

Electricity in the Body

Biomedical Engineering Seminar
Dalhousie University
17 December 2014

Andy Adler

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Systems and Computer Engineering, Carleton University, Ottawa

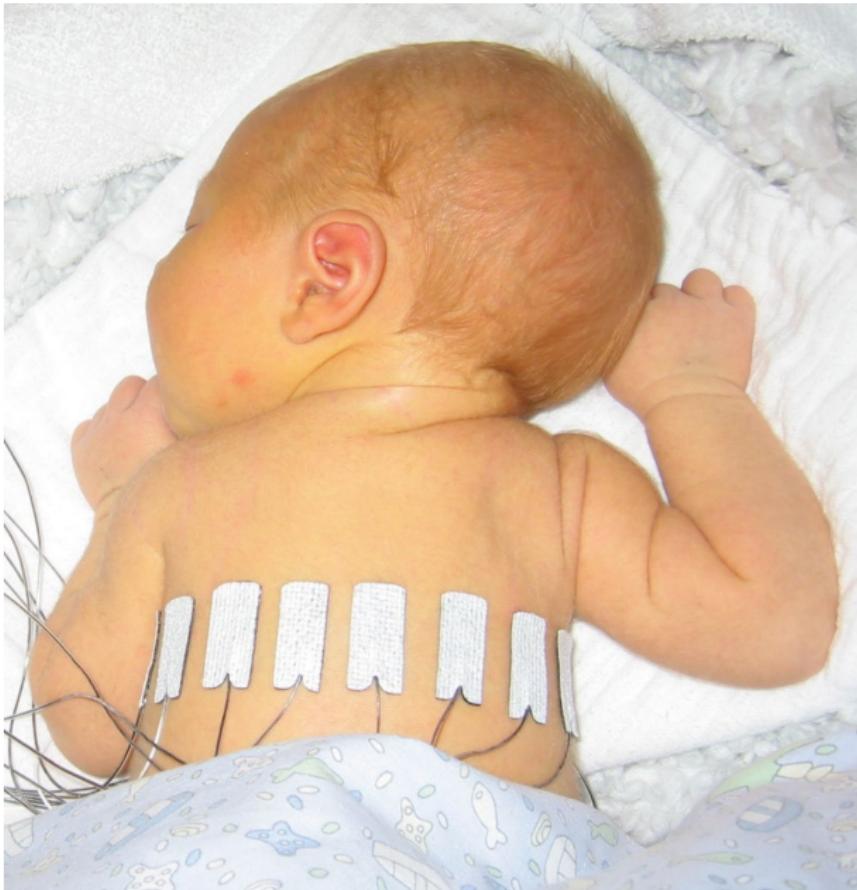
My visit to Halifax . . .

- Tasers
- Cardiac mapping
- EIT

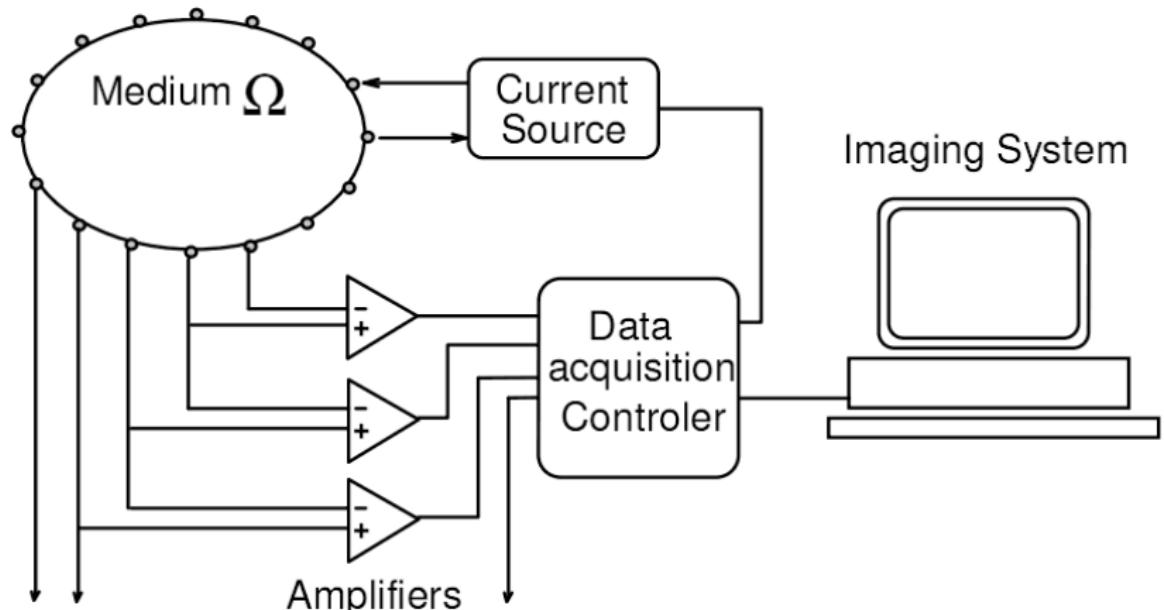
Electrical Impedance Tomography

10-day old healthy
baby with EIT
electrodes

Source:
eidors3d.sf.net/data_contrib/if-neonate-spontaneous



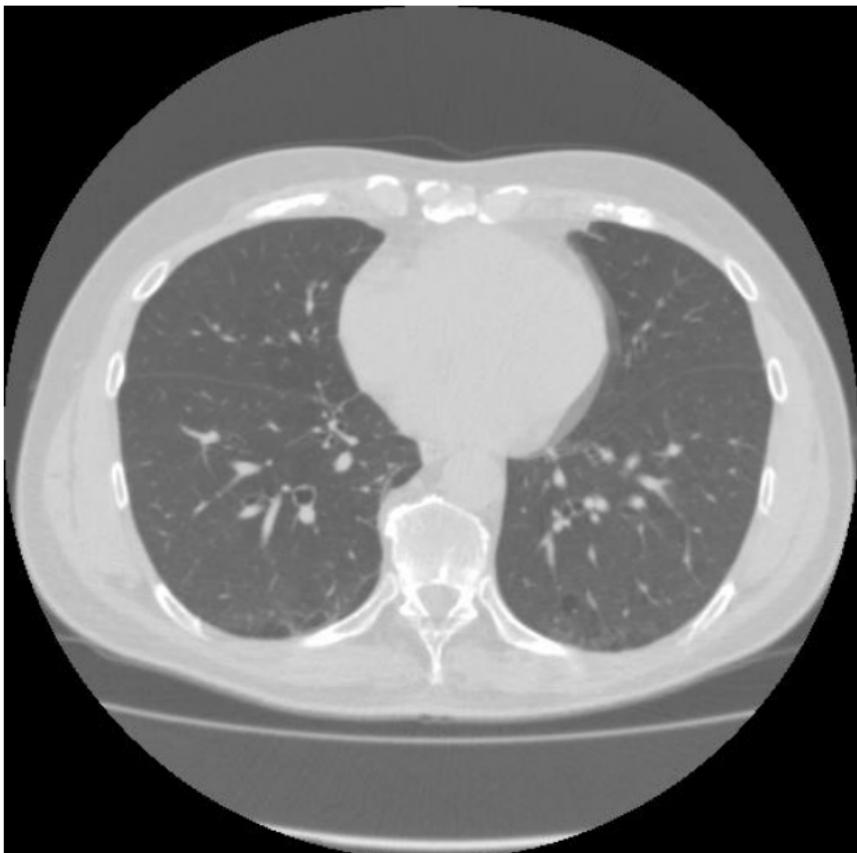
Electronics – Block Diagram



Current Propagation

Healthy Adult Male
CT slide at heart

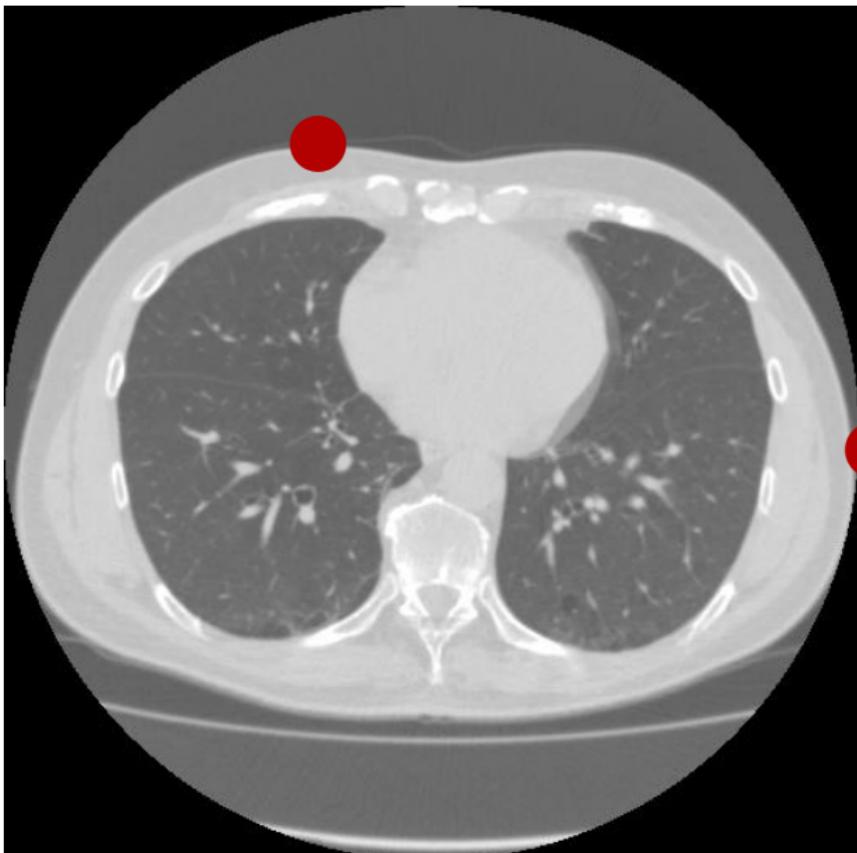
Source: ei-
dors3d.sf.net/tutorial/netgen/extrusion



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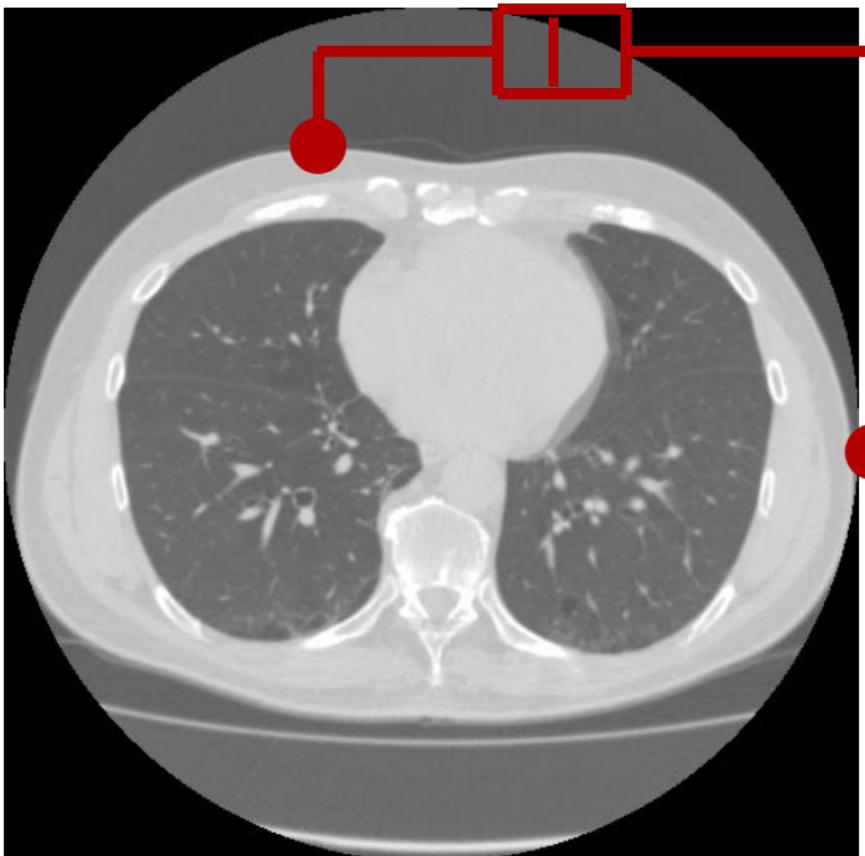
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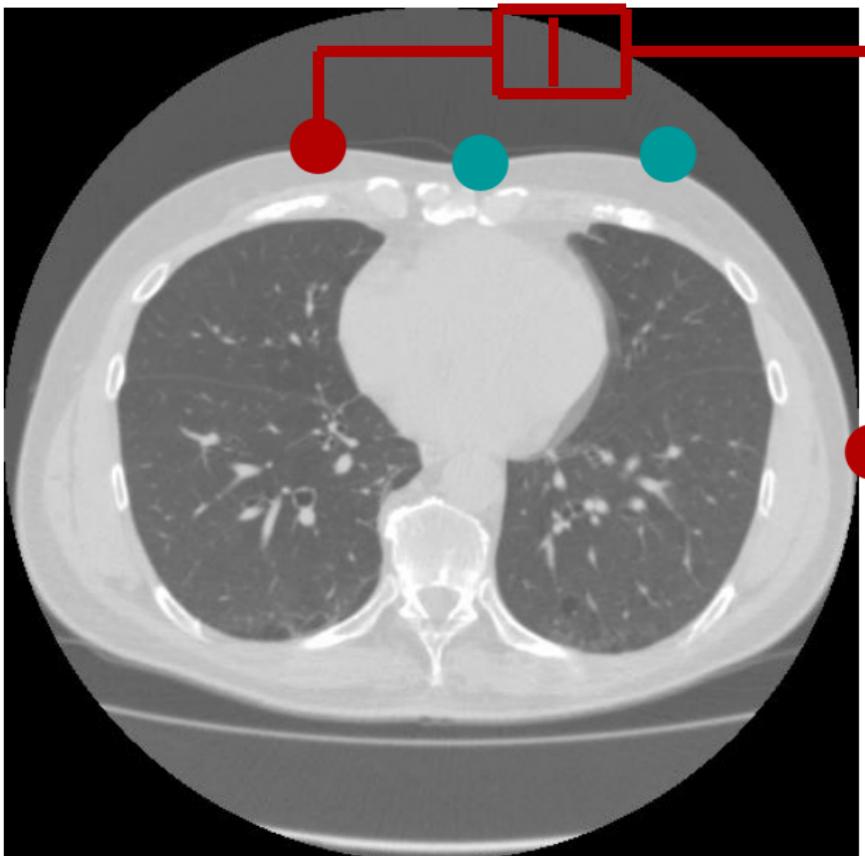
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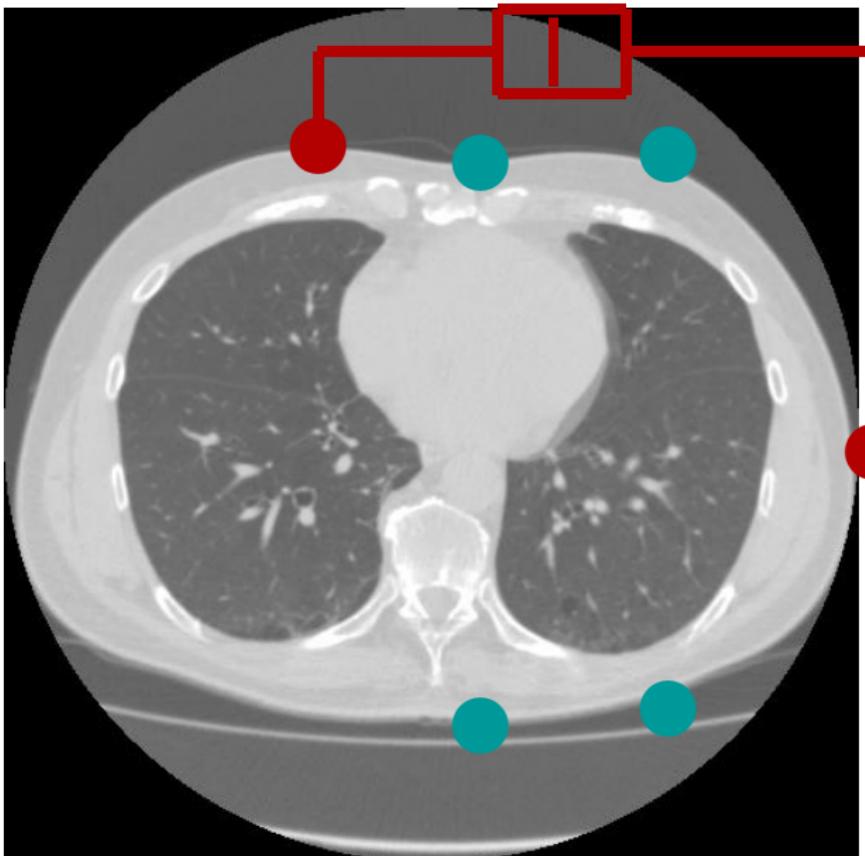
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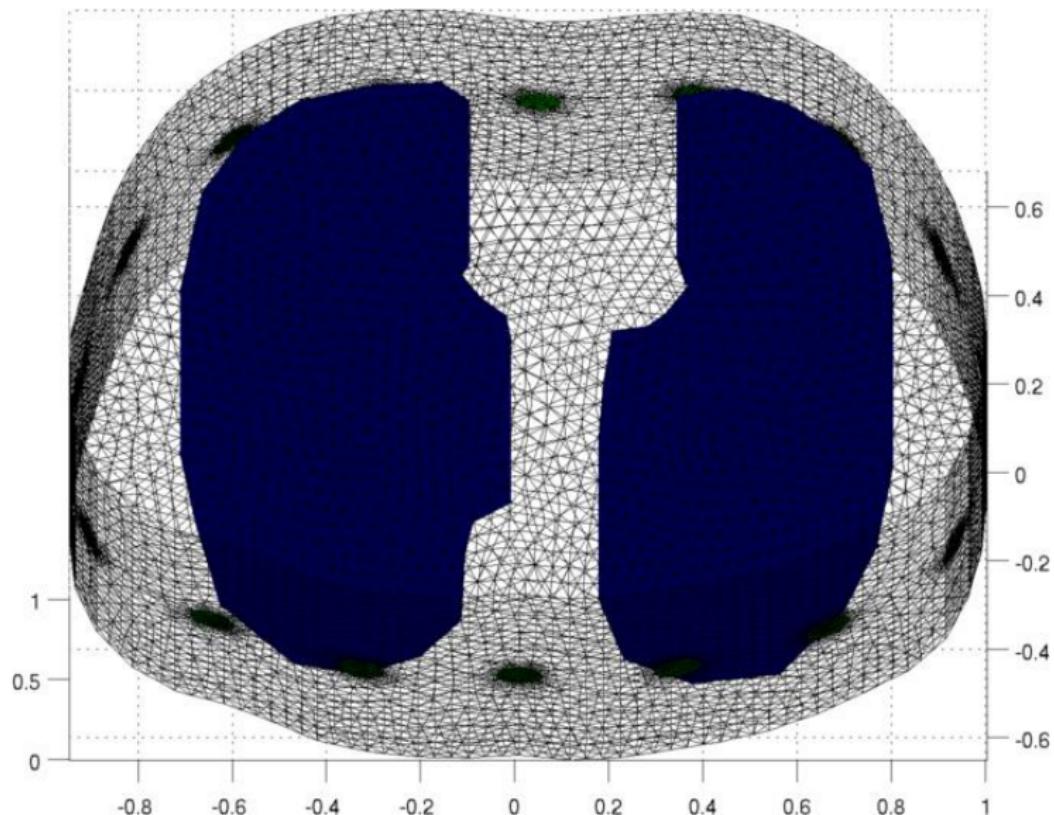
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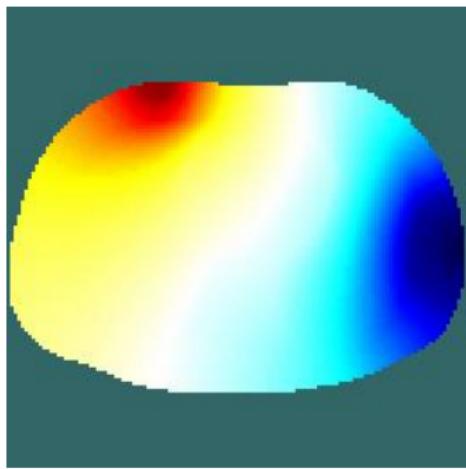
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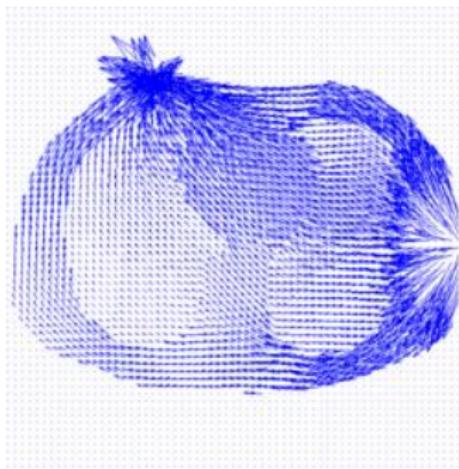
Finite Element Modelling



Finite Element Modelling



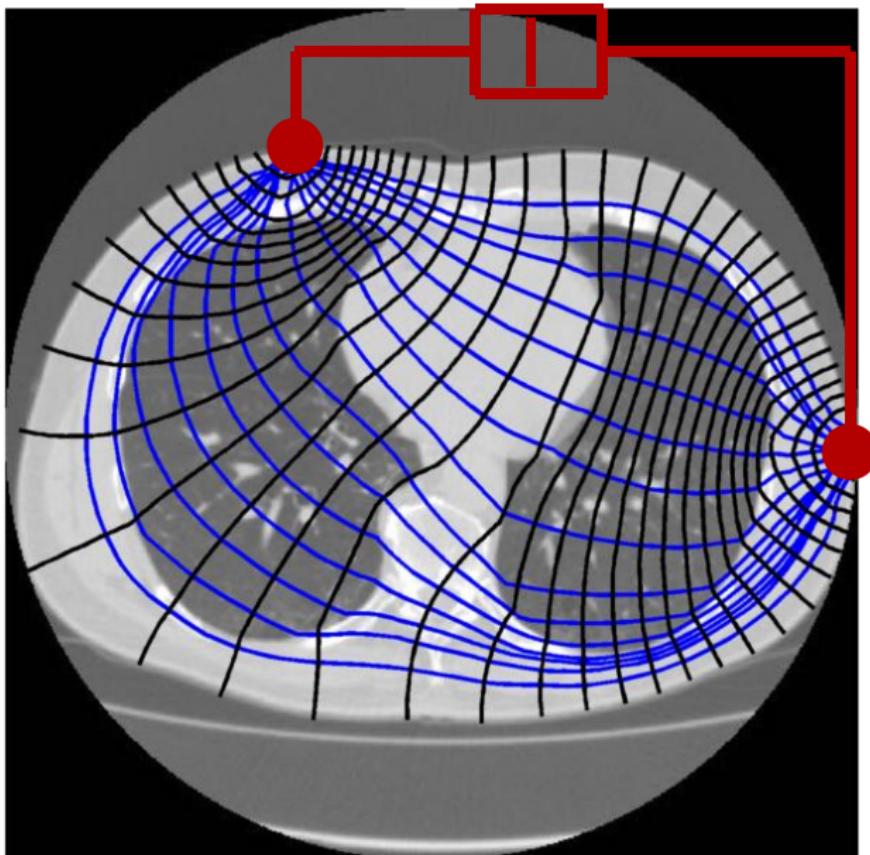
Simulated Voltages



Voxel Currents

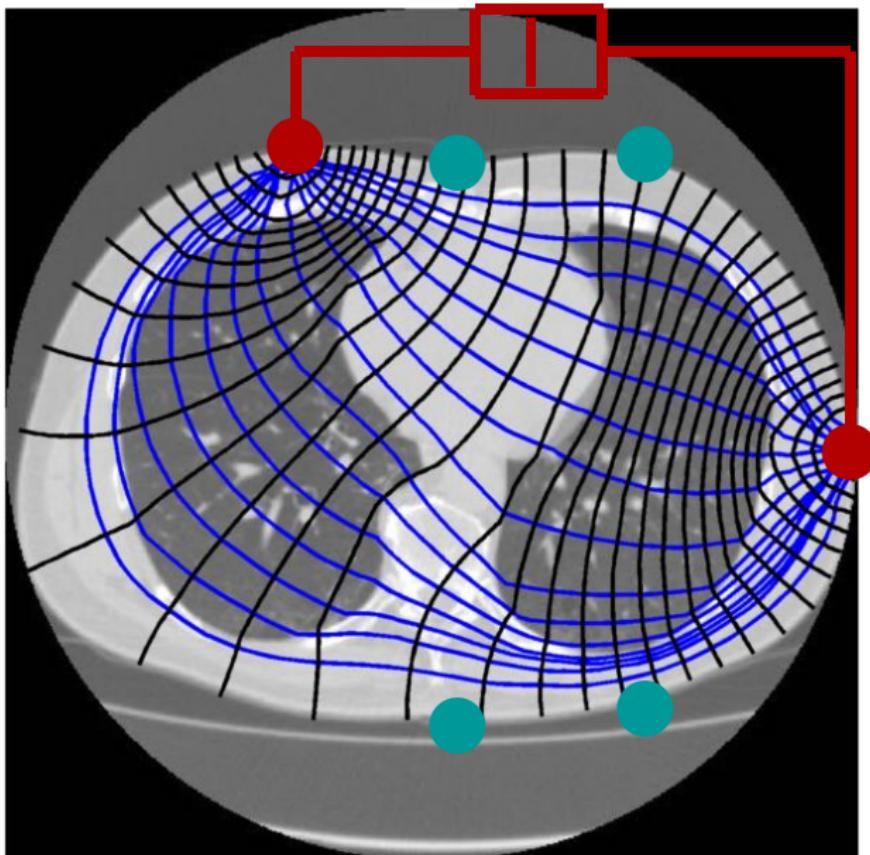
Thorax Propagation

CT Slice with
simulated current
streamlines and
voltage
equipotentials



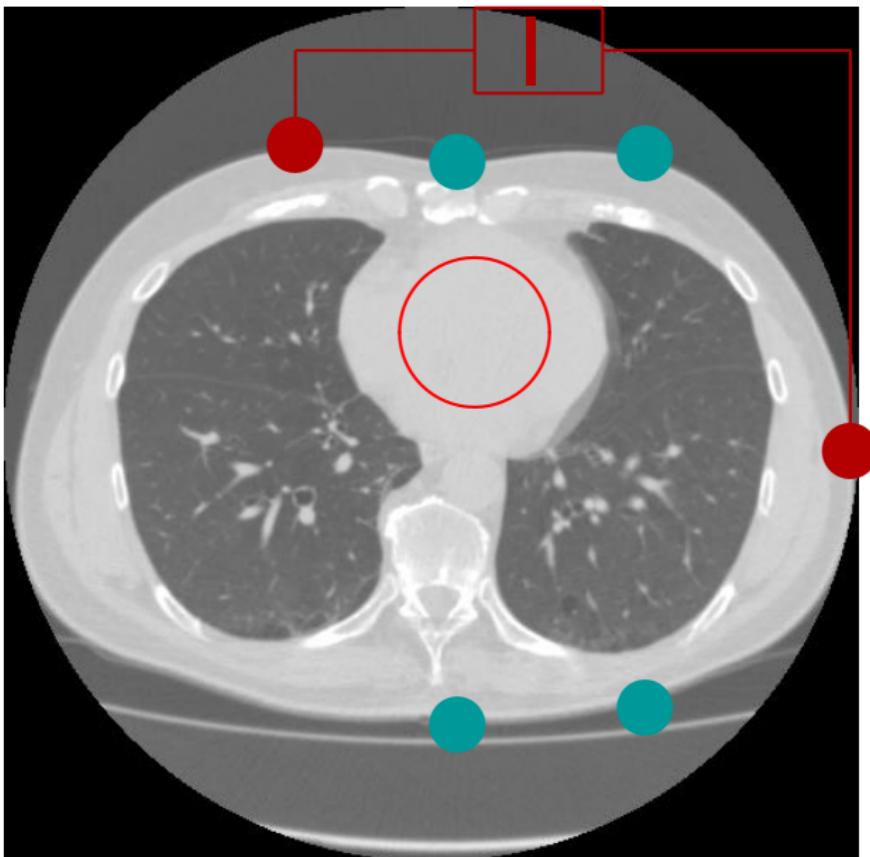
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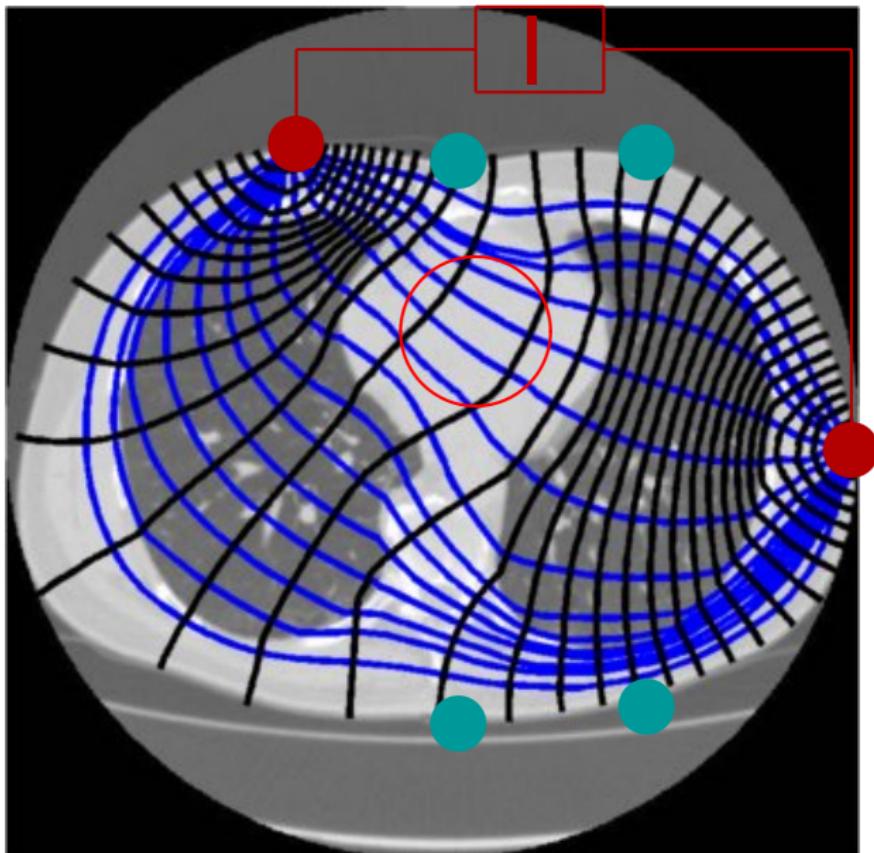
Changing Conductivity

Heart receives blood (diastole) and is more conductive

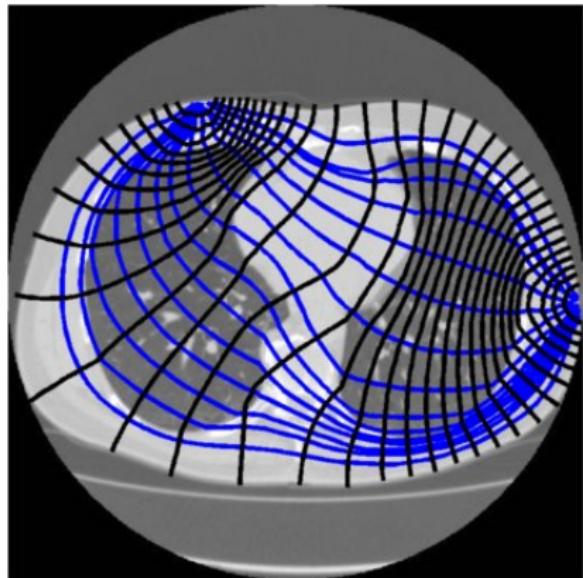
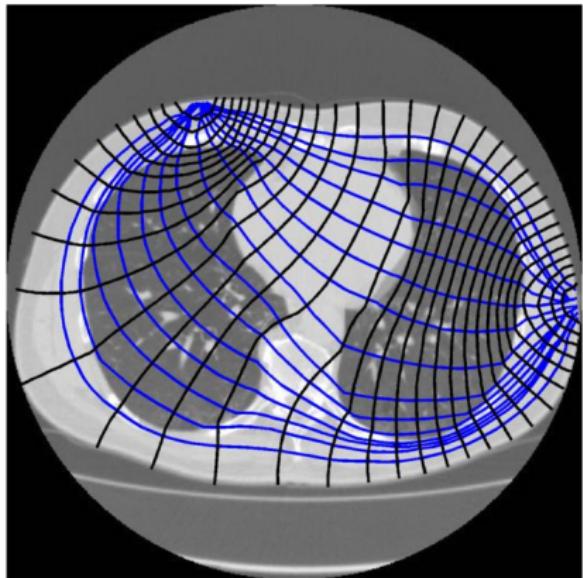


Changing Conductivity

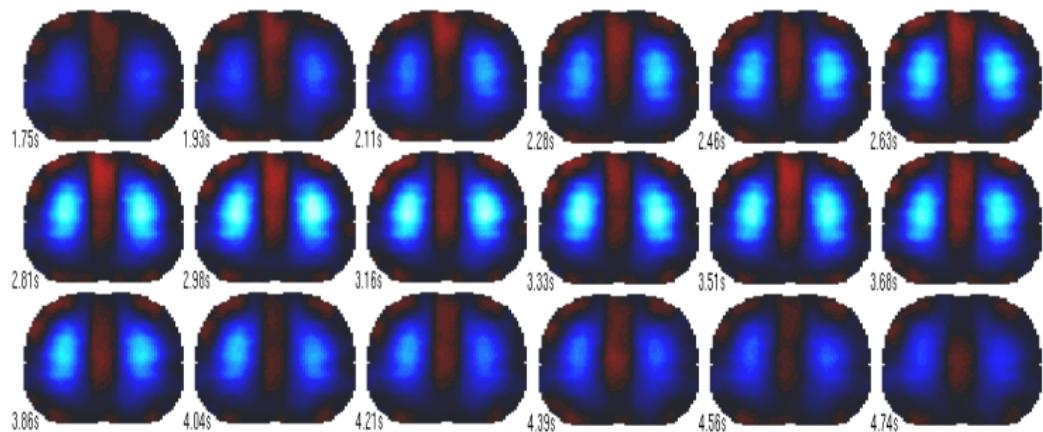
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Changing Conductivity

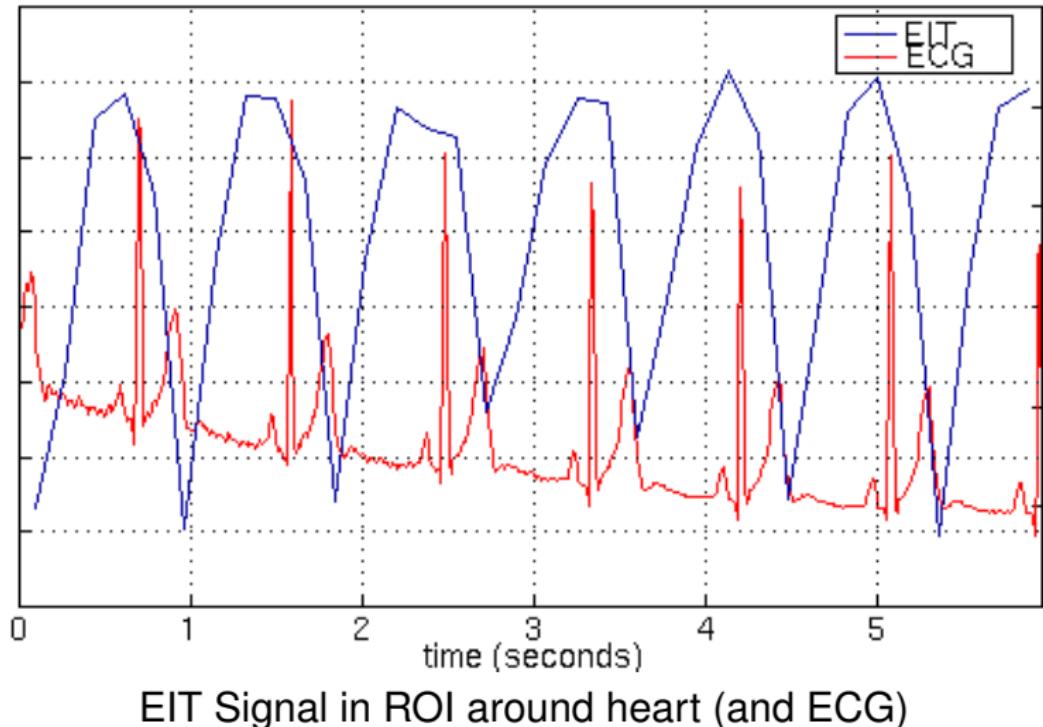


Application: Breathing



Chest images of tidal breathing in healthy adult

Application: Heart



Why Image Lungs? \Rightarrow Respiratory Failure

Inadequate gas exchange by respiratory system

Hypoxemia ($O_2 \downarrow$) or Hypercapnia ($CO_2 \uparrow$)

Why Image Lungs? ⇒ Respiratory Failure

Inadequate gas exchange by respiratory system

Hypoxemia ($O_2 \downarrow$) or Hypercapnia ($CO_2 \uparrow$)

Causes

- Pulmonary dysfunction
 - Asthma, Emphysema, COPD, Pneumonia, Pneumothorax, Hemothorax, ARDS, Cystic Fibrosis
- Cardiac dysfunction
 - Pulmonary Edema, Arrhythmia, Congestive heart failure, Valve pathology

Why Image Lungs? ⇒ Respiratory Failure

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Treatment

- Emergency treatment
- Treatment of underlying cause
- **Mechanical Ventilation**

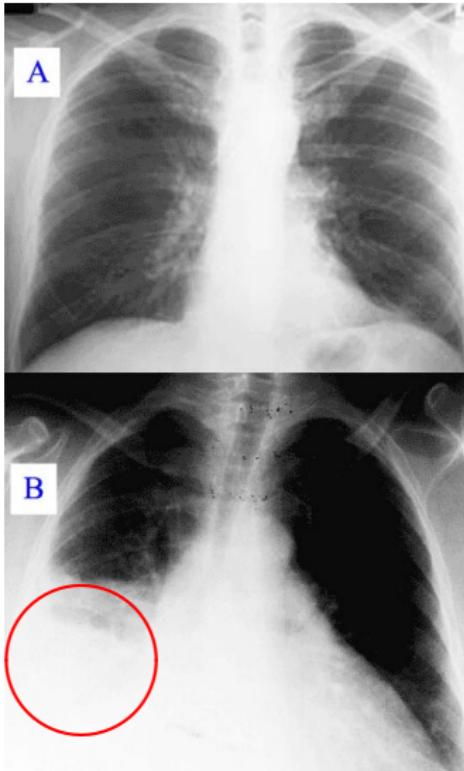
Mechanical Ventilation



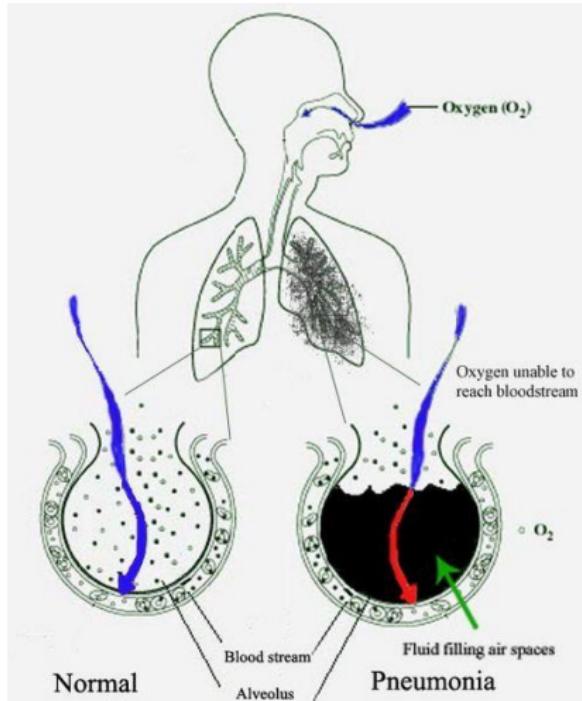
Mechanical Ventilator with EIT monitor

Source: Swisstom.com

Why image lungs? Example: Pneumonia



Source: en.wikipedia.org/wiki/Pneumonia

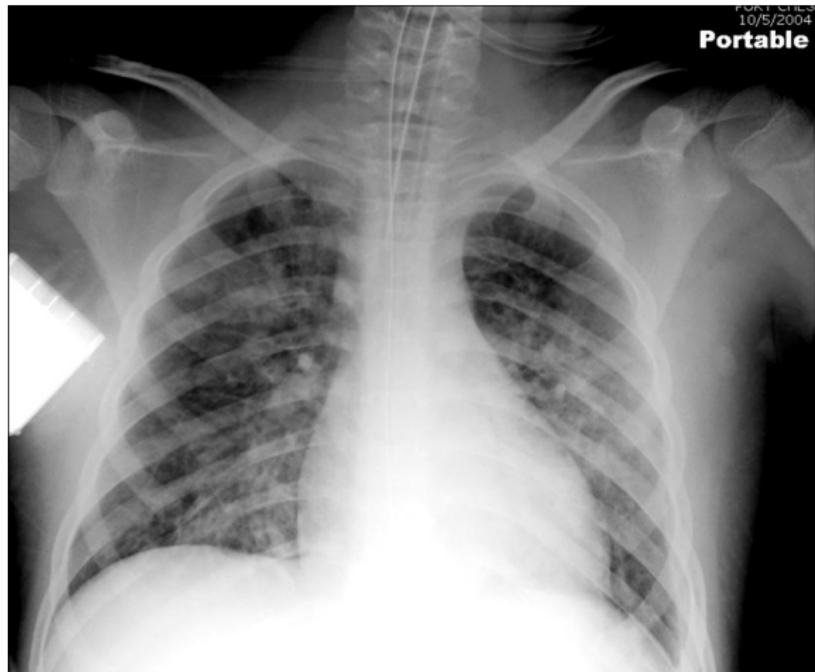


B: fluid in right lung

Acute Respiratory Distress Syndrome (ARDS)

Chest X-ray of
paediatric patient

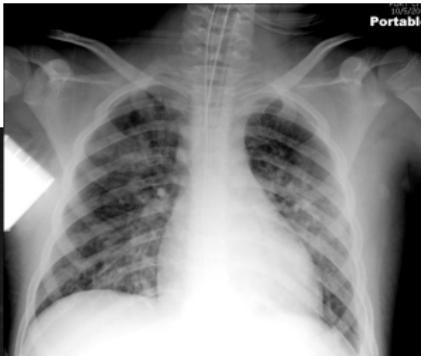
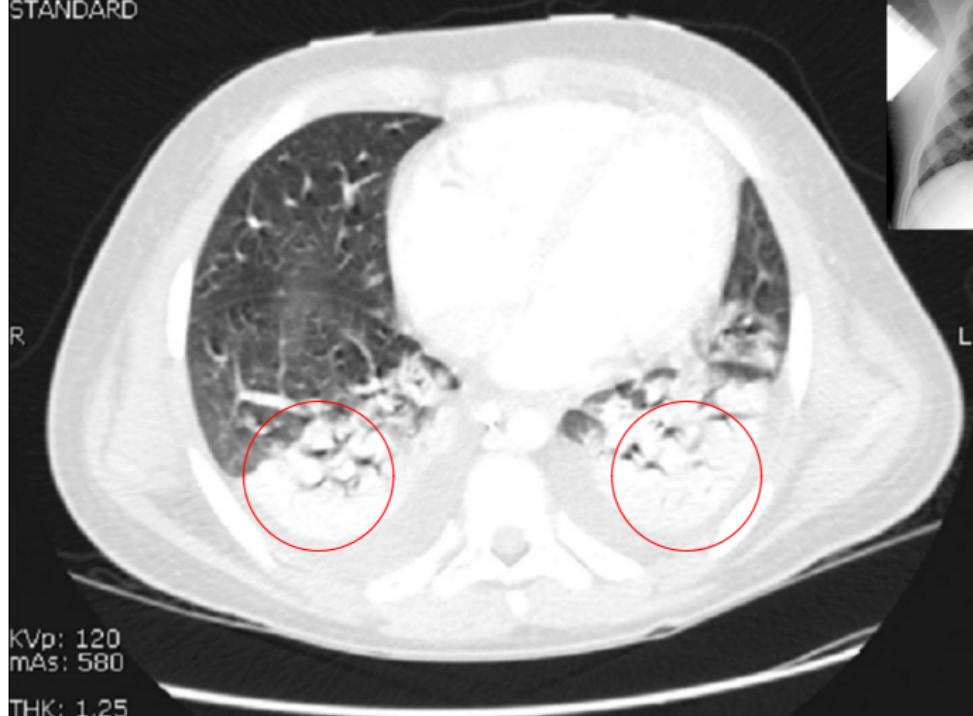
Source: Wolf GK, Arnold JH, in



*Yearbook of Intensive Care and
Emergency Medicine, 2005*

Acute Respiratory Distress Syndrome (ARDS)

STANDARD



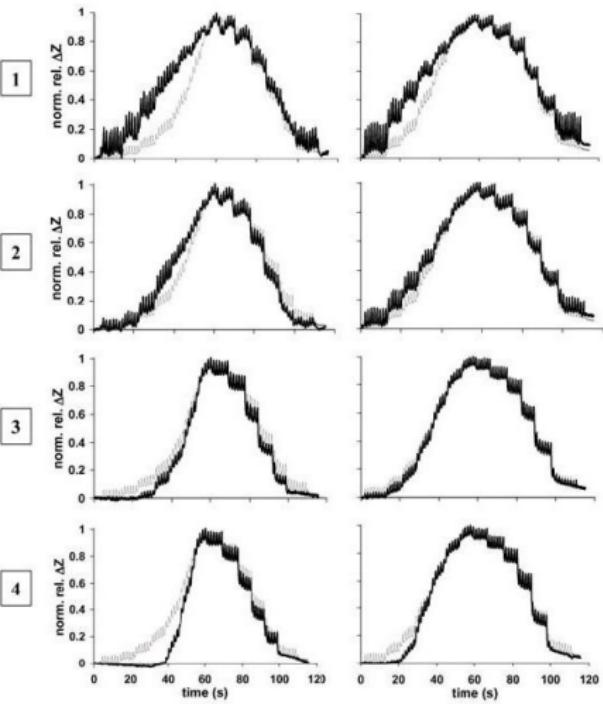
Regional Ventilation

Electrical impedance tomography

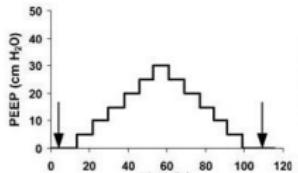
Acute lung injury

Surfactant treatment

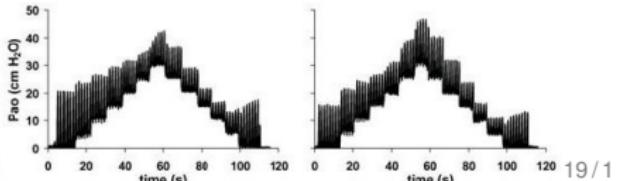
Regions of interest



Ventilatory manoeuvre



Airway pressure

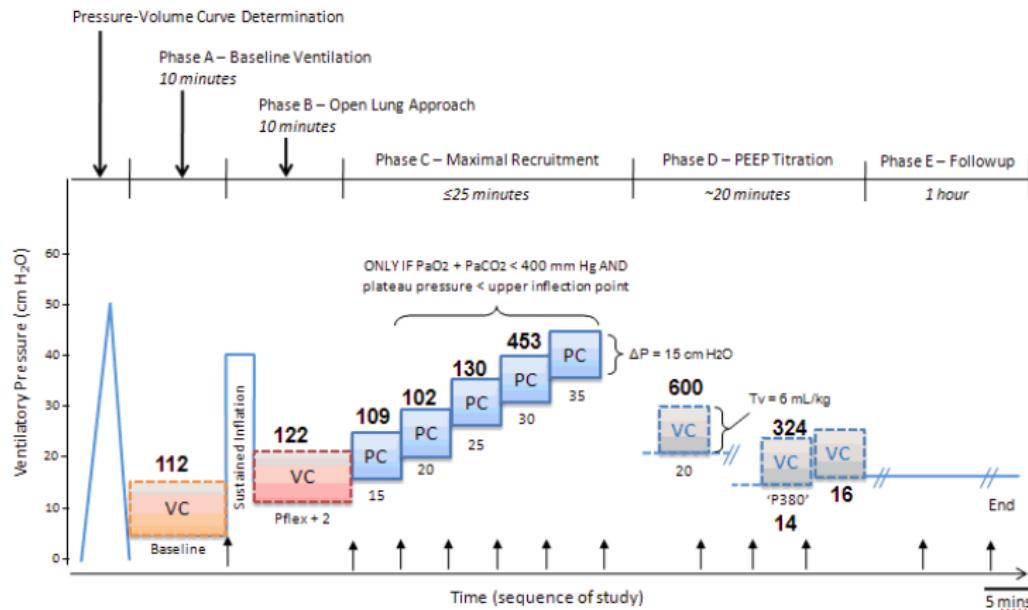


Source: Frerichs *et al*,
Intensive Care Med,
2003

eidors3d.sf.net/tutorial/lung_EIT/if.c

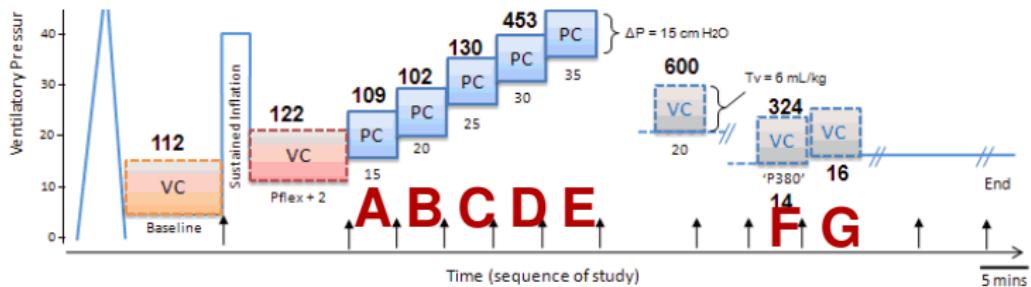
EIT in ARDS

Patient 1 – $\text{PaO}_2 + \text{PaCO}_2$

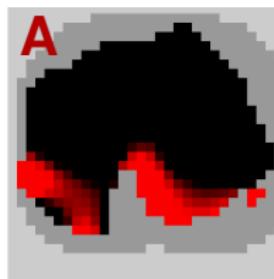
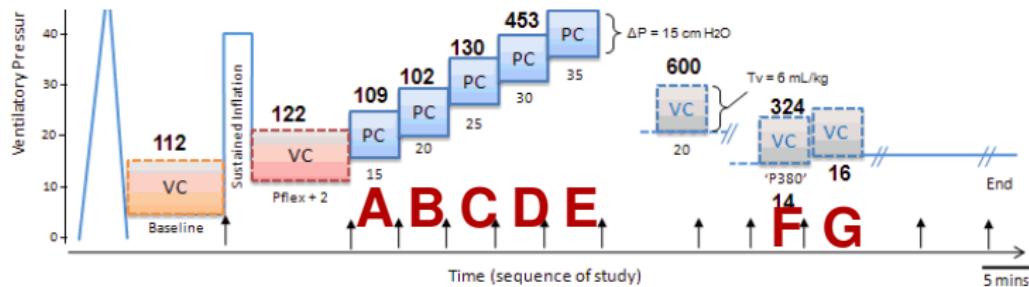


Lung recruitment protocol (Patient: F, 5.9 years, 20 kg, ARDS triggered by parainfluenza pneumonia).

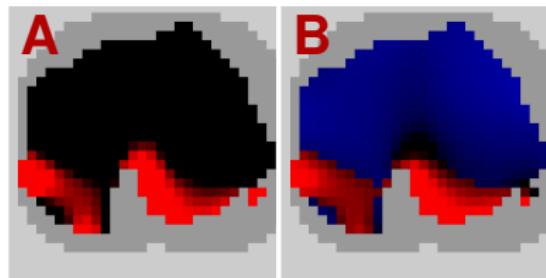
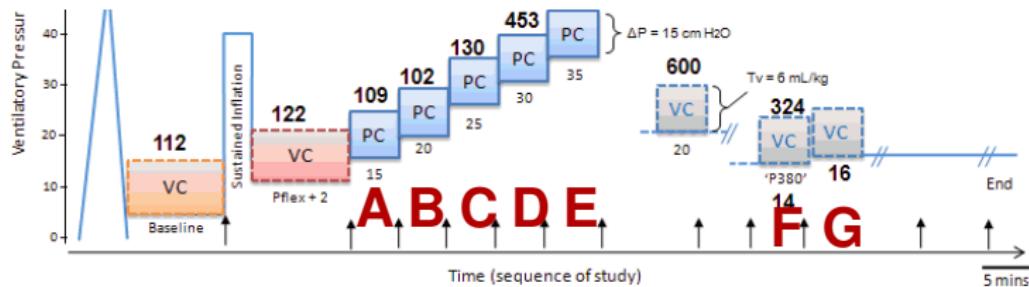
EIT + Lung State



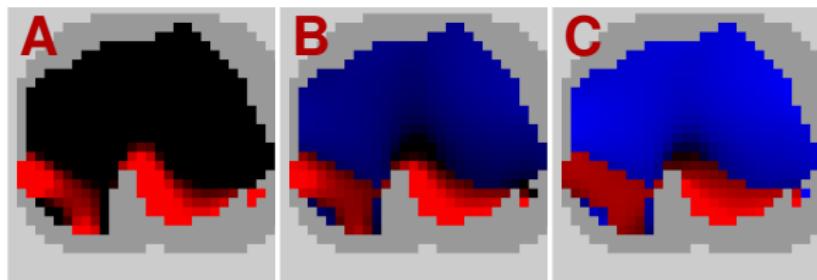
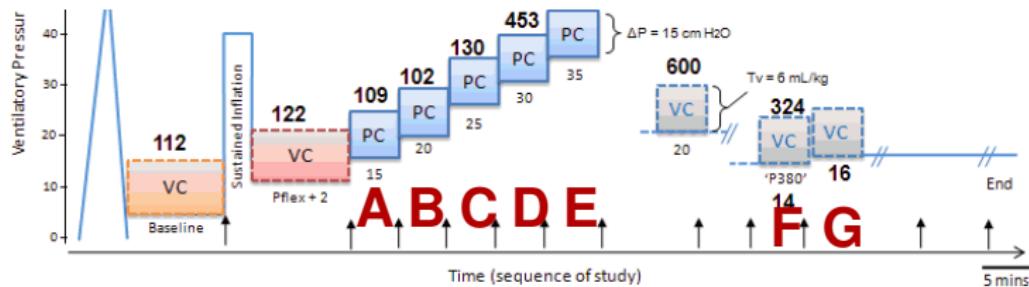
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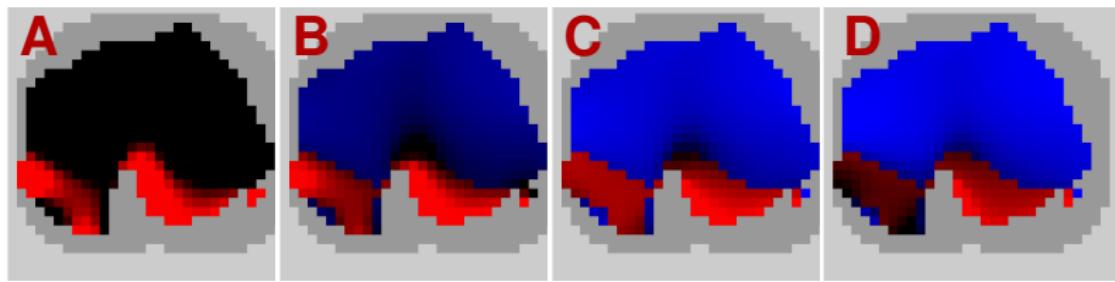
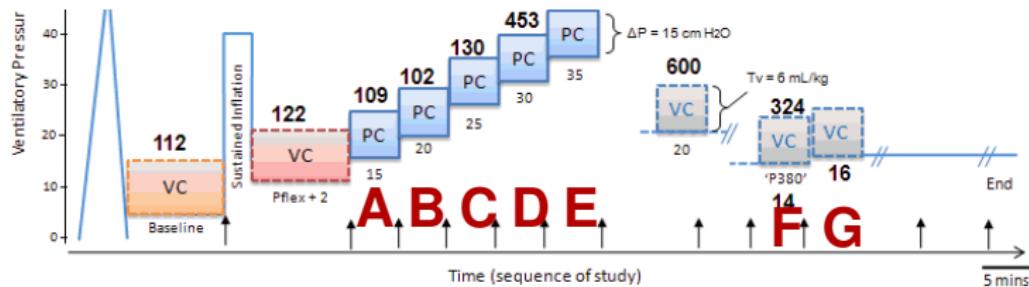
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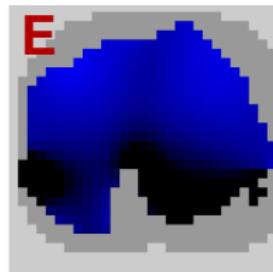
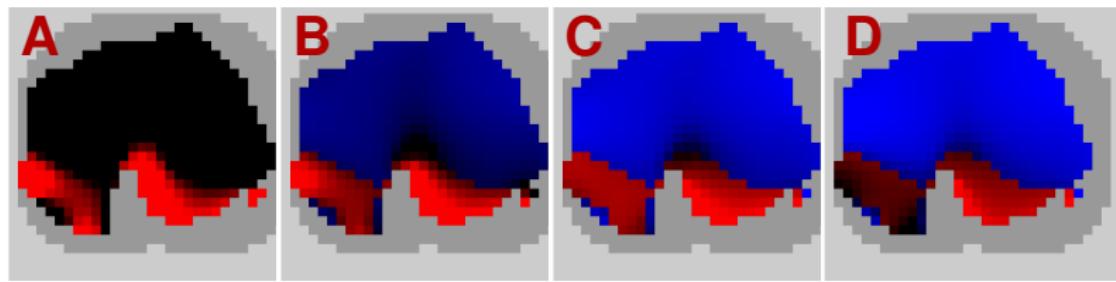
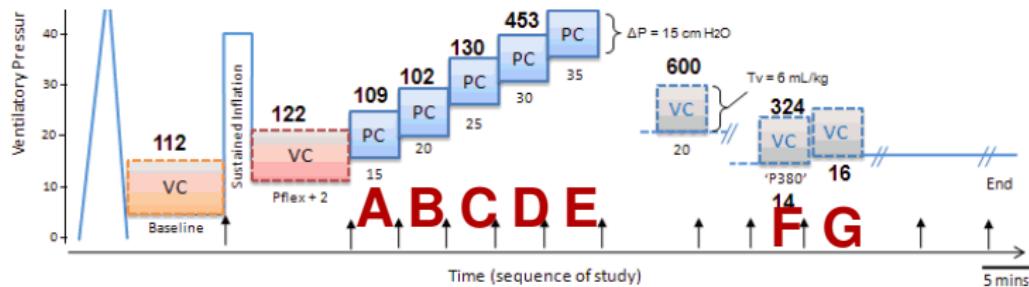


EIT + Lung State

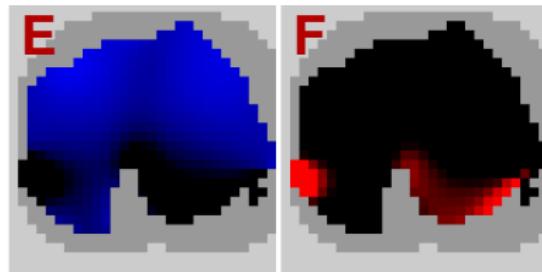
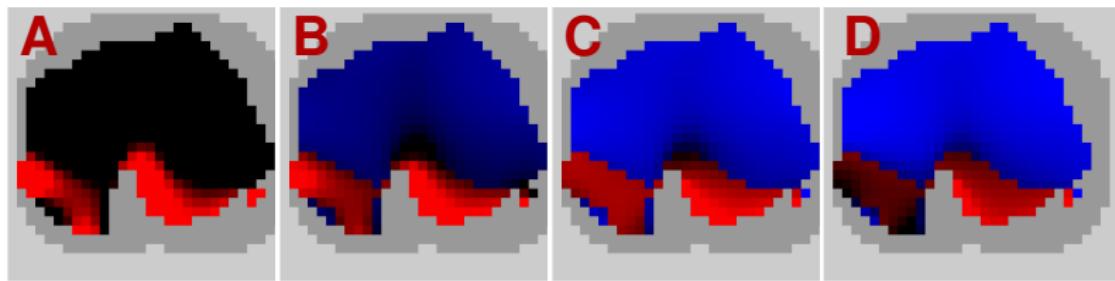
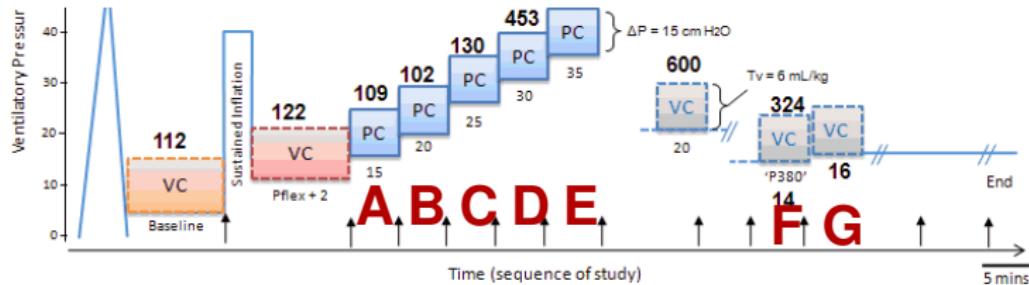


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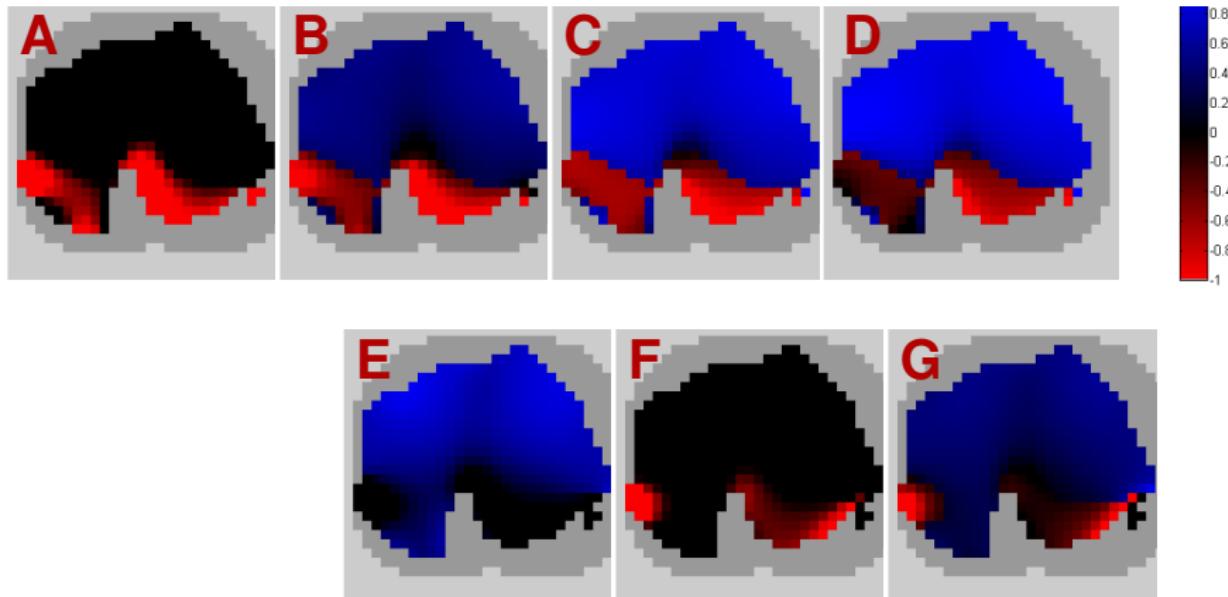
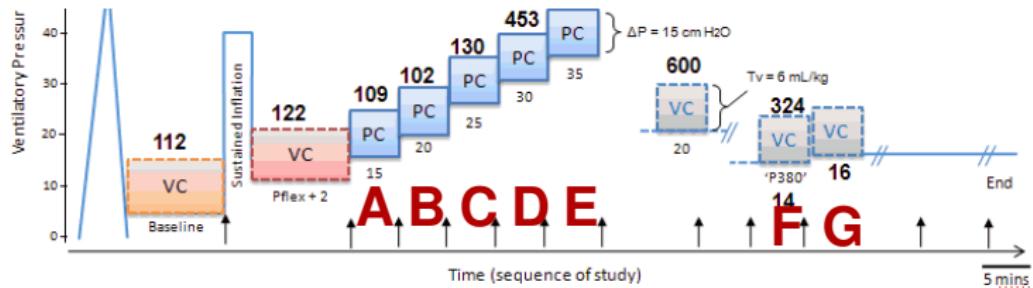
EIT + Lung State



EIT + Lung State



EIT + Lung State



EIT for Non-Invasive Blood Pressure

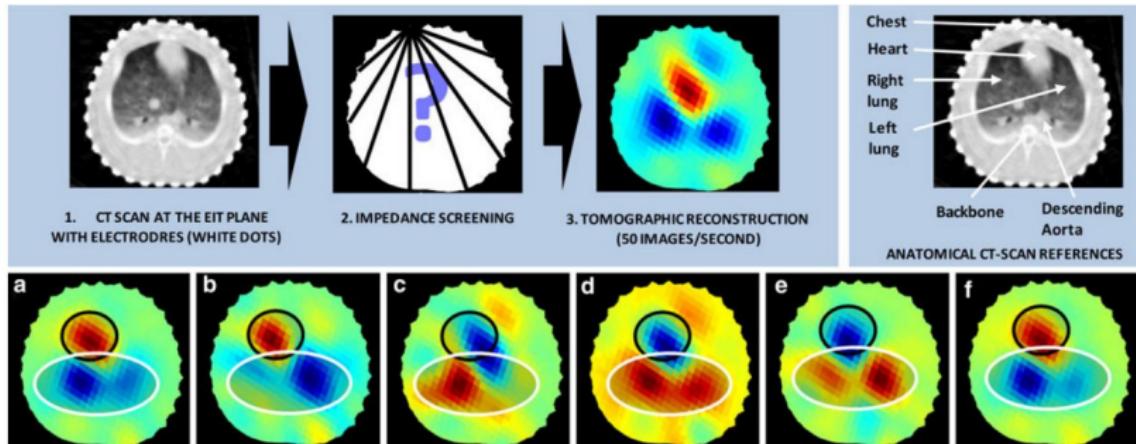


Fig. 1 Tracking the propagation of arterial pressure pulses by EIT: After placing several electrodes around the chest (1), impedance measurements are performed for each electrode pair (2) and used to construct a tomographic impedance image (3). A CT-scan of pig chest is provided as anatomical reference. *Lower panel* shows an example

of pulse propagation during an entire cardiac cycle: **a** and **b** the filling of the heart is observed (black ROI). **c** The heart empties while the right lung (here on the left hand side) is starting to be perfused with conductive blood. **d** and **e** Both lungs are perfused (white ROI). Finally, **f** the cardiac cycle starts again

Pulse transit time from heart to descending aorta using EIT

Source: Sola *et al*, *Med. Biol. Eng. Comput.*, 2011

Neonatal Breathing

- Preterm newborns have complex, unstable physiology
- Ventilatory support is often essential
- Currently, no adequate monitors of breathing
- These data are from a lamb model of neonates

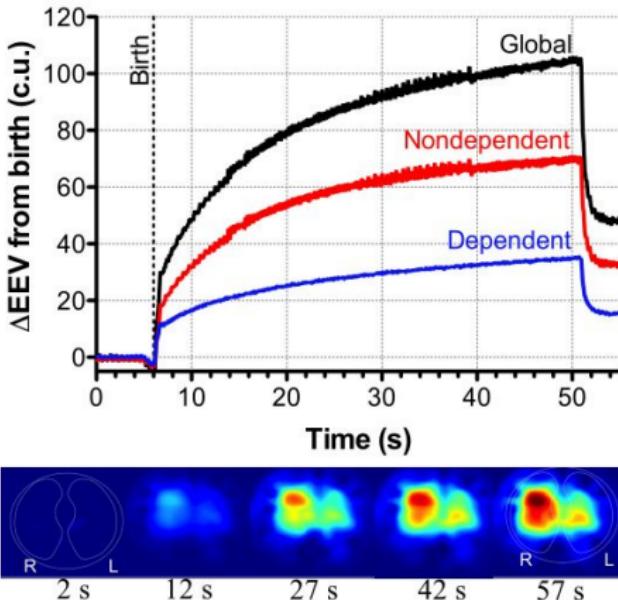


Figure 1. Exponential pattern of volume change during a SI, as measured by EIT, in global thorax and gravity-dependent

EIT for Brain Imaging

Applications:

- Epileptic foci
- Stroke (Ischaemic vs. Haemoragic)
- Fast Neural Imaging

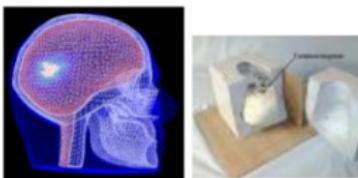
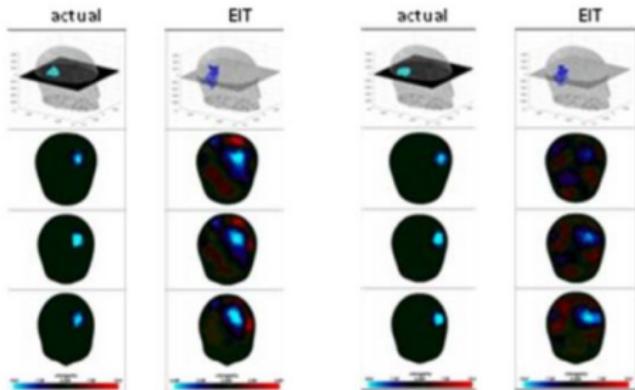


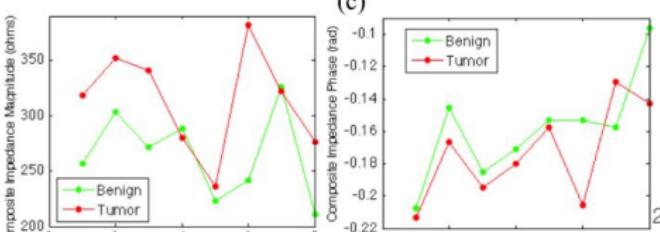
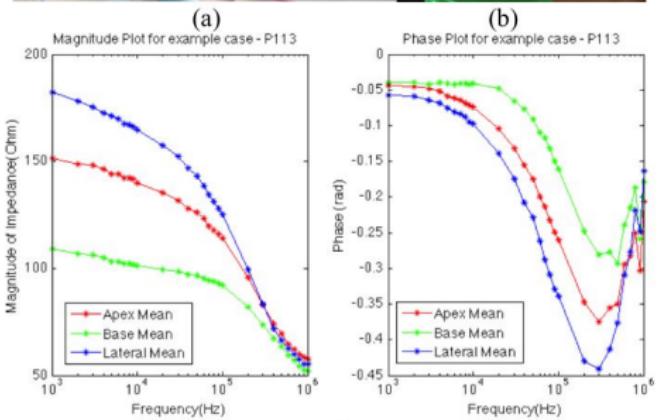
Fig. 2. Left : Finite element of the head used to produce images. Right: Example of EIT images produced in a saline filled tank



Source: Holder,
www.ucl.ac.uk/medphys/research/eit/pubs/brain_EIT_over

EIT for Cancer Imaging: Breast/Prostate

- Cancerous tissue has different electrical properties
- Image tissue
- Image increased vascularization



Source: Khan, Mahara, Halter *et al*, Conf. EIT, 2014

Non-medical applications

- Flow in pipes
- Mixing tanks
- Imaging metallic ores
- Hydro-geology

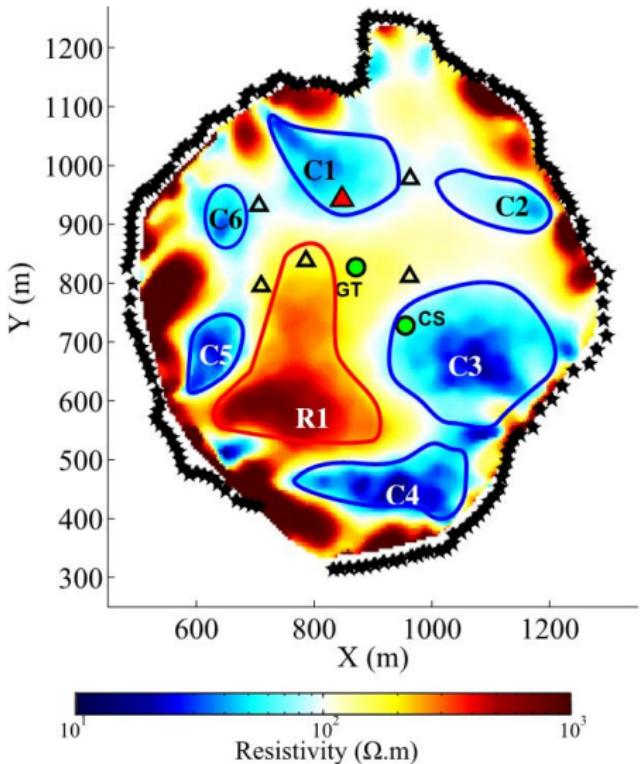


Figure shows resistivity in a cross-section of La Soufrière de Guadeloupe volcano.

Source: N. Lesparre *et al*, Conf. EIT, 2014

Reconstruction in Pictures

- Forward Problem

$$\begin{array}{c} \text{Measurements} \\ \text{(difference)} \end{array} \quad \begin{array}{c} = \\ \times \end{array} \quad \begin{array}{c} \text{Image} \\ \text{(difference)} \end{array} + \text{noise}$$

Jacobian

The diagram illustrates the forward problem in matrix form. It shows a vertical vector of green squares labeled "Measurements (difference)" being multiplied by a matrix labeled "Jacobian" (represented by a grid of gray squares). The result is a vertical vector of teal squares labeled "Image (difference)". Finally, "noise" is added to the image difference.

Reconstruction in Pictures

- Forward Problem

$$\text{Measurements (difference)} = \begin{matrix} \text{Jacobian} \\ \times \end{matrix} \text{Image (difference)} + \text{noise}$$

The diagram illustrates the forward problem in matrix form. On the left, a vertical vector of green squares is labeled "Measurements (difference)". An equals sign follows. To the right of the equals sign is a gray square matrix labeled "Jacobian". To the right of the matrix is another vertical vector of teal squares labeled "Image (difference)". A plus sign is followed by the word "noise". Red arrows point from the labels to their respective components.

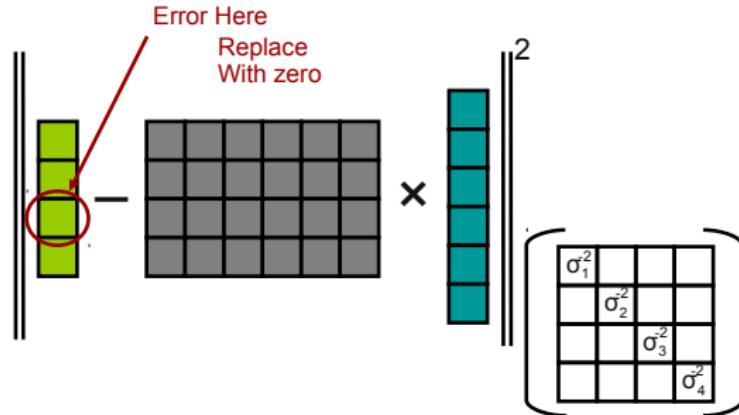
- Linear Solution: Minimize norm

$$\left\| \text{Measurements (difference)} - \text{Jacobian} \times \text{Image (difference)} \right\|^2 + \text{Penalty Function} \left(\text{Norm weighted by measurement accuracy} \right)$$

The diagram shows the linear solution for reconstruction. It consists of two main parts separated by a plus sign. The first part is enclosed in vertical bars and represents the squared norm of the difference between the measured data and the model's prediction. The second part is labeled "Penalty Function" and is enclosed in a bracket. Below the bracket, a red arrow points to the text "Norm weighted by measurement accuracy".

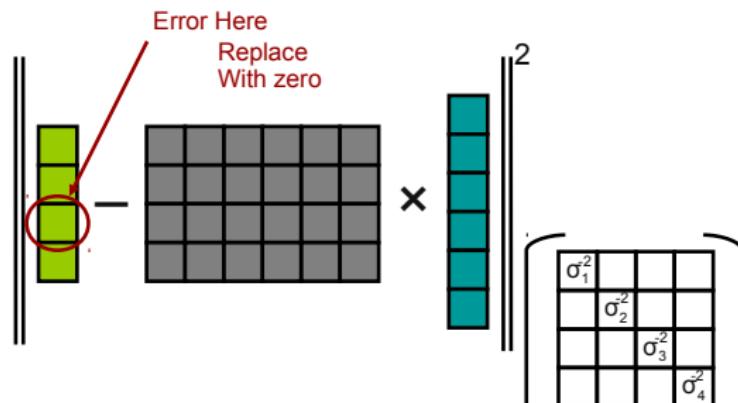
Idea #1: Reconstruction with Data Errors

“Traditional”
Solution

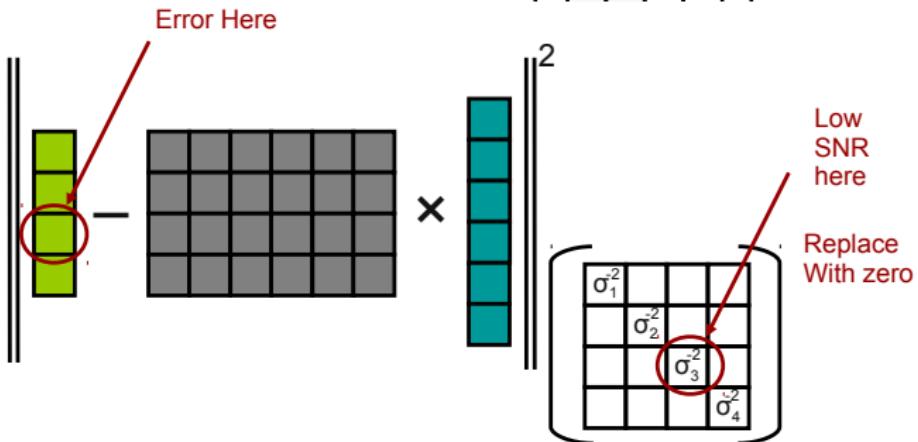


Idea #1: Reconstruction with Data Errors

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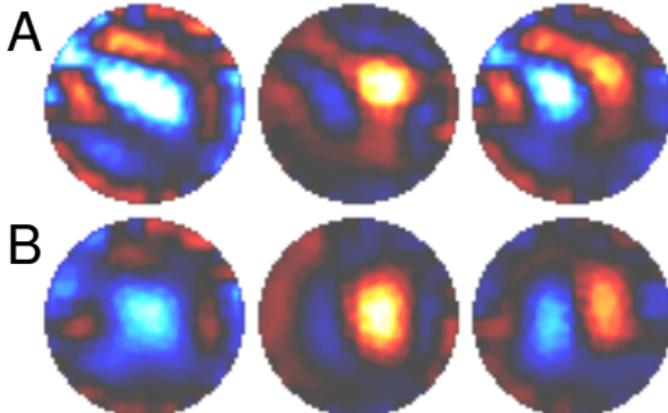


Error Model
Solution



Electrode Error compensation

- Offline compensation using “jack-knife” approach (2005)



EIT images in anaesthetised, ventilated dog

A: uncompensated, *B*: compensated. *Left*: ventilation *Centre*: saline (right lung) *Right*: ventilation and saline

- Automatic detection (via reciprocity comparison) (2009)
- New work to speed online calculation & use data quality

Idea #2: Electrode movement

Sensitivity to
sensor
movement

$$\begin{matrix} \text{green vertical bar} \\ = \end{matrix} \begin{matrix} \text{gray grid} \\ \times \end{matrix} \begin{matrix} \text{teal vertical bar} \\ + \text{noise} \end{matrix}$$

Jacobian now includes measurement change due to movement

"image" now includes x,y sensor movement

The diagram illustrates the effect of electrode movement on a Jacobian matrix. On the left, a green vertical bar represents the sensor movement. This is followed by an equals sign. To the right of the equals sign is a gray grid representing the Jacobian matrix. To the right of the grid is a multiplication sign. To the right of the multiplication sign is a teal vertical bar representing the image. After the teal bar is a plus sign and the word "noise". Red arrows point from the text "Jacobian now includes measurement change due to movement" to the gray grid, and from the text "'image' now includes x,y sensor movement" to the teal bar.

Idea #2: Electrode movement

Sensitivity to
sensor
movement

$$\begin{matrix} \text{green bar} \\ = \end{matrix} \begin{matrix} \text{gray grid} \\ \times \end{matrix} \begin{matrix} \text{blue bar} \\ + \text{noise} \end{matrix}$$

Jacobian now includes measurement change due to movement

"image" now includes x,y sensor movement

Adapted
penalty
function

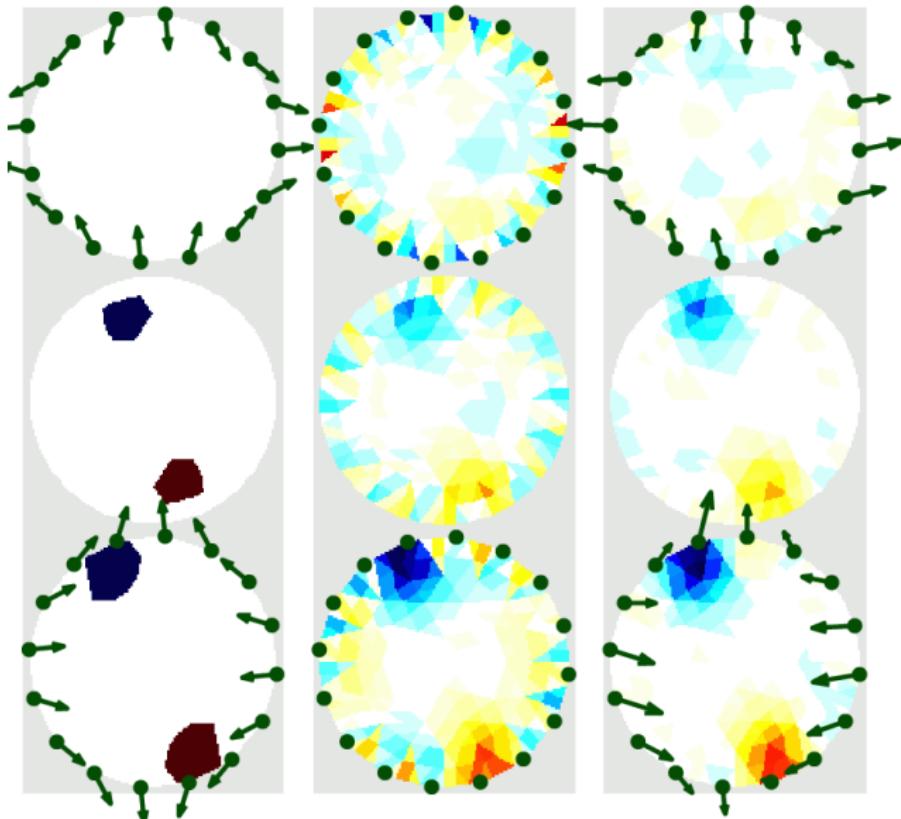
$$\left\| \begin{matrix} \text{blue bar} \\ - \end{matrix} \begin{matrix} \text{Expected image} \\ \text{---} \\ \text{Expected movement} \end{matrix} \right\|^2$$

"Unlikelyhood" of movement and image co-variance

"Unlikelyhood" of movement

The diagram illustrates the adapted penalty function. It shows a vertical vector of sensor measurements (blue bar) minus the sum of two terms: "Expected image" (dashed line) and "Expected movement". This result is squared to calculate the penalty. A covariance matrix is then multiplied by this squared difference. The matrix has a repeating pattern of values: 1, -1/2, -1/2; -1/2, 1, -1/2; -1/2, -1/2, 1. A red circle highlights the bottom-right corner of the matrix, where the value is 1.

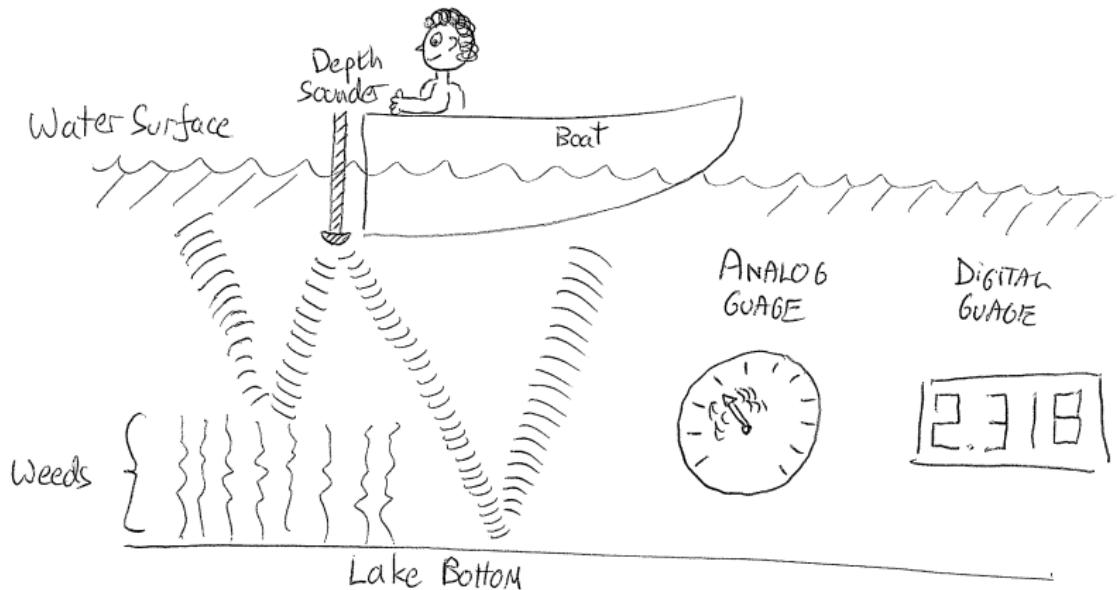
Electrode movement compensation



Source: Gómez-Laberge *et al*, Phys. Meas., 2006

Idea #3: Data Quality

Idea #3: Data Quality



Depth Sounder – with analog and digital guages

What's the problem?

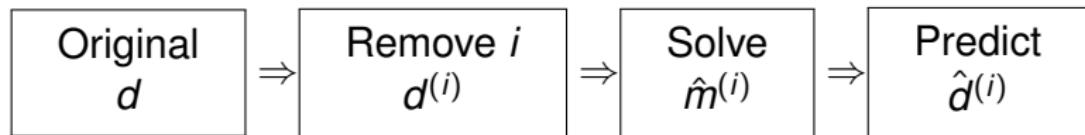
With strong priors and complex algorithms, algorithms give us pretty pictures, even when they are irrelevant.

Question:

- how can we know when to trust a pretty picture?
- how can we know when the data are junk?

Data Quality Measure: Concept

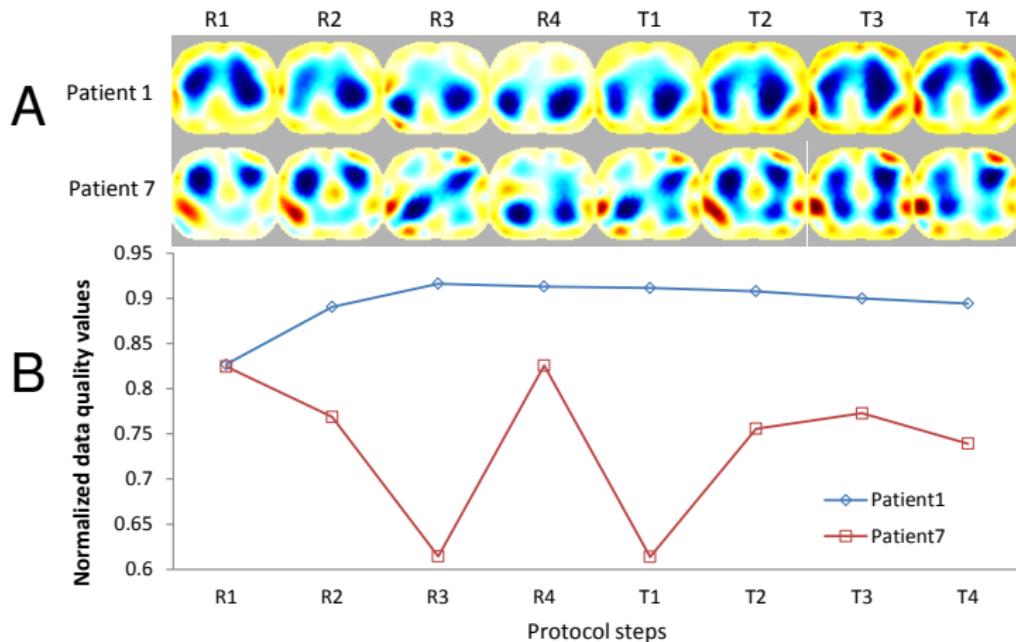
- *Concept:* High Quality Data is Consistent
- *Idea:* Use IP to predict each data point from all others



- Calculate error

$$\epsilon_i = d_i - \hat{d}_i^{(i)}$$

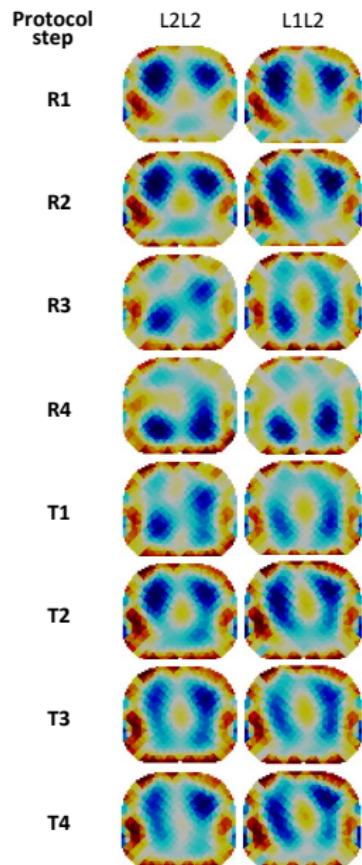
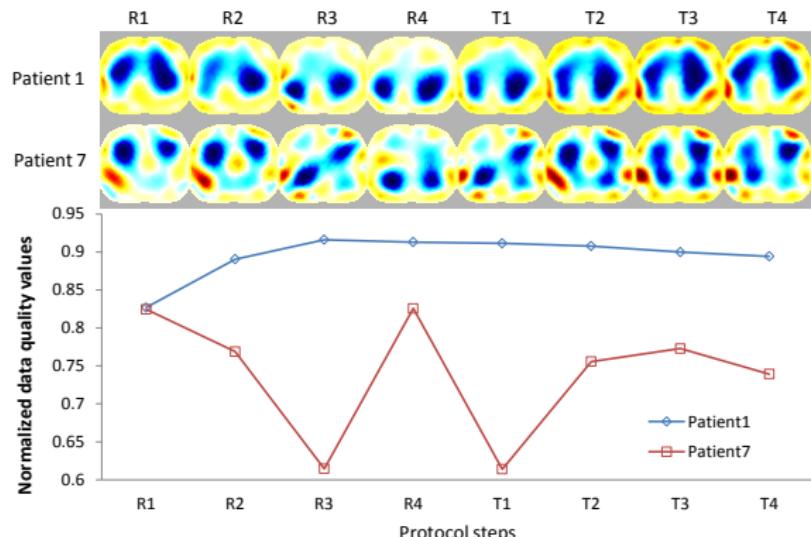
Example: Data quality measures



Clinical data and data quality metric for each stage of the protocol
(R1–R4 — recruitment: PEEP↑, T1–T4 — titration: PEEP↓).

A: EIT images B: Calculated data quality.

Data Quality vs. Robust Algorithms



Perspectives

- Data analysis is hard
- powerful algorithms are useful
- we live in a world of big data
- complex systems fail in complex ways
- users like pretty pictures

So . . . the situation will get worse

Solutions?

Solutions?



Solutions?



Solutions?



Solutions?



Thus, we need

Solutions?



Thus, we need

- Open Data

Solutions?

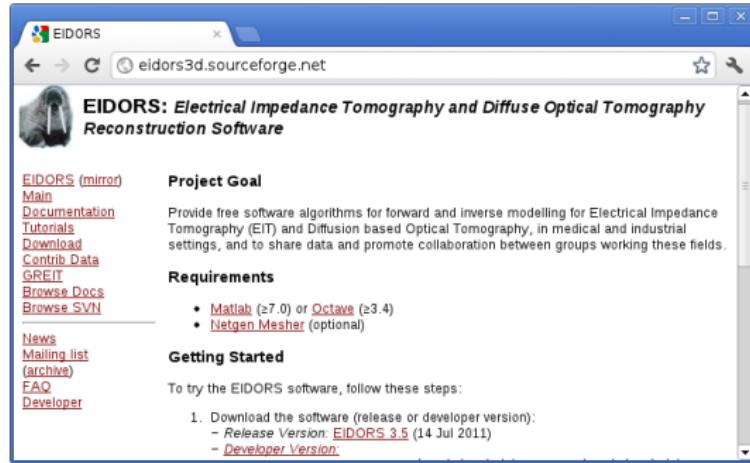


Thus, we need

- Open Data
- Open source analysis

For EIT ...

For EIT ...



The screenshot shows a web browser window with the URL "eidors3d.sourceforge.net". The page title is "EIDORS: Electrical Impedance Tomography and Diffuse Optical Tomography Reconstruction Software". On the left, there is a sidebar with links: "EIDORS (mirror)", "Main", "Documentation", "Tutorials", "Download", "Contrib Data", "GREIT", "Browse Docs", "Browse SVN", "News", "Mailing list (archive)", "FAQ", and "Developer". The main content area has sections for "Project Goal" and "Requirements". The "Project Goal" section states: "Provide free software algorithms for forward and inverse modelling for Electrical Impedance Tomography (EIT) and Diffusion based Optical Tomography, in medical and industrial settings, and to share data and promote collaboration between groups working these fields." The "Requirements" section lists: "• Matlab (≥7.0) or Octave (≥3.4)" and "• Netgen Mesher (optional)". Below these, the "Getting Started" section says: "To try the EIDORS software, follow these steps: 1. Download the software (release or developer version): - Release Version: [EIDORS 3.5](#) (14 Jul 2011) - Developer Version: [Developer Version](#)".

For EIT ...

EIDORS

eidors3d.sourceforge.net

EIDORS: Electrical Impedance Tomography and Diffuse Optical Tomography Reconstruction Software

Project Goal

Provide free software algorithms for forward Tomography (EIT) and Diffusion based Opt settings, and to share data and promote c

Requirements

- Matlab (≥7.0) or Octave (≥3.4)
- Netgen Mesher (optional)

Getting Started

To try the EIDORS software, follow these :

- Download the software (release or
- Release Version: [EIDORS 3.5](#) (1)
- Developer Version:

EIDORS

eidors3d.sourceforge.net/data_contrib/lf-neonate-spontaneous/index.html

Contributed EIT Data:

Authors: S. Heinrich, H. Schiffmann, A. Frerichs, A. Klockgether-Radke, I. Frerichs

Date: 2006

Description: 10-day old spontaneously breathing neonate lying in the prone position with the head turned to left. Data were published in S. Heinrich, H. Schiffmann, A. Frerichs, A. Klockgether-Radke, I. Frerichs, [Body and head position effects on regional lung ventilation in infants: an electrical impedance tomography study](#), Intensive Care Med., 32:1392-1398, 2006.

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Attribution Requirement: Use or presentation of these data must acknowledge Inéz Frerichs, and reference this publication:
S. Heinrich, H. Schiffmann, A. Frerichs, A. Klockgether-Radke, I. Frerichs, [Body and head position effects on regional lung ventilation in infants: an electrical impedance tomography study](#), Intensive Care Med., 32:1392-1398, 2006.

Format: EIT data were acquired with the Göttingen Goe-MF II device, 220 frames, 13 frames/s. Data are .GET file format.

Methods: Neonate in prone position, with electrode #1 at the front of the chest, electrode #5 on the left side of the chest, electrode #9 on the back and electrode #13 on the right side of the chest

Data: [Data \(zip format\)](#)

Image of Experimental Configuration:





Traffic jam on the way to Carleton