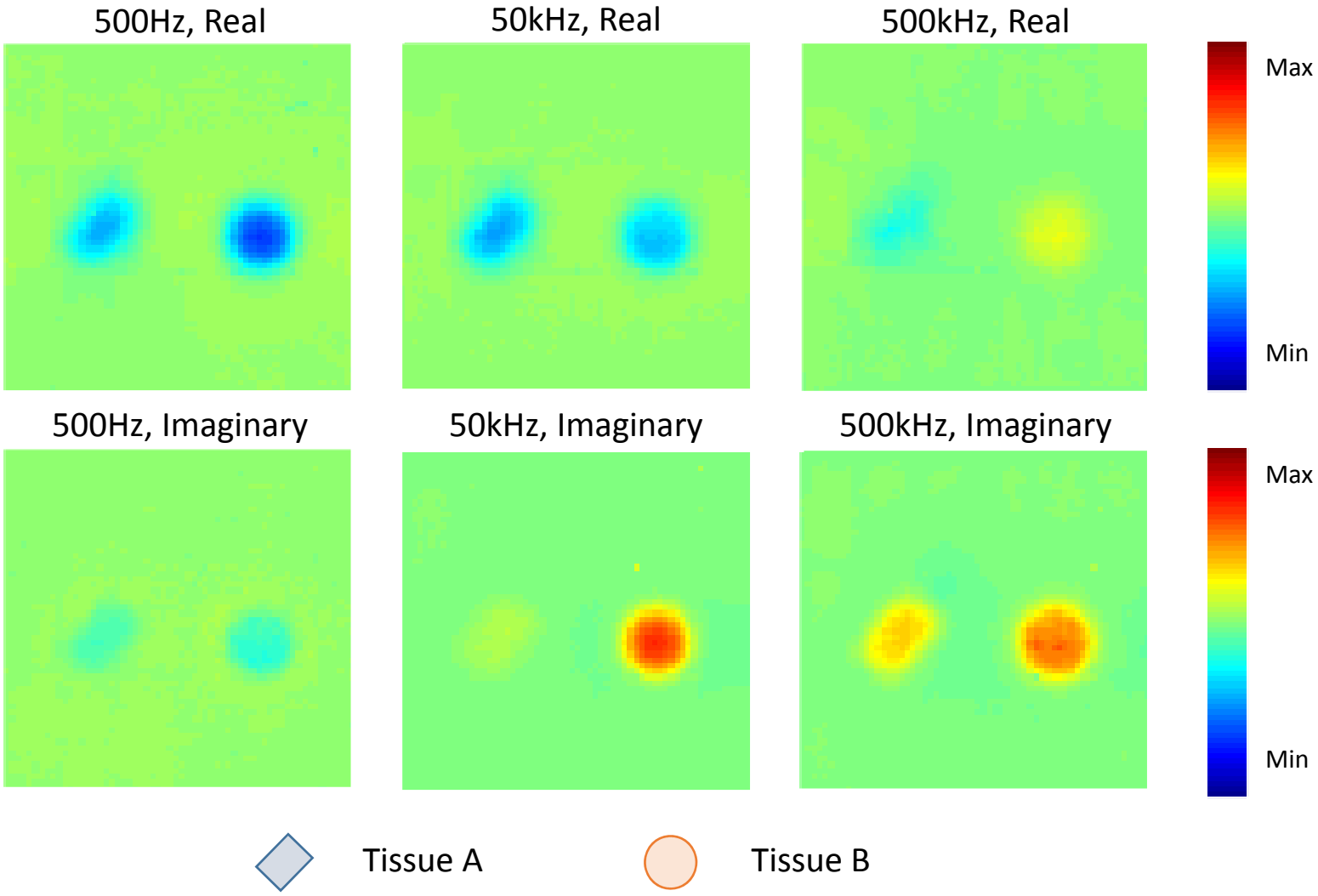


Size : 10mm^3

TAM (Trans-admittance Mammography)



TAM Image


500Hz, Real
50kHz, Real
500kHz, Real
Max
Min
500Hz, Imaginary
50kHz, Imaginary
500kHz, Imaginary
Max
Min
Tissue A
Tissue B

Conductivity Imaging Problem

Voltage

$$\begin{cases} \nabla \cdot \big(\sigma(\mathbf{r},t)\nabla u(\mathbf{r},t)\big) = 0 \text{ in } \Omega \\ -\sigma(\mathbf{r},t)\nabla u(\mathbf{r},t)\cdot \mathbf{n} = g \text{ on } \partial\Omega \end{cases}$$

Conductivity Injection Current

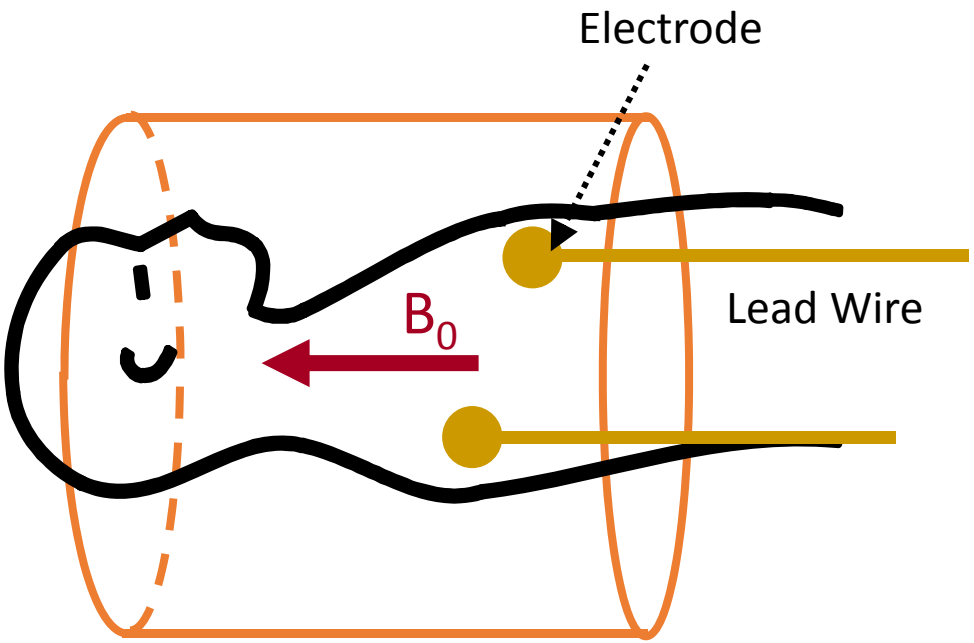
$$\mathbf{J}(\mathbf{r},t) = -\sigma(\mathbf{r},t)\nabla u(\mathbf{r},t)$$

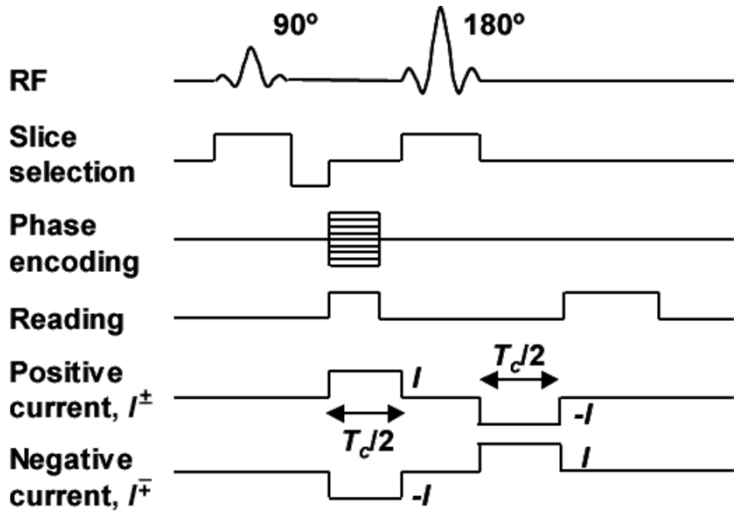
Current Density

Magnetic Flux Density

$$\mathbf{B}(\mathbf{r},t) = \frac{\mu_0}{4\pi}\int_{\Omega} \frac{\mathbf{J}(\mathbf{r}',t)\times(\mathbf{r}-\mathbf{r}')}{|\mathbf{r}-\mathbf{r}'|^3}\,d\mathbf{r}'$$

MREIT (Magnetic Resonance Electrical Impedance Tomography)





$$\mu_0 \mathbf{J} = \nabla \times \mathbf{B}$$

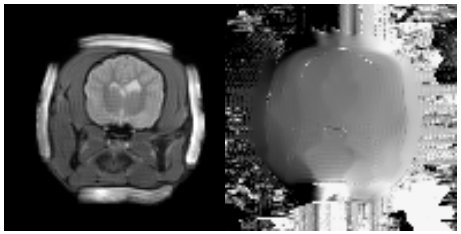
$$\mathbf{J}(\mathbf{r}) = -\sigma(\mathbf{r}) \nabla u(\mathbf{r})$$

$$\nabla^2 \mathbf{B} = -\mu_0 \nabla u \times \nabla \sigma$$

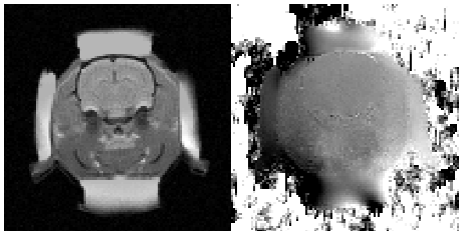
$$\nabla^2 B_z = \mu_0 \left(\frac{\partial \sigma}{\partial x}, \frac{\partial \sigma}{\partial y} \right) \cdot \left(\frac{\partial u}{\partial y}, -\frac{\partial u}{\partial x} \right)$$

MREIT using MRI

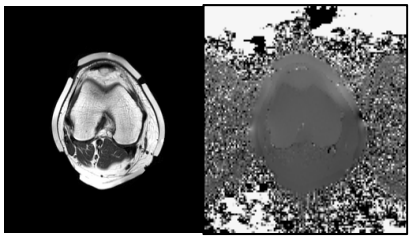
3T (IIRC, KHU)



9.4T (YU)

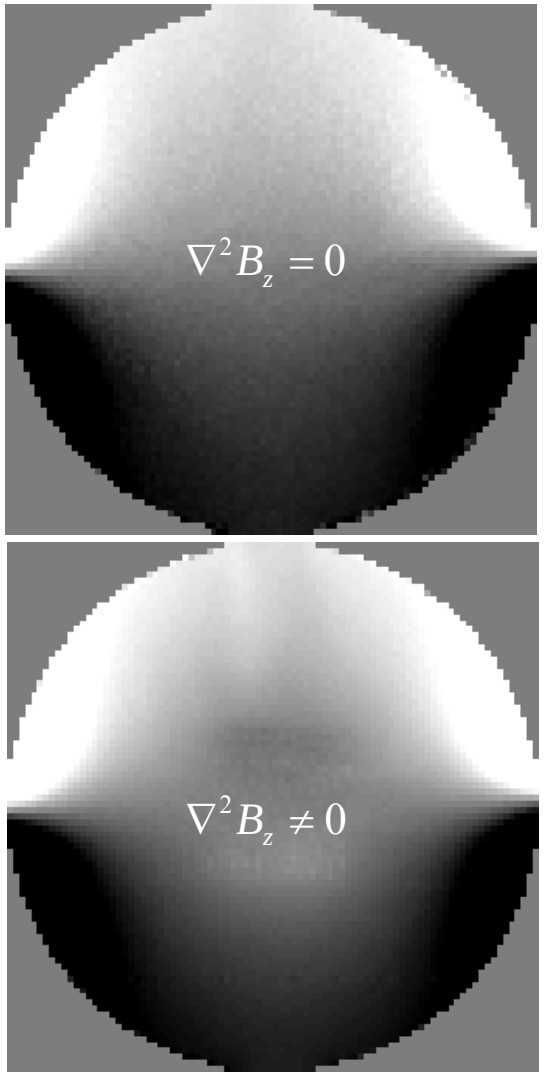


3T (KHUH)



Magnetic Field Imaging using MRI

Horizontal Injection Current

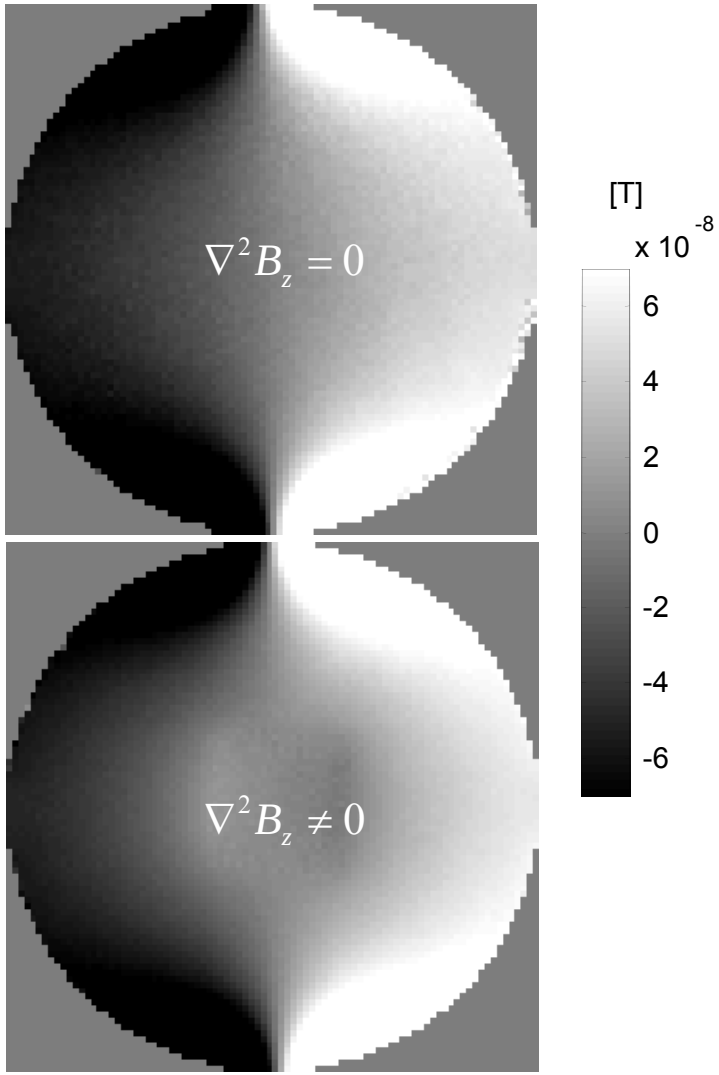


$$\mu_0 \mathbf{J} = \nabla \times \mathbf{B}$$

$$\mathbf{J} = -\sigma \nabla u$$

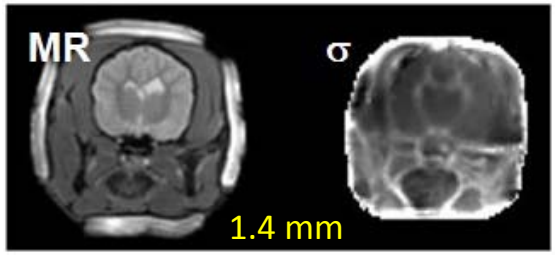
$$\nabla^2 \mathbf{B} = -\mu_0 \nabla u \times \nabla \sigma$$

Vertical Injection Current

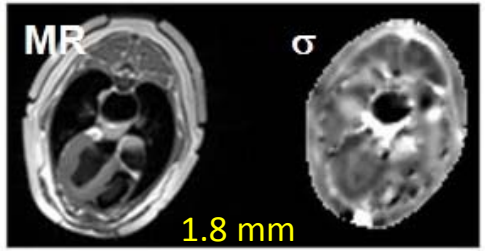


MREIT Image

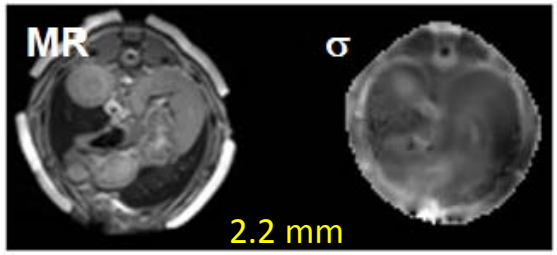
Canine Head



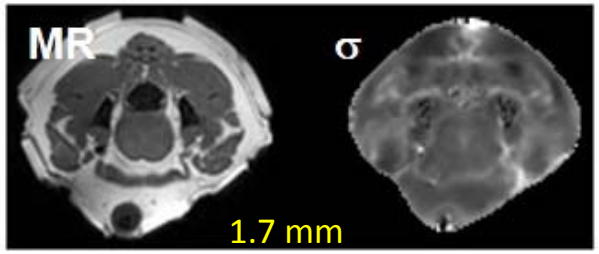
Canine Chest



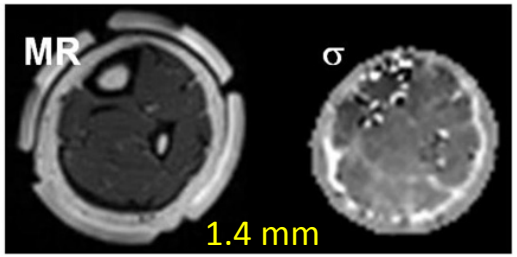
Canine Abdomen



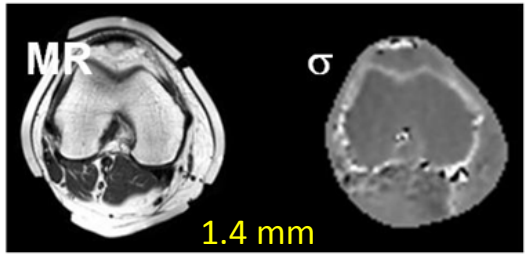
Canine Pelvis



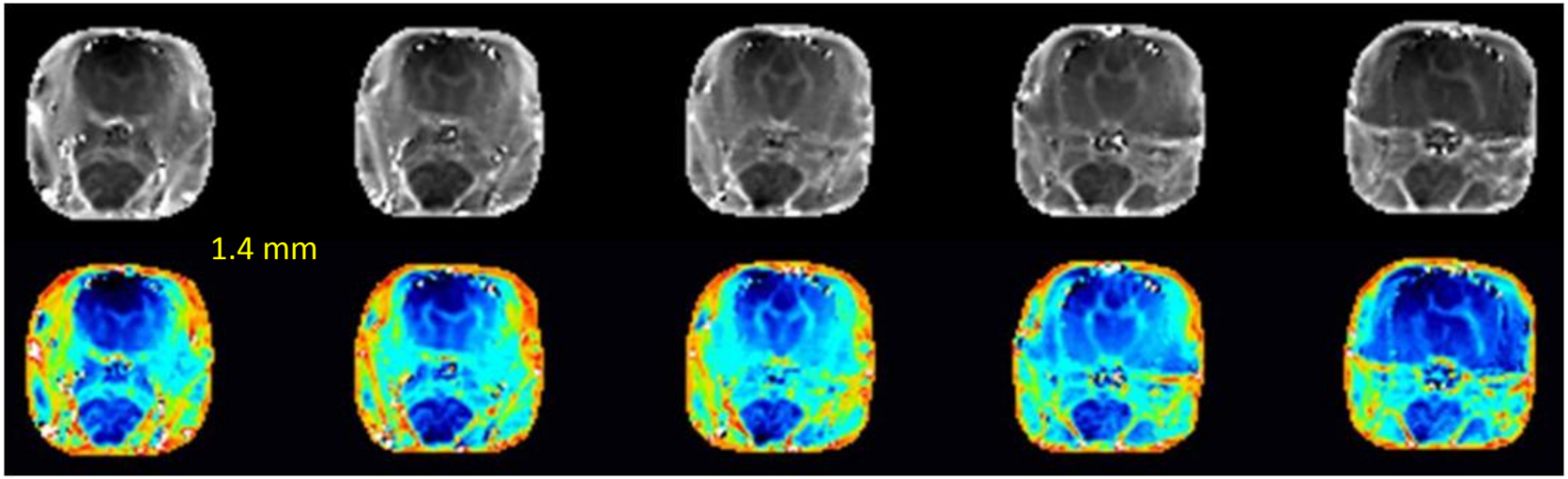
Human Leg



Human Knee

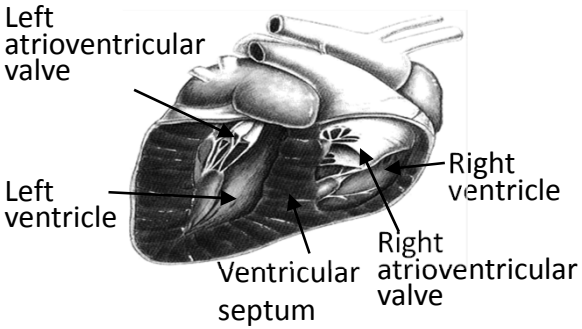


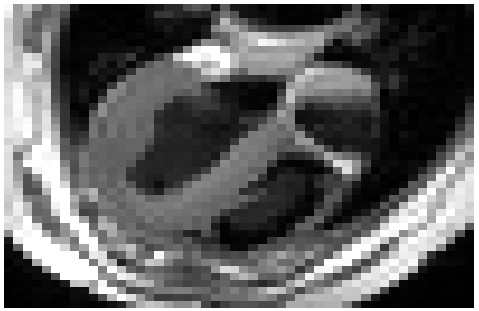
Canine Head

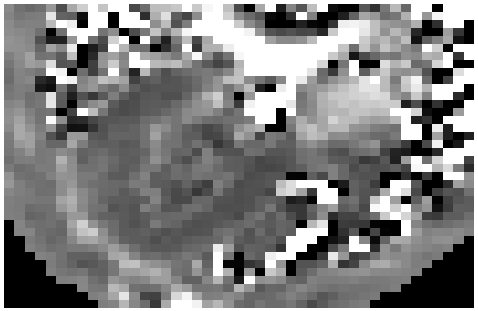


MRI vs. Conductivity Image

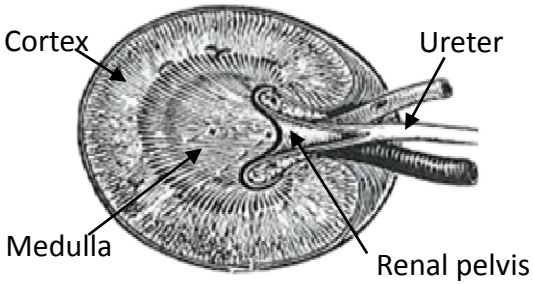
Heart

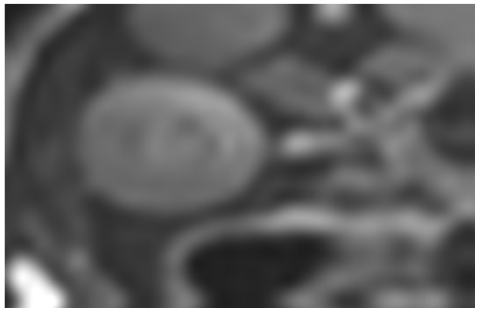


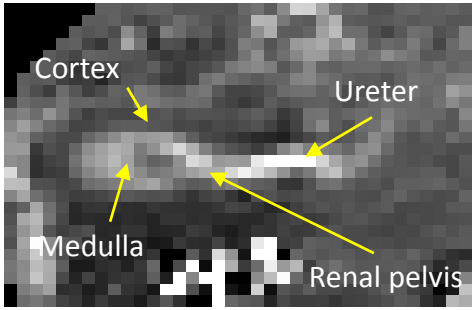




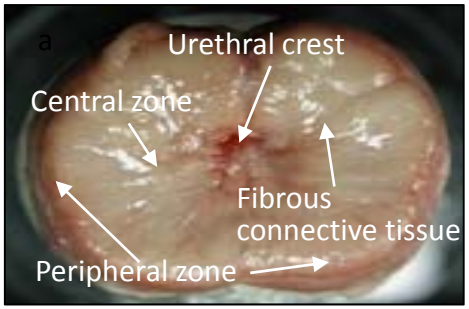
Kidney

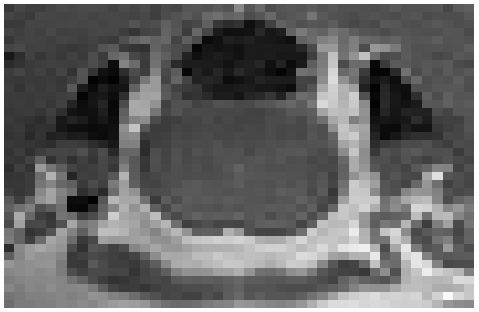


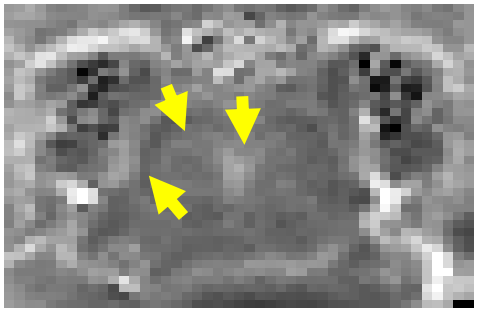




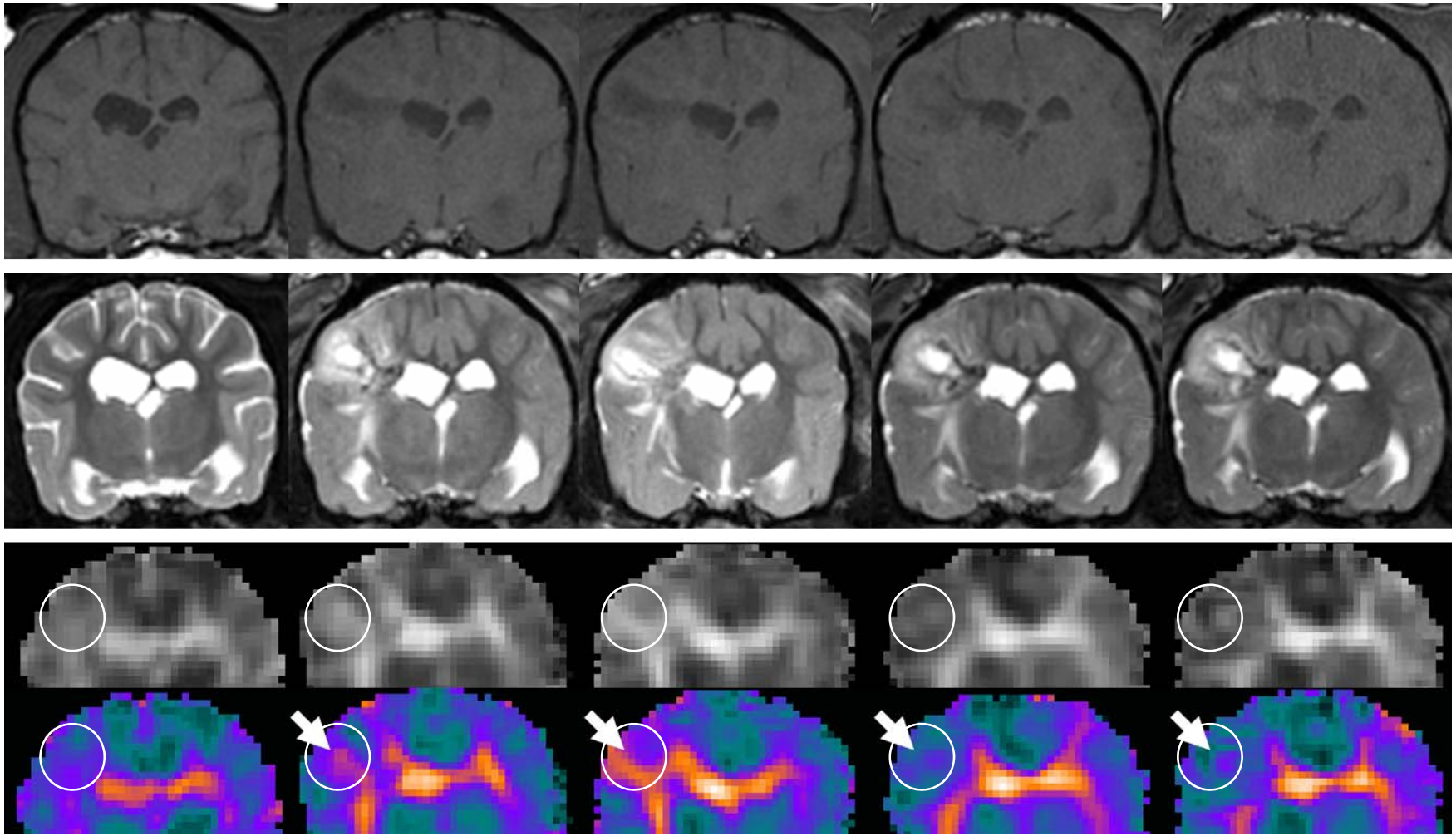
Prostate







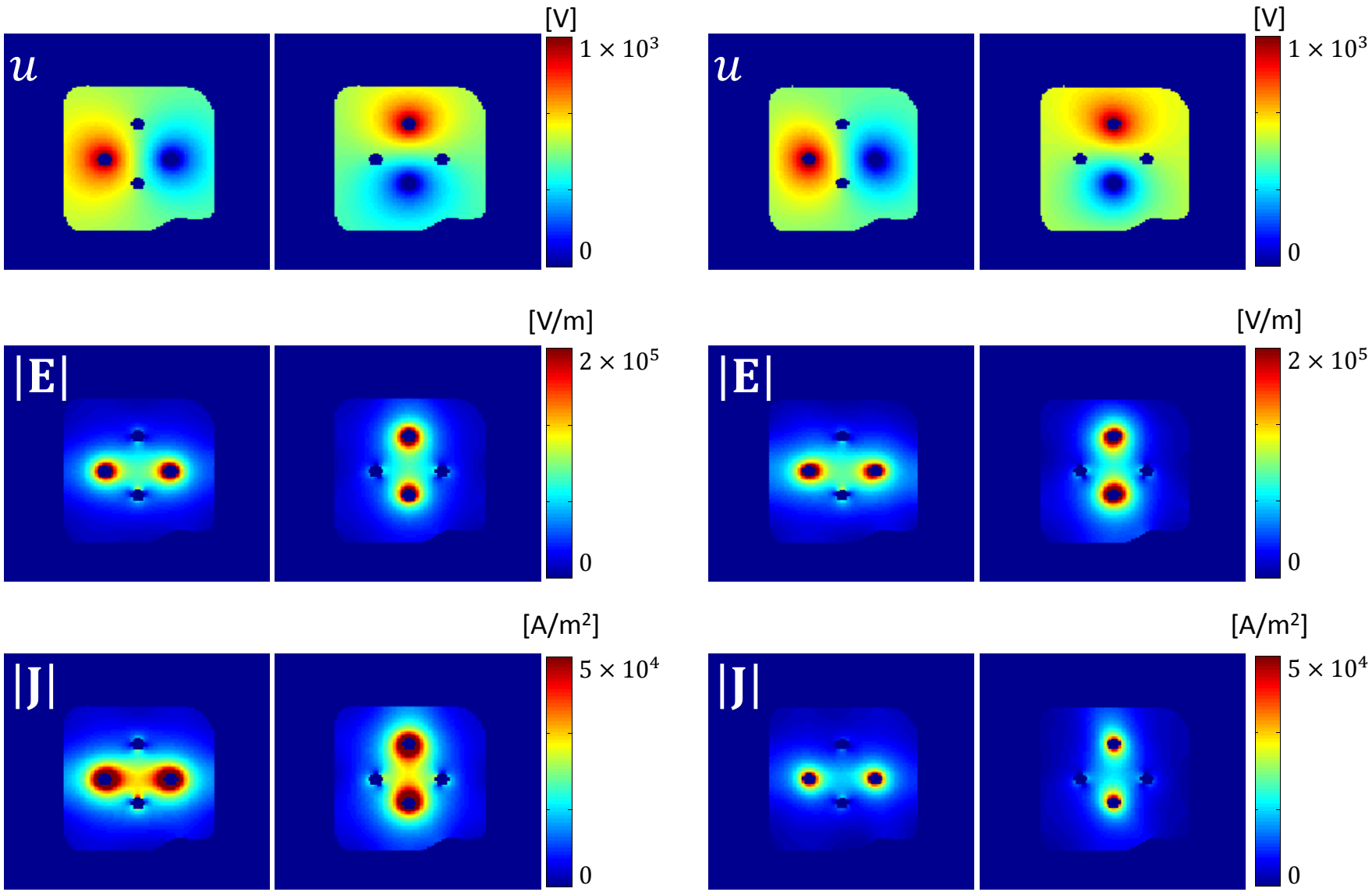
Animal Disease Model (Brain Abscess)



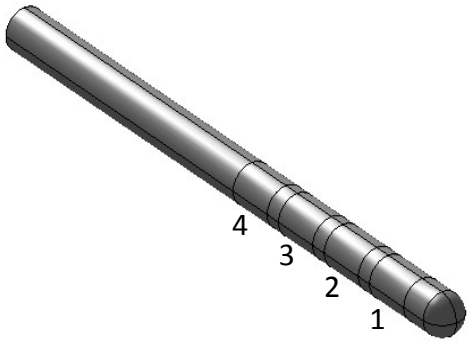
Before	6 hours	12 hours	18 hours	24 hours

Normal → Edema → Ring-shaped Membrane → Necrosis

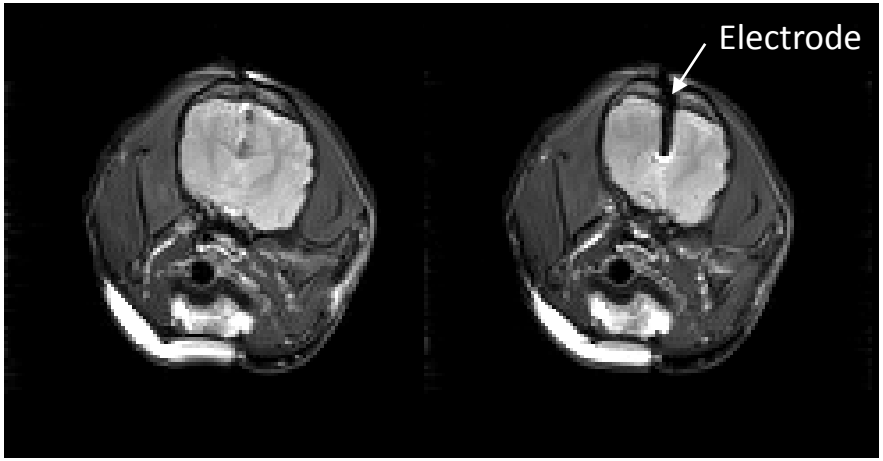
Treatment Planning (Electroporation)



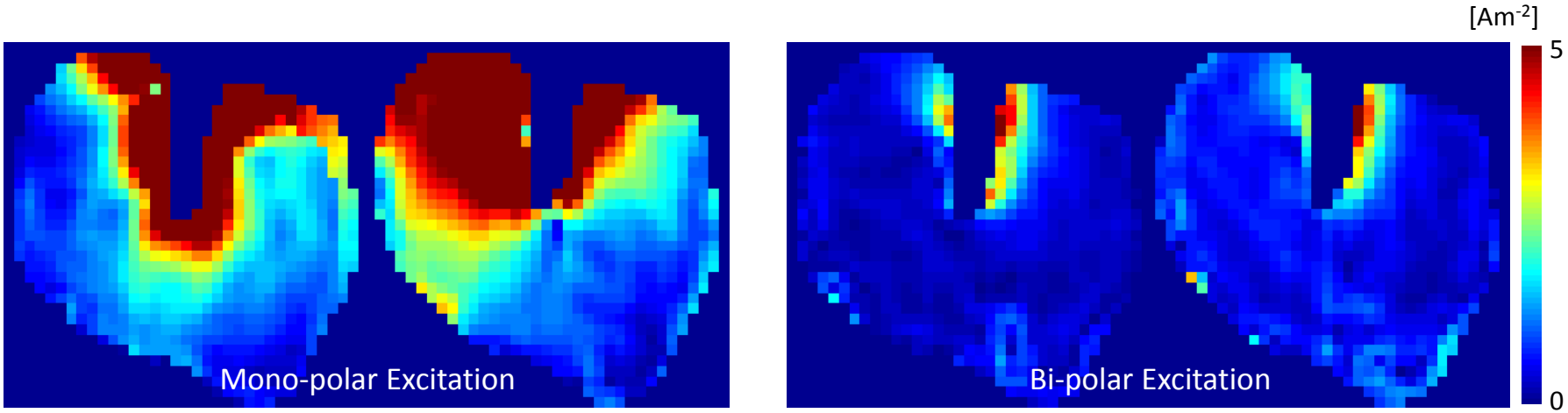
Treatment Monitoring (DBS)



DBS Electrode

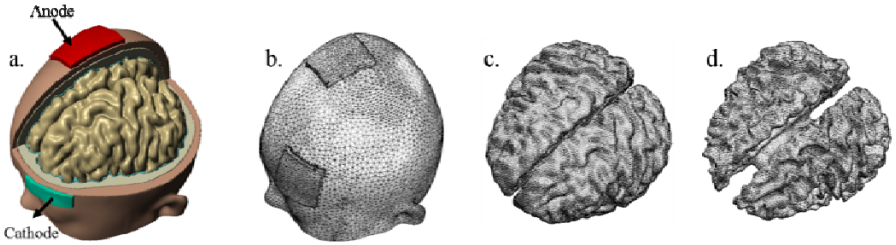


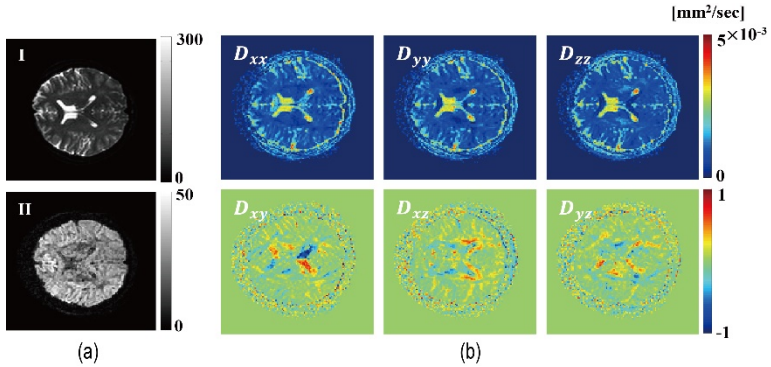
MR Magnitude Image



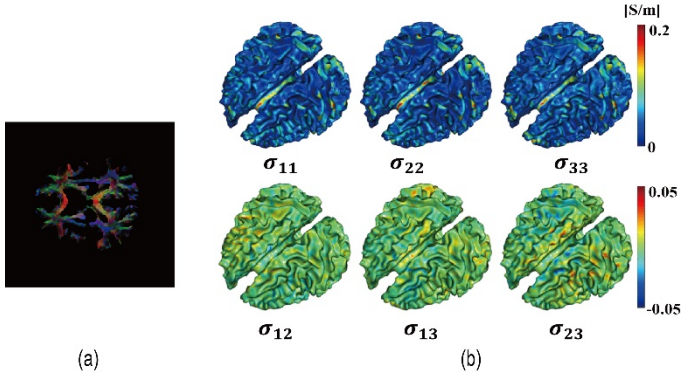
Current Density Image

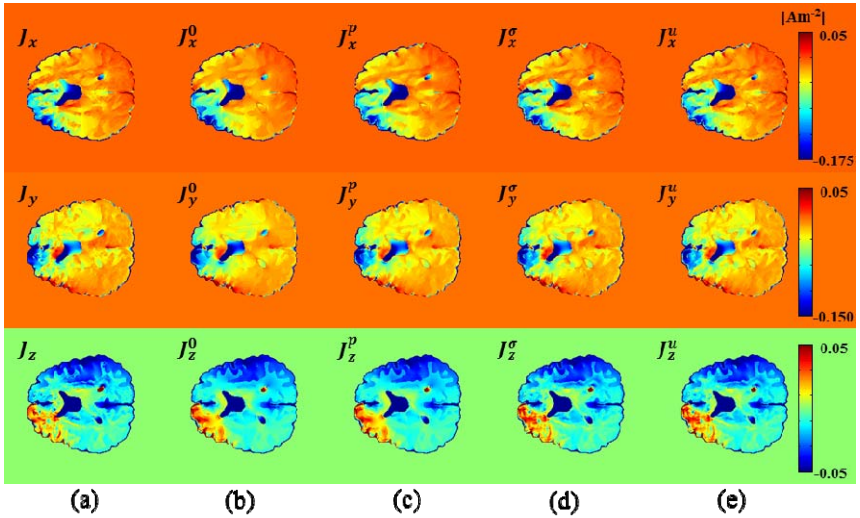
Treatment Monitoring (tDCS)

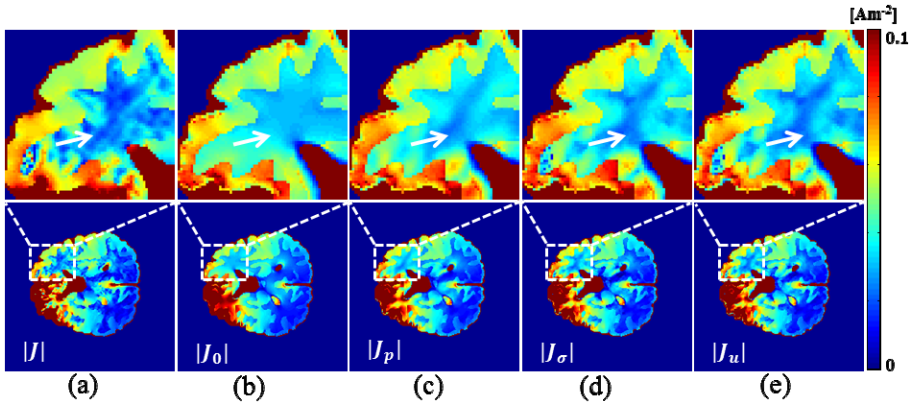




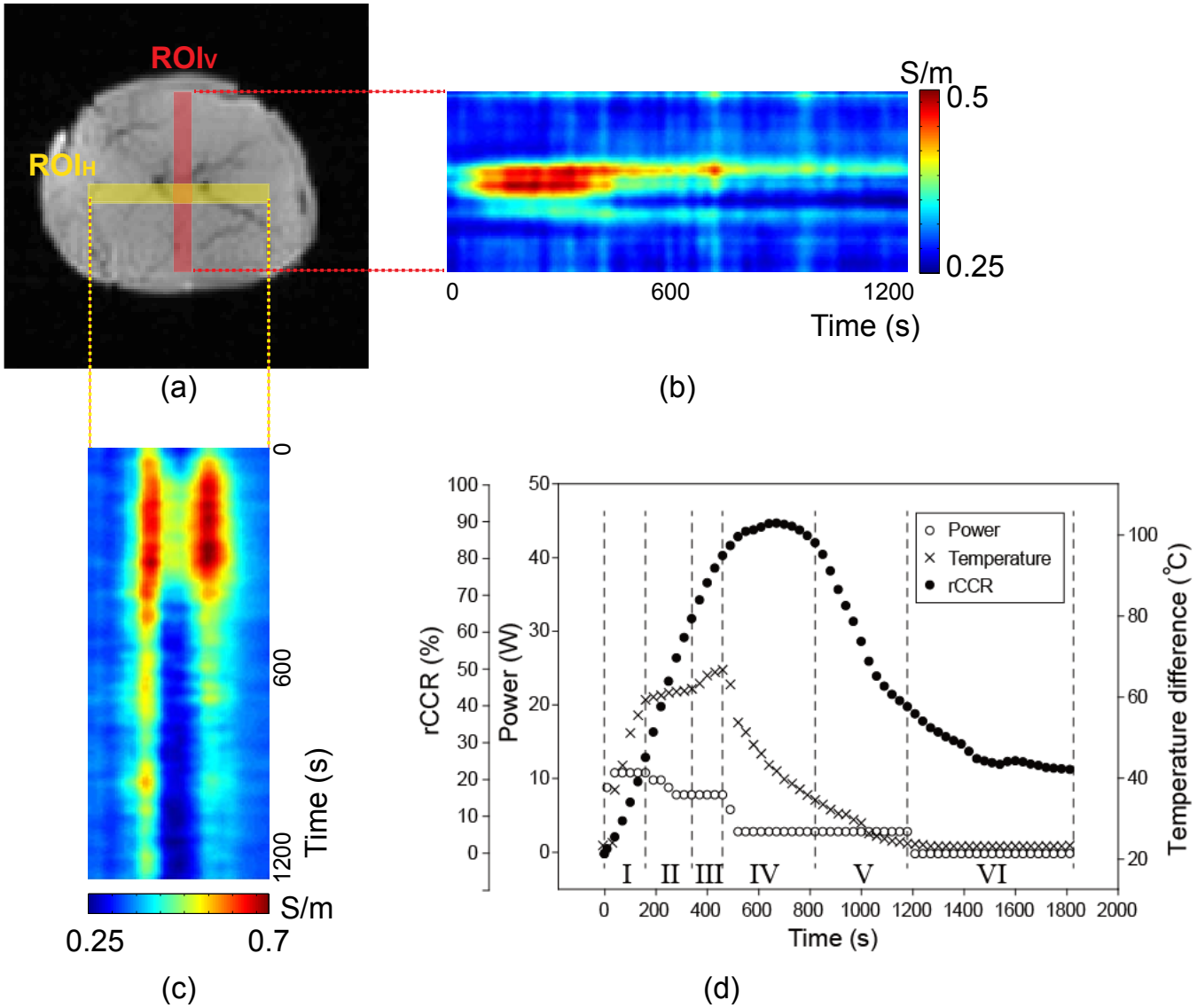
$$\eta \mathbf{D} = \mathbf{C}$$



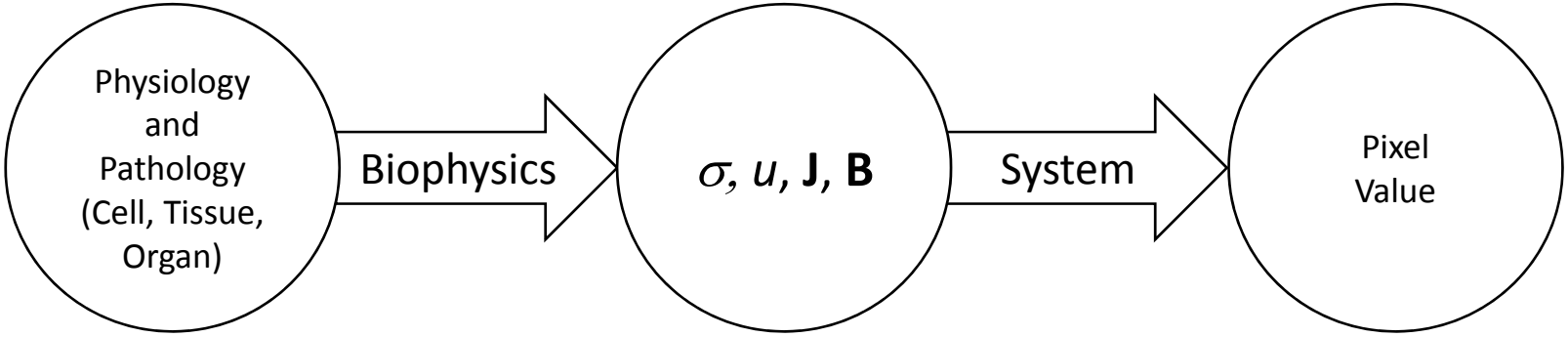




Treatment Monitoring (RF Ablation)



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