

Electricity in the Body

Carleton University Biomedical Engineering Society
Professor Presentation Night
11 February 2015

Andy Adler

Professor & Canada Research Chair in Biomedical Engineering
Systems and Computer Engineering, Carleton University, Ottawa

From Andy Adler: Can you please tell me more about what you want to hear? ...

From: Vicky Madge via sce.carleton.ca

If you could talk about how you are involved at Carleton; what classes you teach currently (and maybe talk about your classes from uOttawa), your research projects currently underway (include objective, methods, and tools if possible) and anything else you can think of that will give the students a good indication of what to expect in the next couple years in undergrad and what to expect in a future in biomedical engineering. How does that sound?

... what you want to hear?

... Six hours later ...

... what you want to hear?

Classes

- Electronics & Bio-electronics
- Digital signal processing
- Biomedical instrumentation
- Medical imaging
- Introduction to Biomedical Engineering (grad)

Research ...

Electricity in the body

- Electrical imaging
- Cardiac mapping
- Tasers

...the future

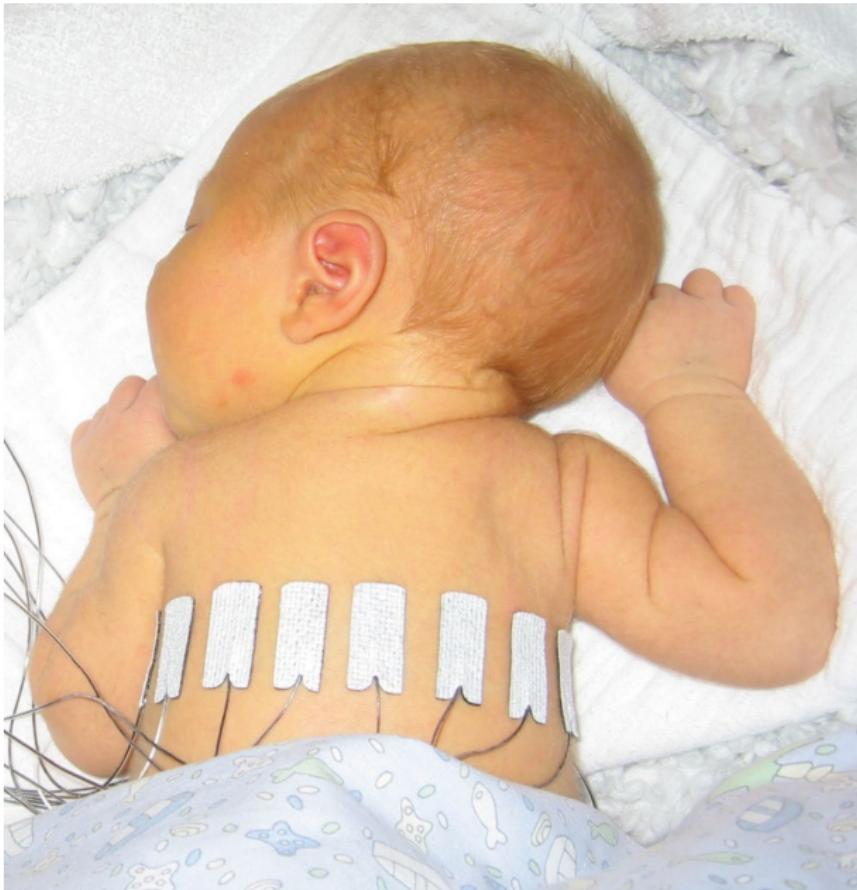
Prediction is difficult, especially about the future.

— Niels Bohr

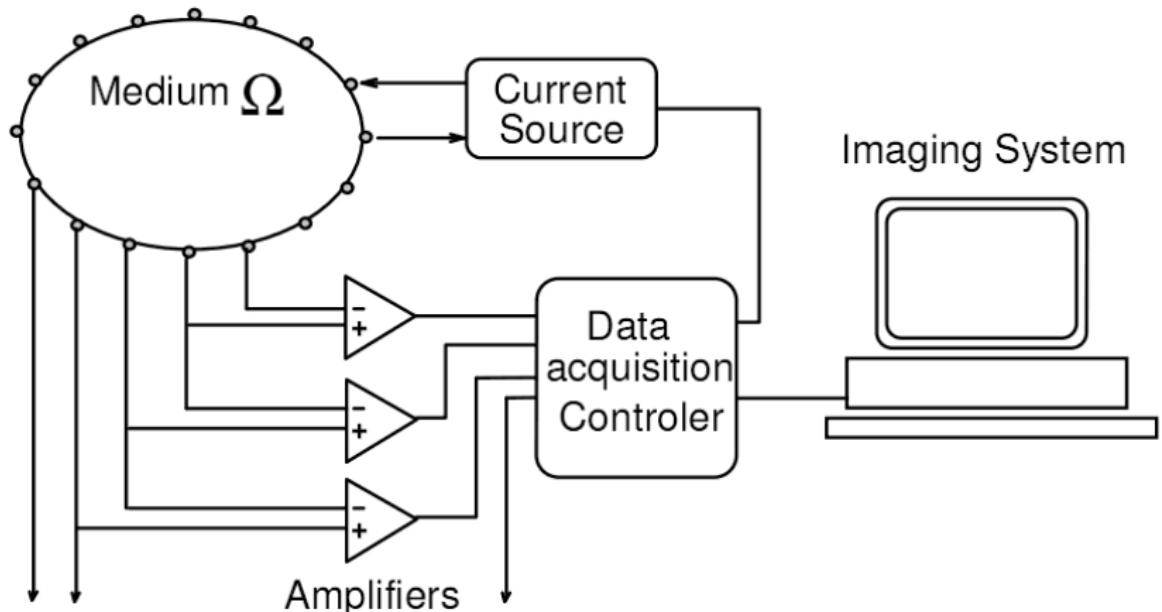
Electrical Impedance Tomography

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 slice at heart

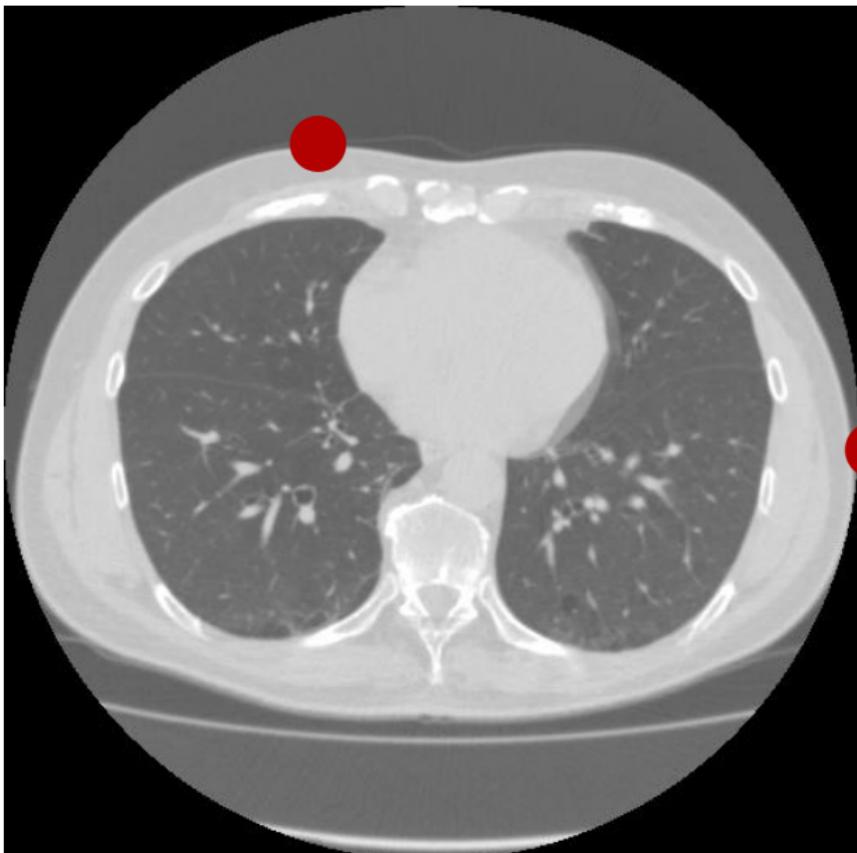
Source: ei-
dors3d.sf.net/tutorial/netgen/extrusion



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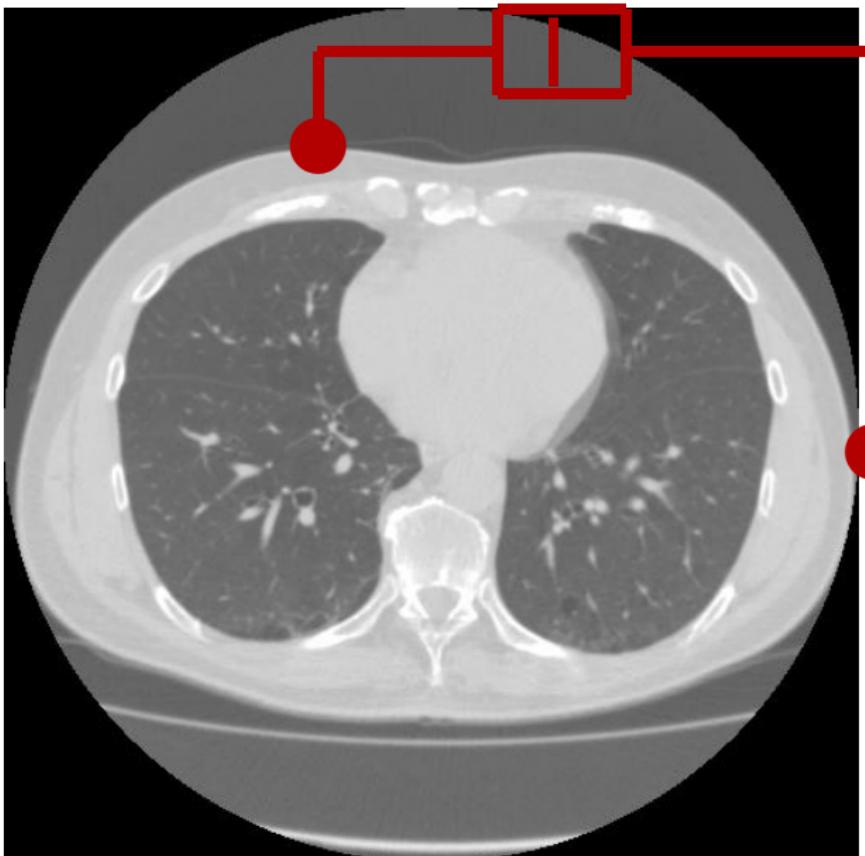
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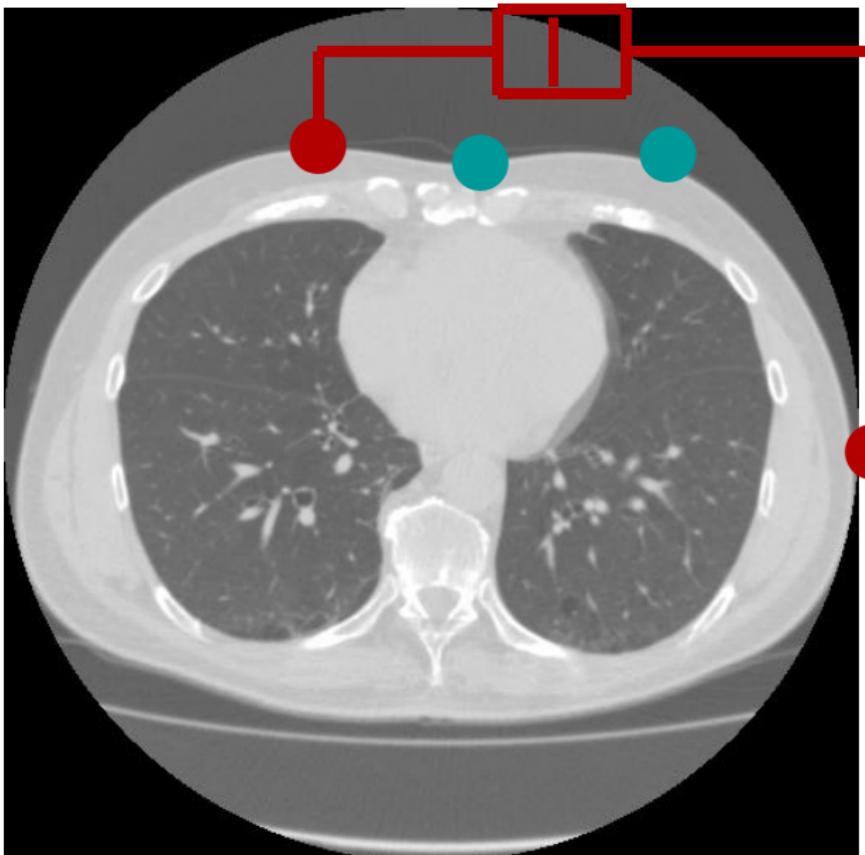
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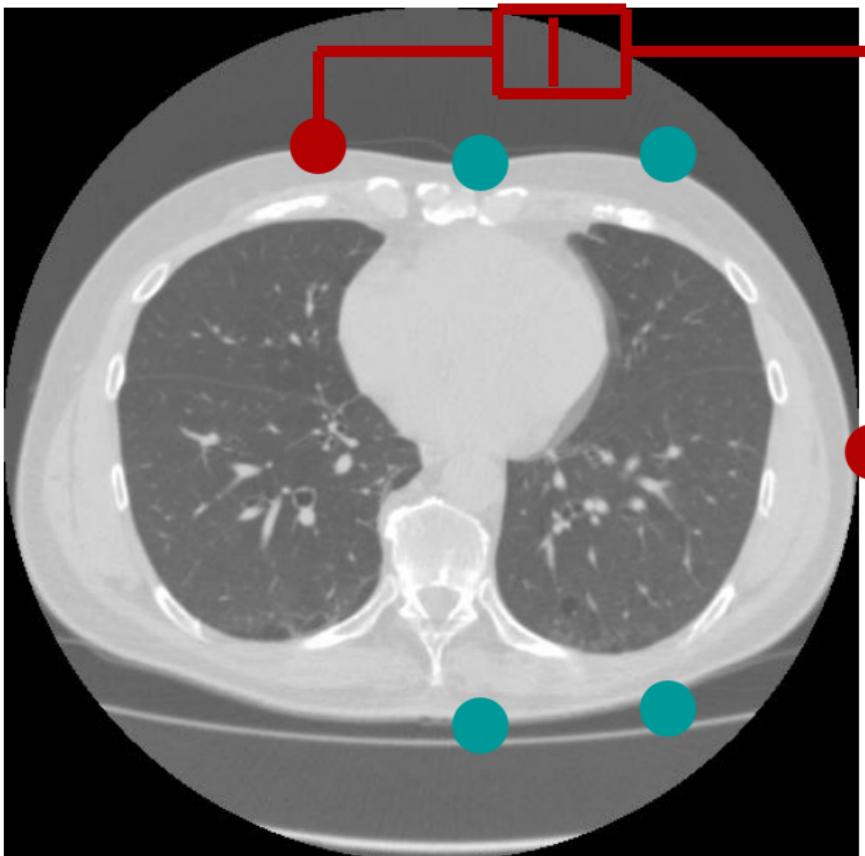
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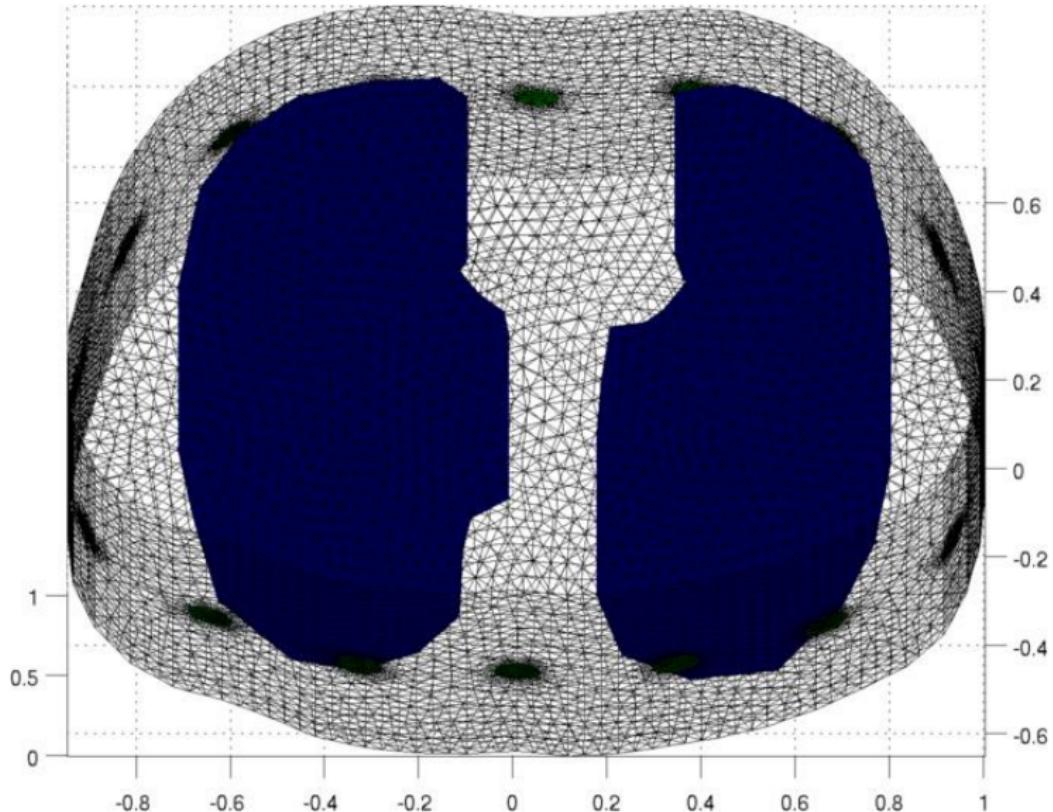
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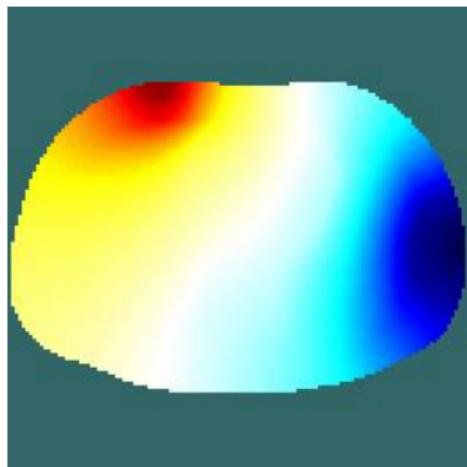
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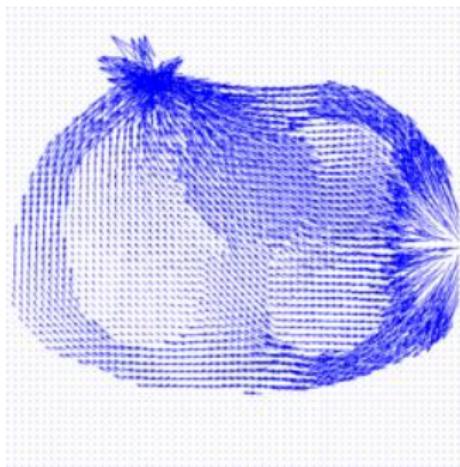
Finite Element Modelling



Finite Element Modelling



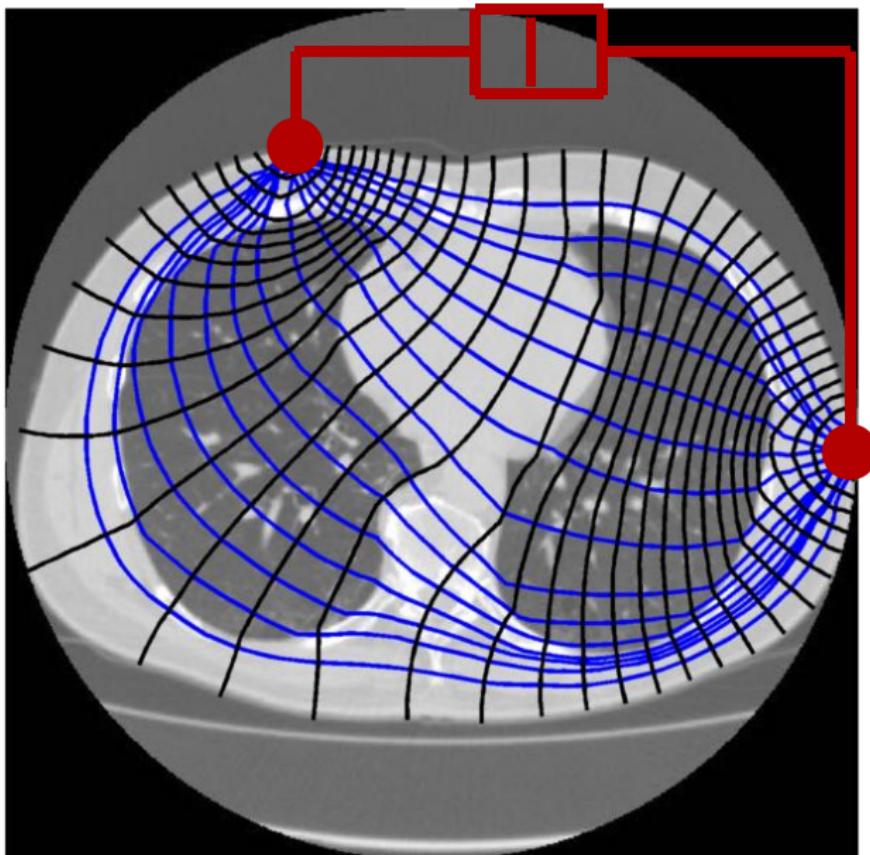
Simulated Voltages



Voxel Currents

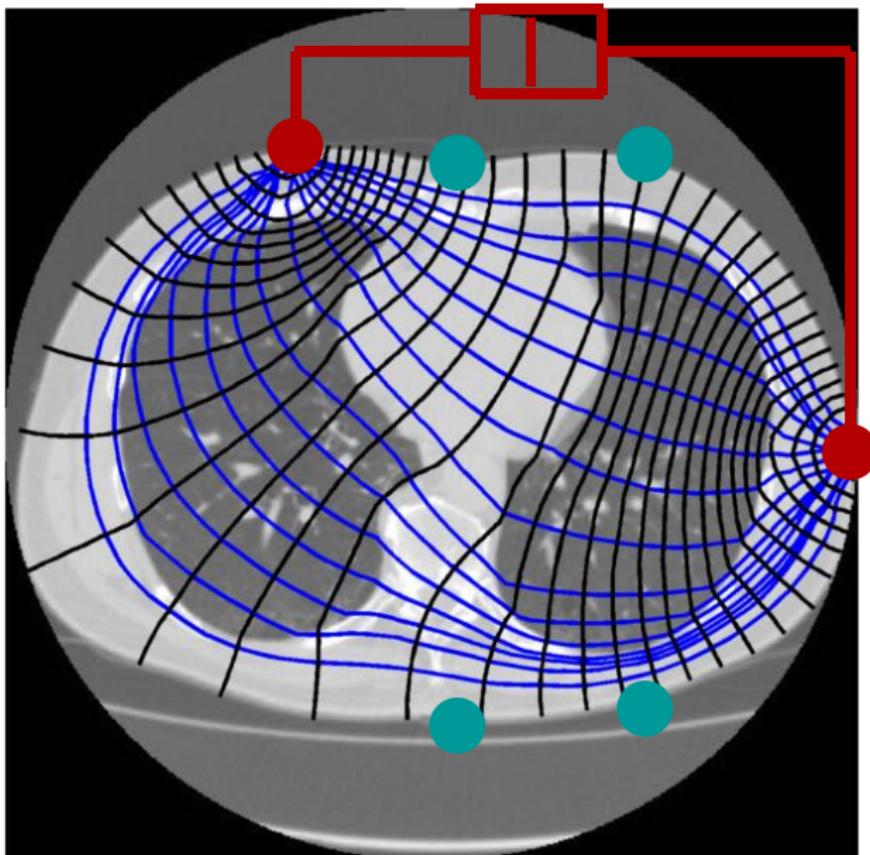
Thorax Propagation

CT Slice with
simulated current
streamlines and
voltage
equipotentials



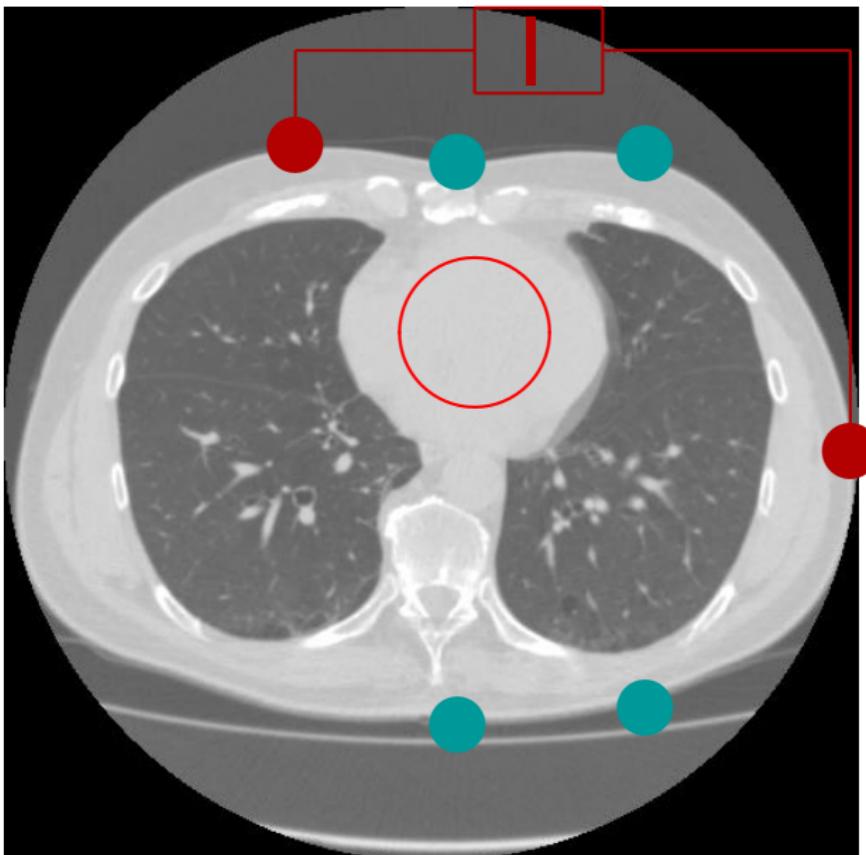
Thorax Propagation

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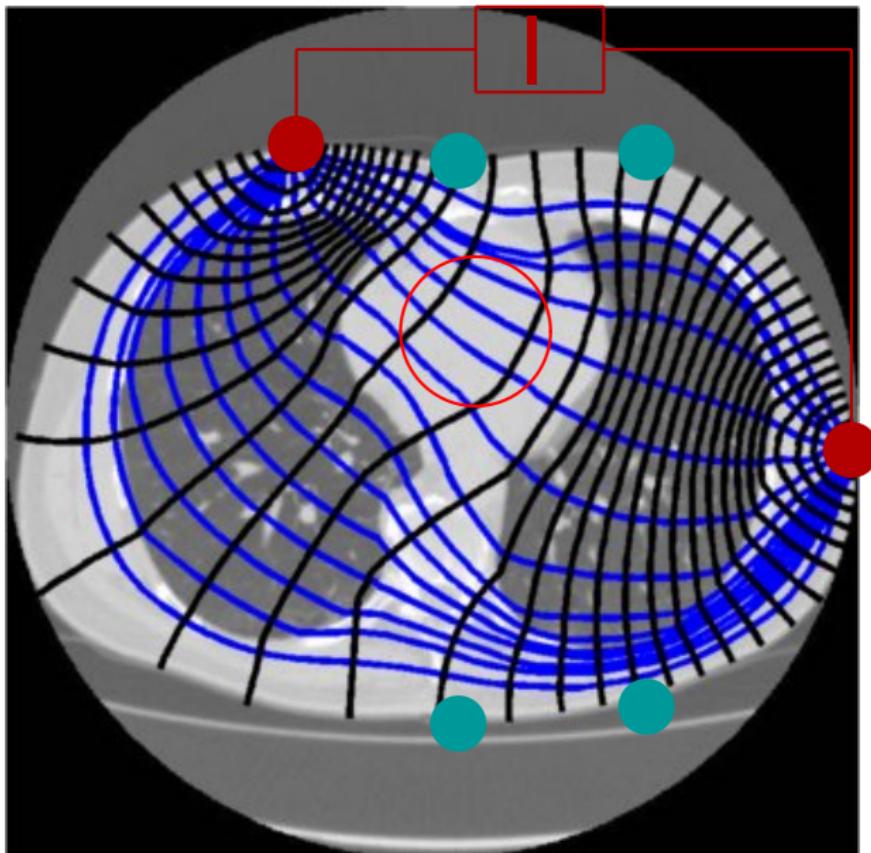
Changing Conductivity

Heart receives blood (diastole) and is more conductive

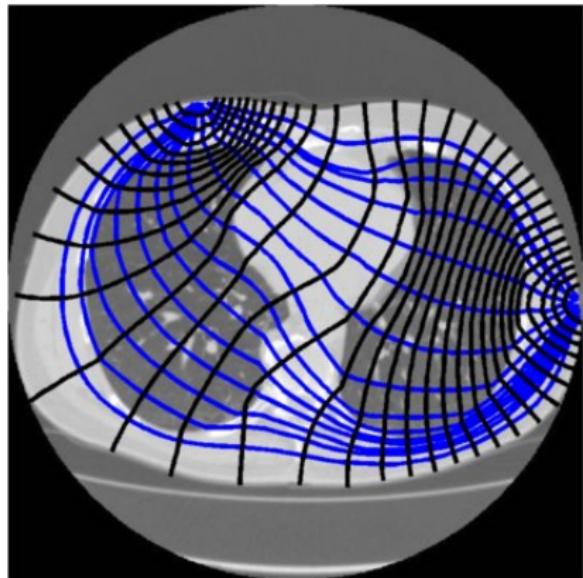
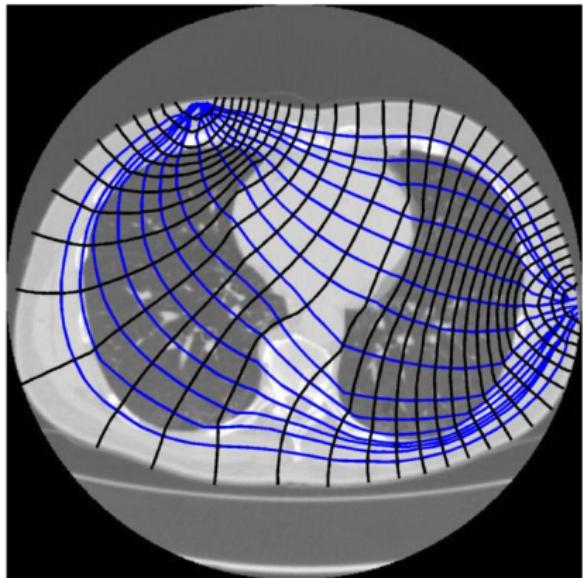


Changing Conductivity

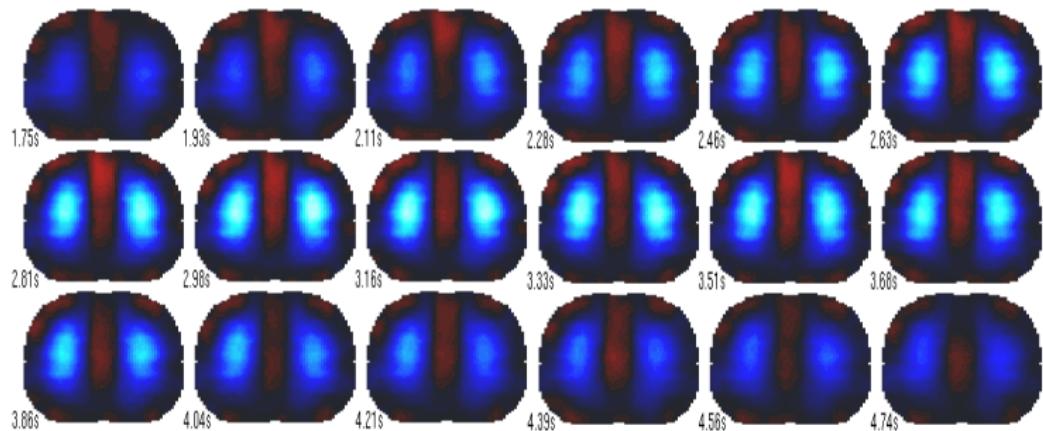
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Changing Conductivity

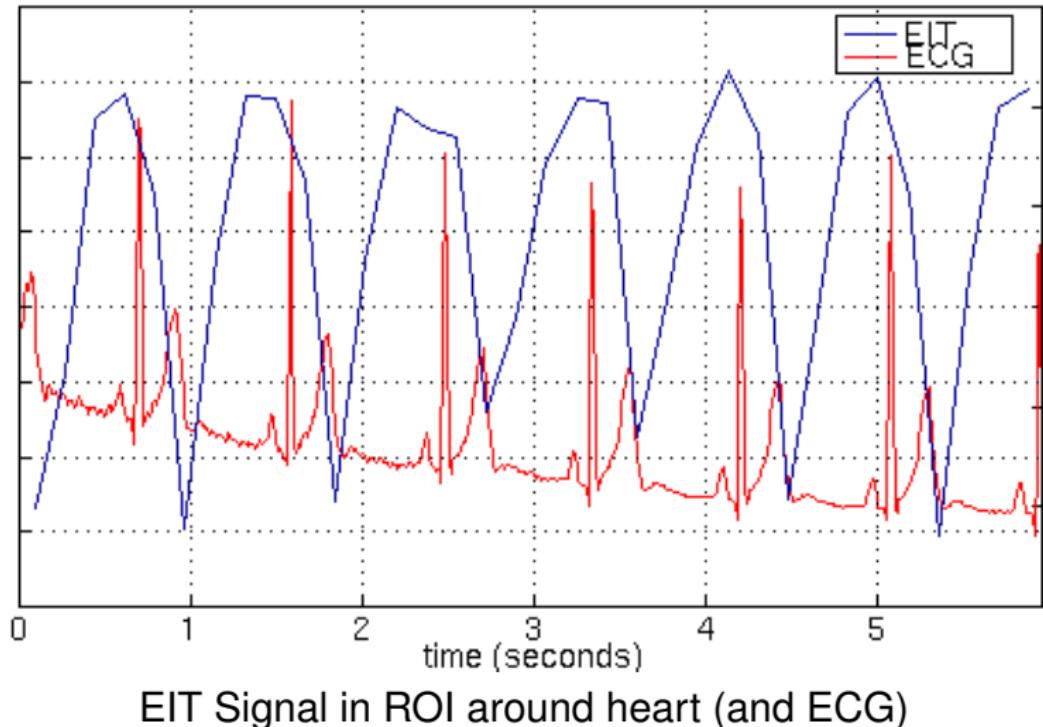


Application: Breathing



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**

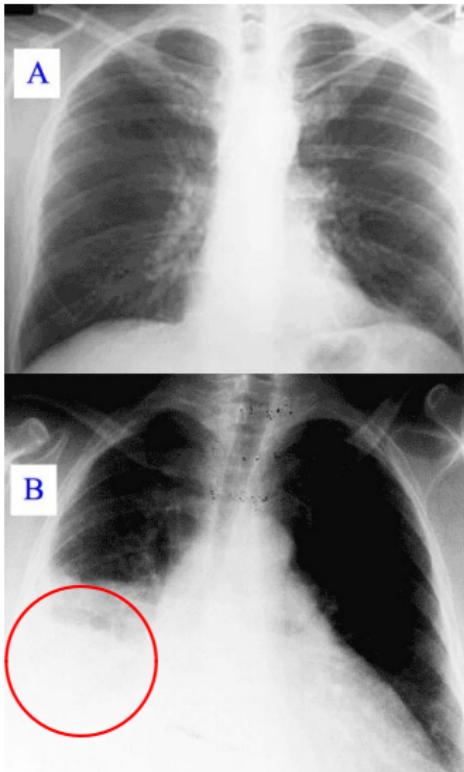
Mechanical Ventilation



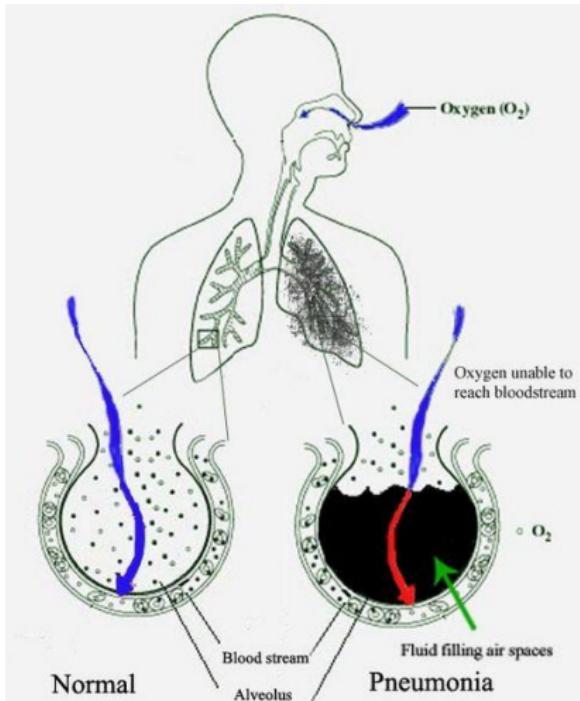
Mechanical Ventilator with EIT monitor

Source: Swisstom.com

Why image lungs? Example: Pneumonia



Source: en.wikipedia.org/wiki/Pneumonia

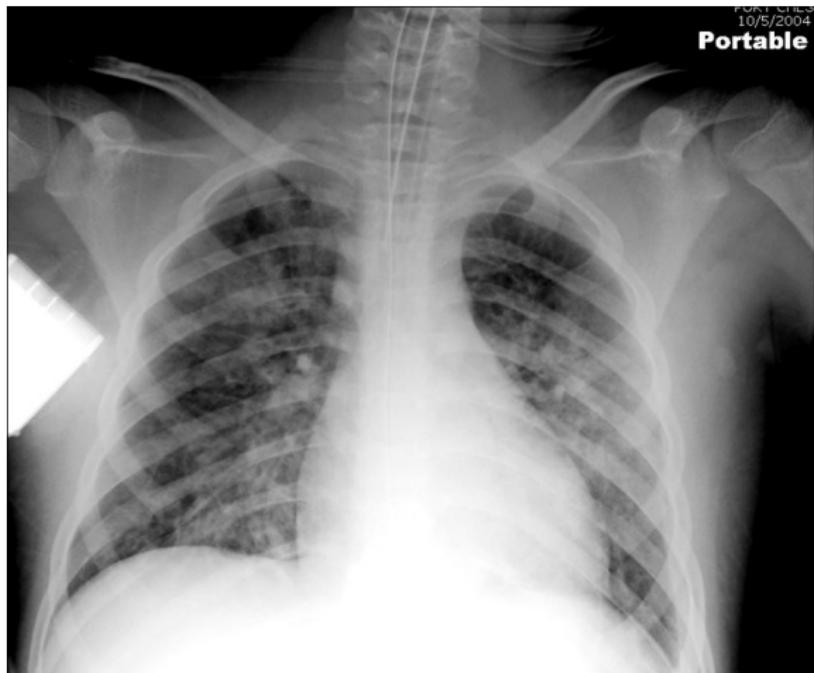


B: fluid in right lung

Acute Respiratory Distress Syndrome (ARDS)

Chest X-ray of
paediatric patient

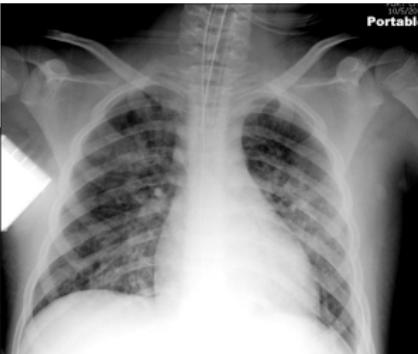
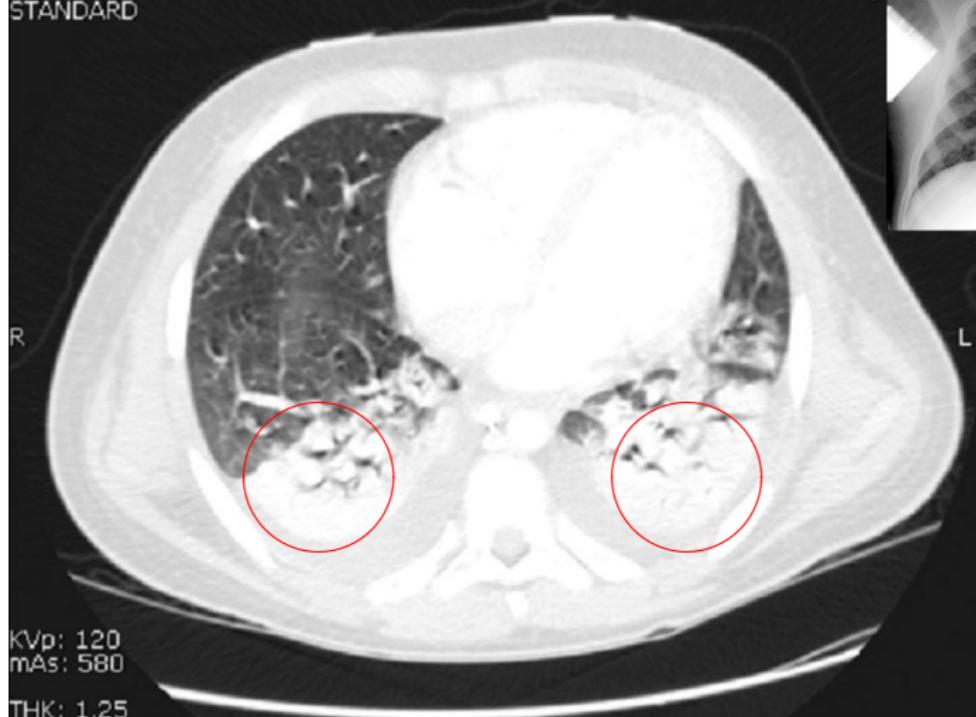
Source: Wolf GK, Arnold JH, in



*Yearbook of Intensive Care and
Emergency Medicine, 2005*

Acute Respiratory Distress Syndrome (ARDS)

STANDARD



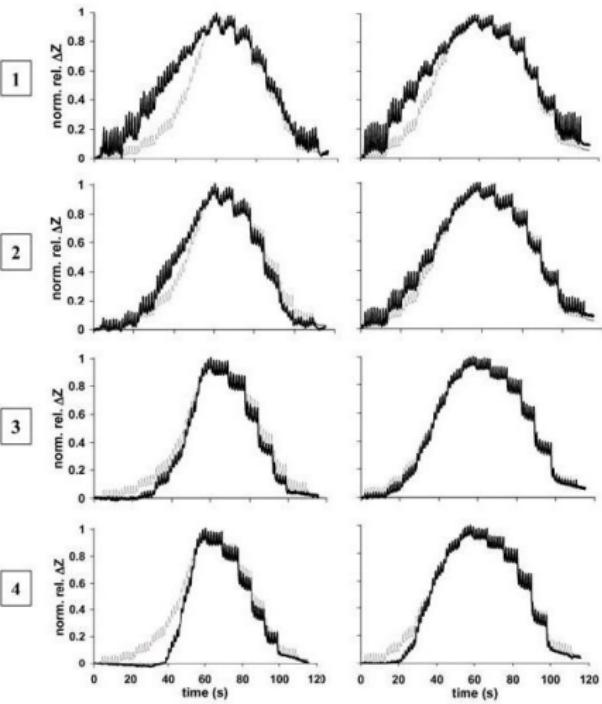
Regional Ventilation

Electrical impedance tomography

Acute lung injury

Surfactant treatment

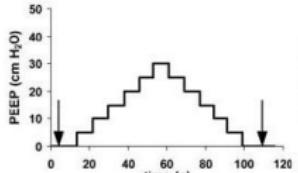
Regions of interest



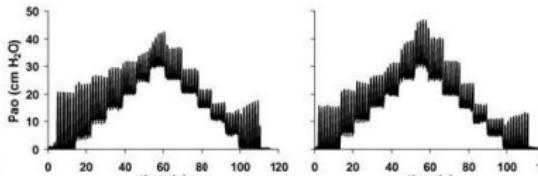
Ventilatory manoeuvre

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

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

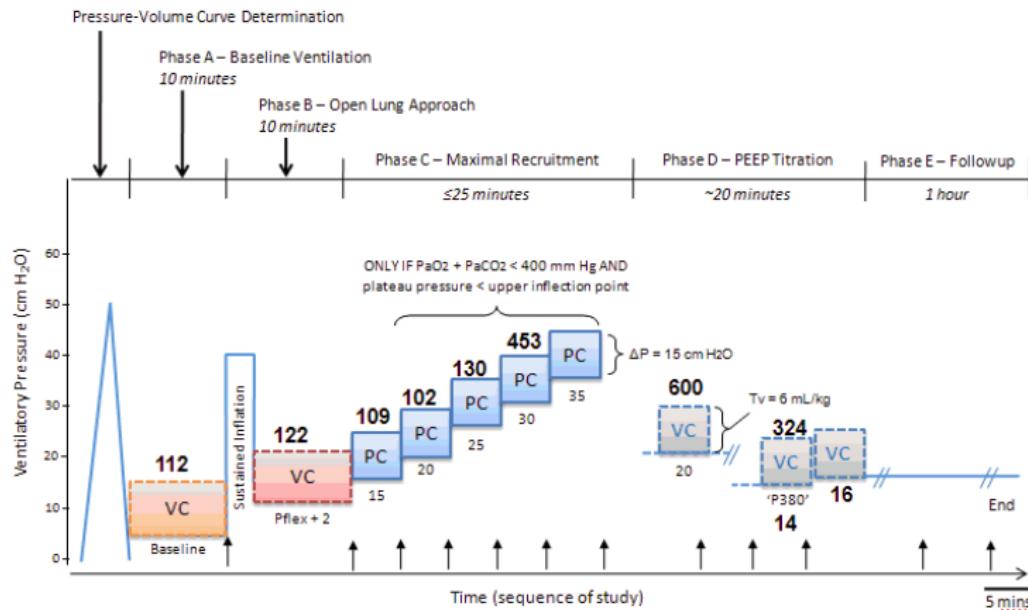


Airway pressure



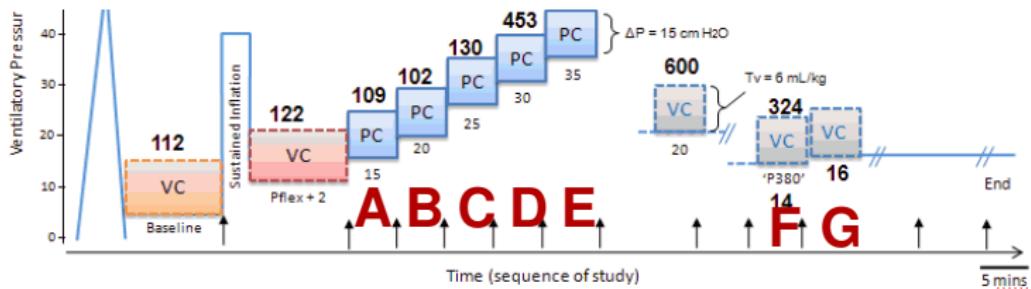
EIT in ARDS

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

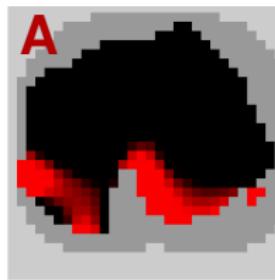
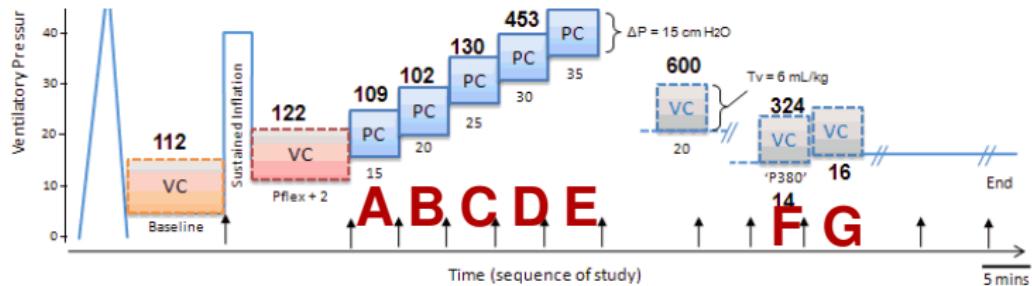


Lung recruitment protocol (Patient: F, 5.9 years, 20 kg, ARDS triggered by parainfluenza pneumonia).

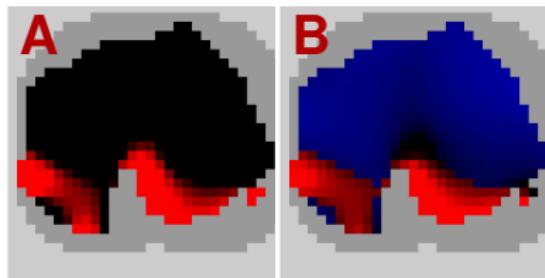
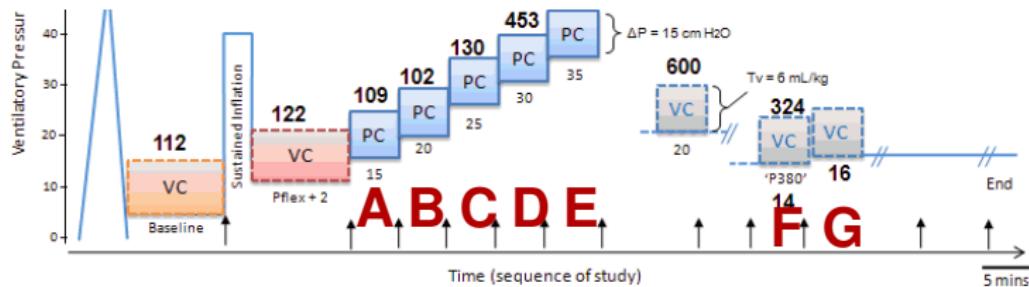
EIT + Lung State



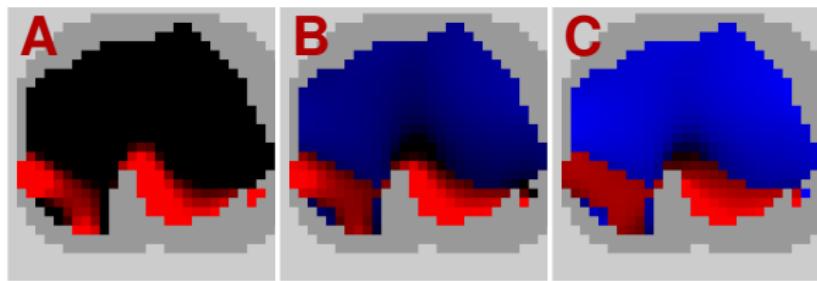
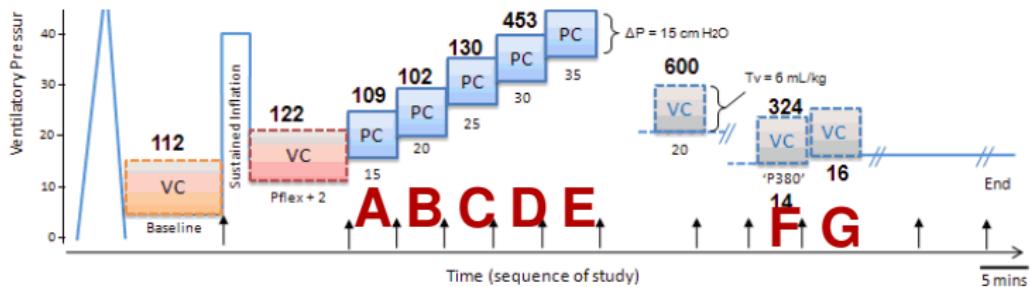
EIT + Lung State



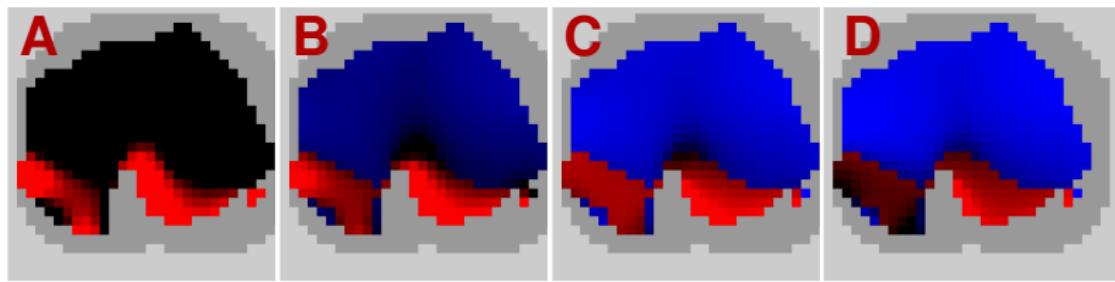
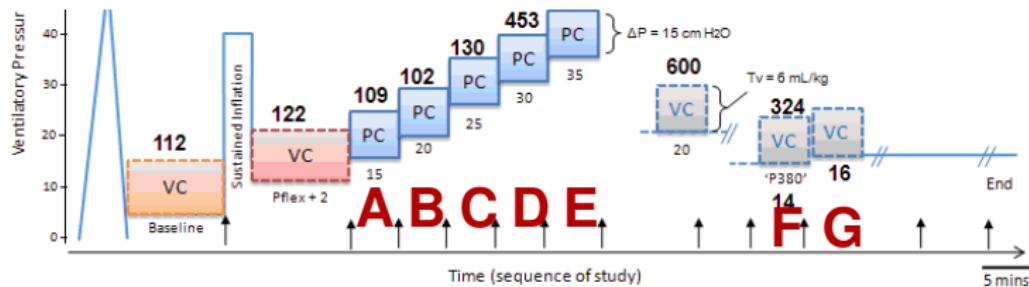
EIT + Lung State



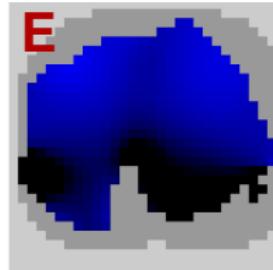
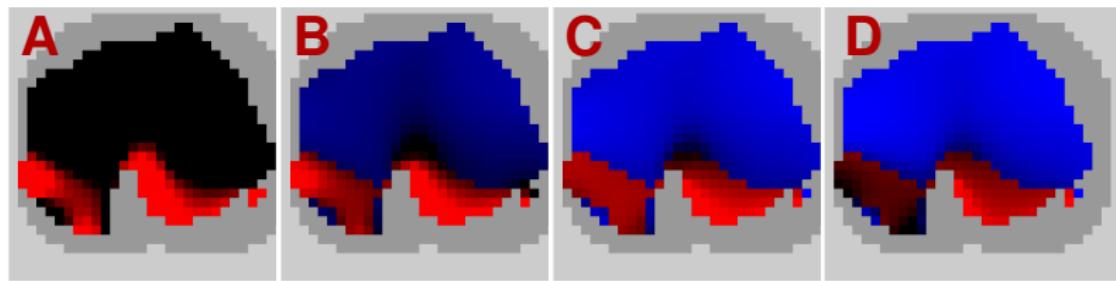
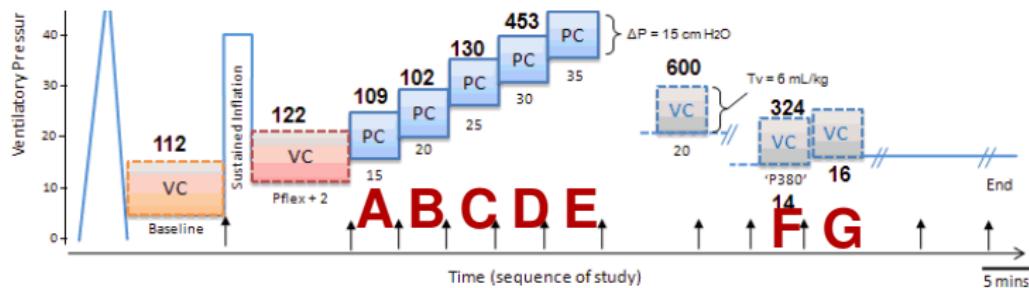
EIT + Lung State



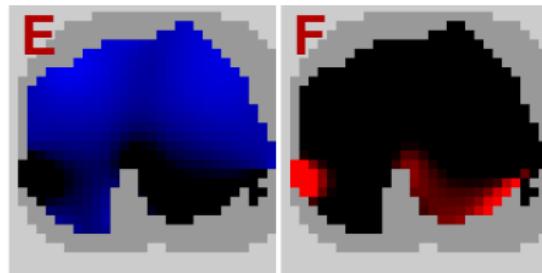
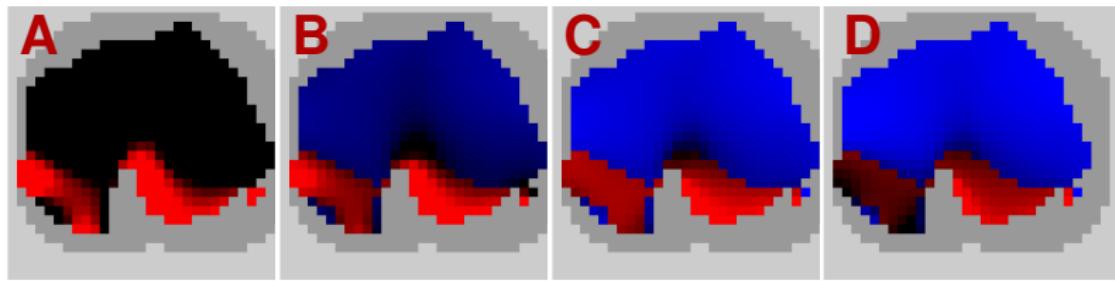
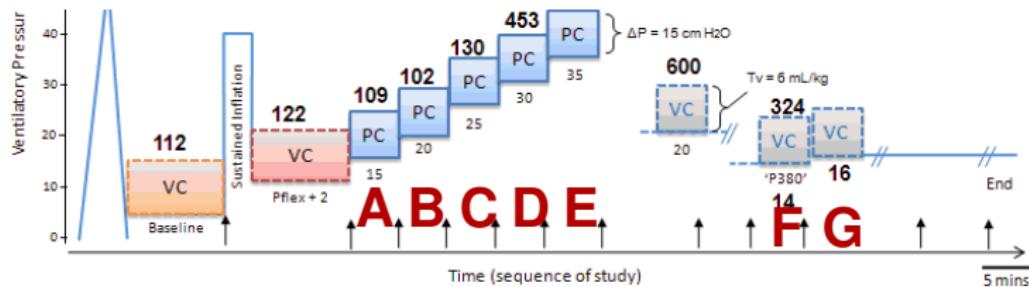
EIT + Lung State



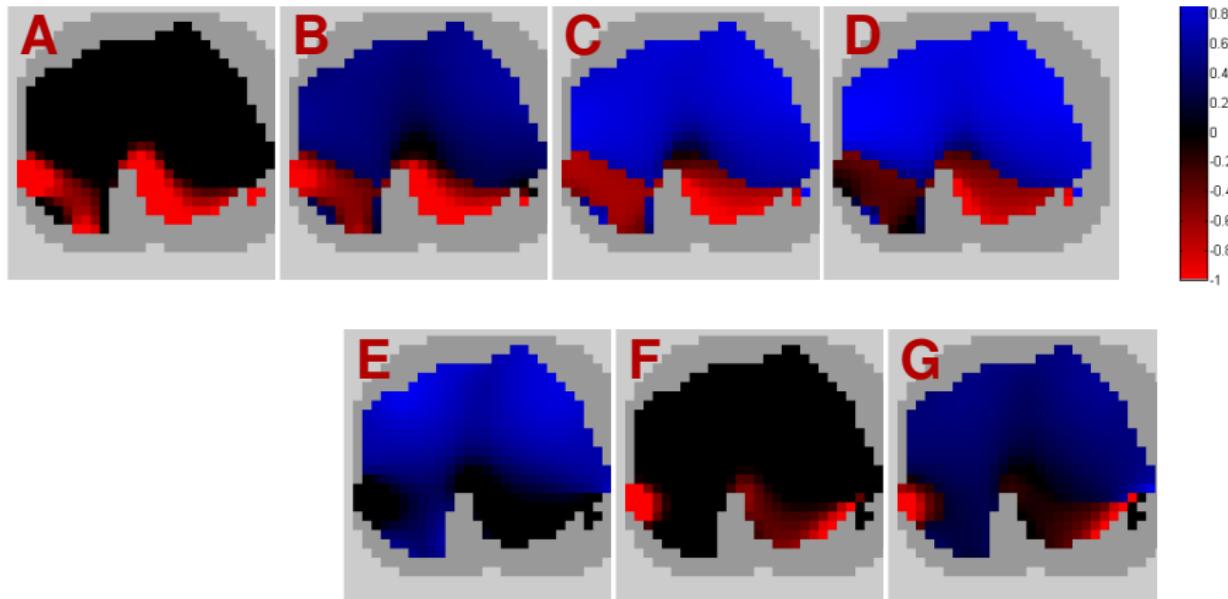
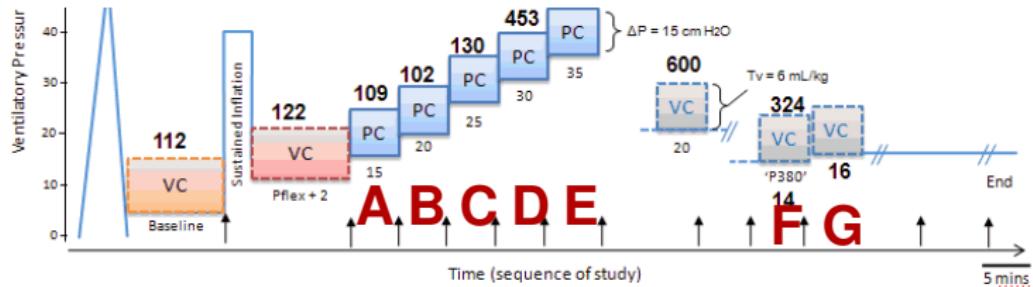
EIT + Lung State



EIT + Lung State



EIT + Lung State



EIT for Non-Invasive Blood Pressure

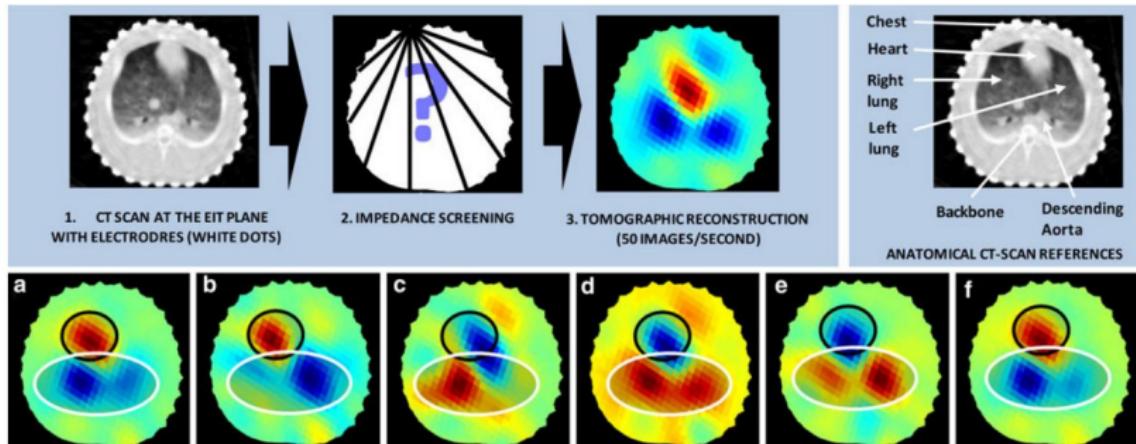


Fig. 1 Tracking the propagation of arterial pressure pulses by EIT: After placing several electrodes around the chest (1), impedance measurements are performed for each electrode pair (2) and used to construct a tomographic impedance image (3). A CT-scan of pig chest is provided as anatomical reference.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

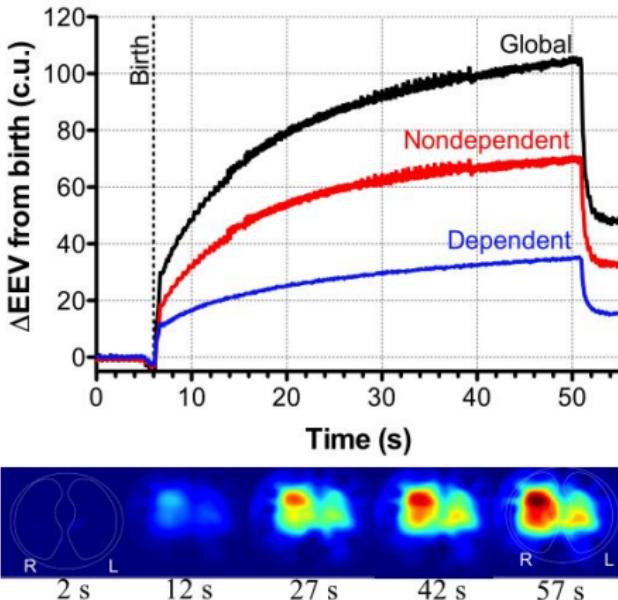


Figure 1. Exponential pattern of volume change during a SI, as measured by EIT, in global thorax and gravity-dependent

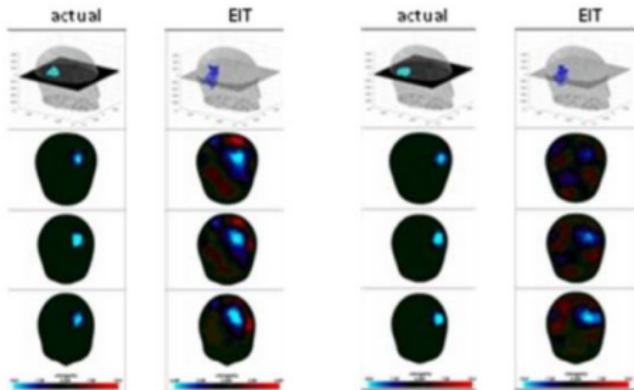
EIT for Brain Imaging

Applications:

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



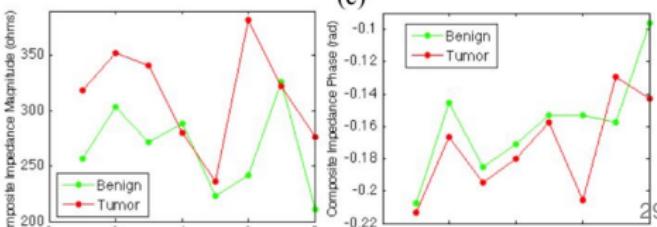
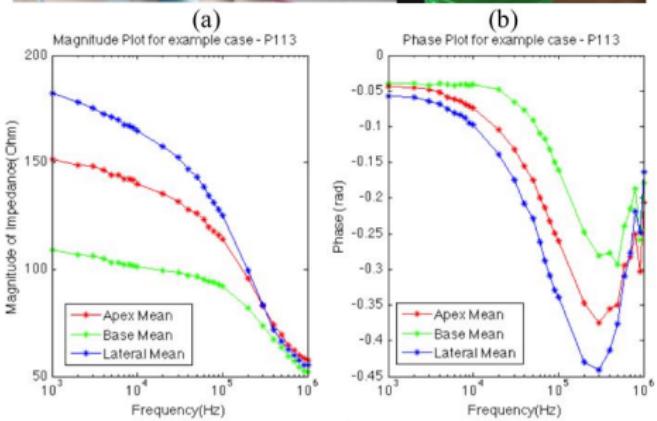
Fig. 2. Left : Finite element of the head used to produce images. Right: Example of EIT images produced in a saline filled tank



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

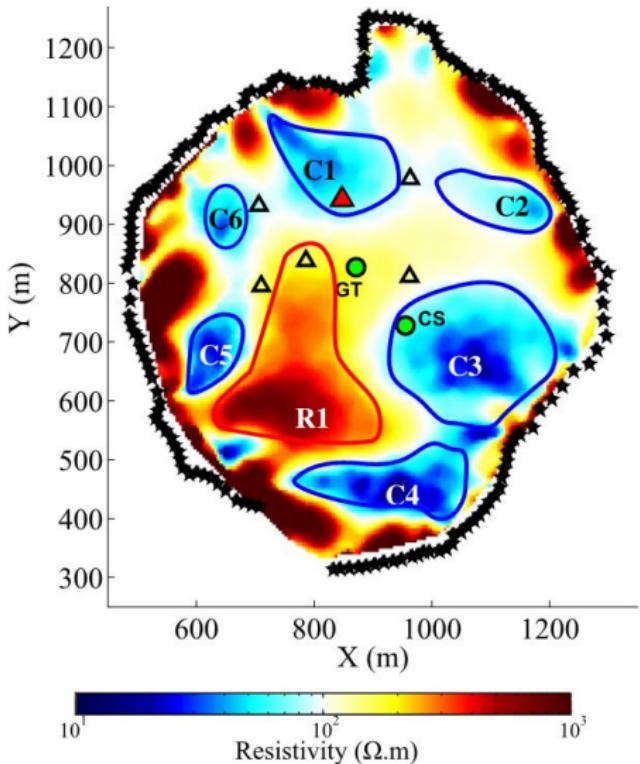


Figure shows resistivity in a cross-section of La Soufrière de Guadeloupe volcano.

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 four green squares labeled "Measurements (difference)" being multiplied by a matrix labeled "Jacobian" (represented by a 4x4 grid of gray squares). The result is a vertical vector of five teal squares labeled "Image (difference)". Finally, the "Image (difference)" vector is combined with "noise" to produce the final output.

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 arrow points from this vector to the first term in the equation. In the center, there is an equals sign followed by a multiplication symbol. To the left of the multiplication symbol is a 3x3 grid of gray squares labeled "Jacobian". An arrow points from this grid to the second term in the equation. To the right of the multiplication symbol is a vertical vector of teal squares labeled "Image (difference)". An arrow points from this vector to the third term in the equation. The final term, "+ noise", is positioned to the right of the image vector.

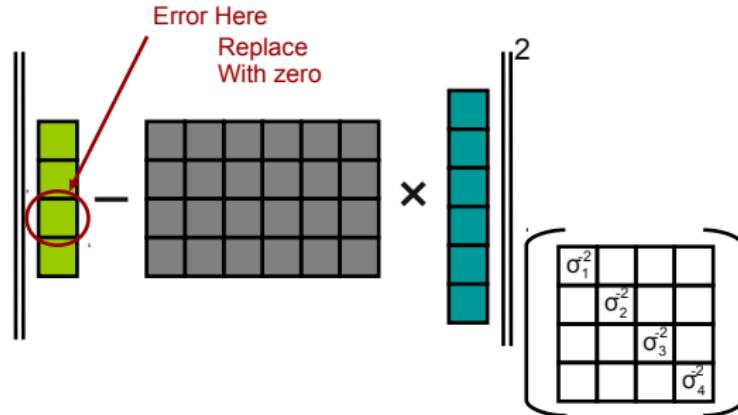
- Linear Solution: Minimize norm

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

The diagram illustrates the linear solution for reconstruction. It shows the forward problem equation with a squared norm term and a penalty function. The squared norm term is represented by a vertical vector of green squares minus a vertical vector of teal squares, all enclosed in large vertical double bars indicating a squared norm. An arrow points from this term to the first part of the equation. A plus sign follows this term. To the right of the plus sign is the label "Penalty Function" above a vertical bracket enclosing a vertical vector of teal squares. Below the bracket is the label "Norm weighted by measurement accuracy".

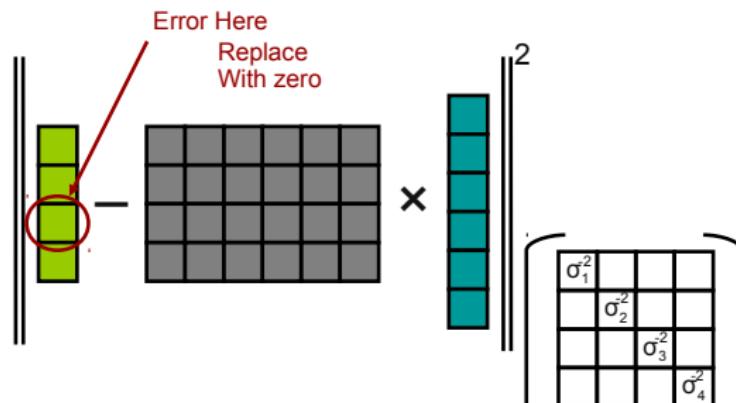
Idea #1: Reconstruction with Data Errors

“Traditional”
Solution

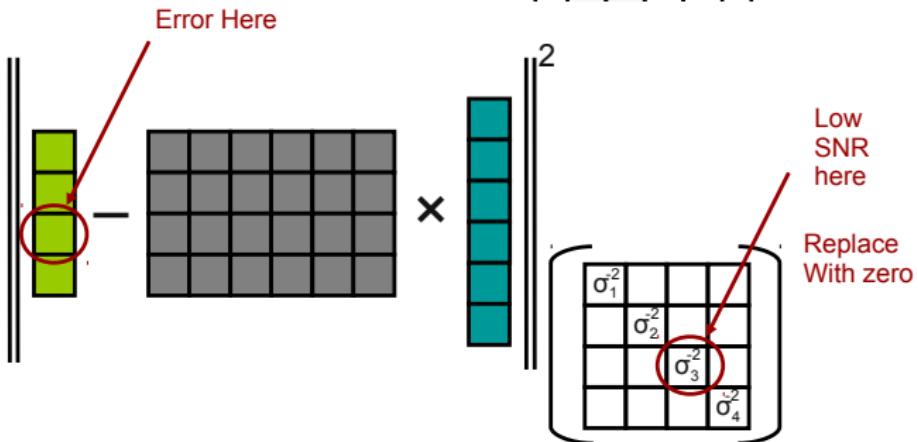


Idea #1: Reconstruction with Data Errors

“Traditional”
Solution

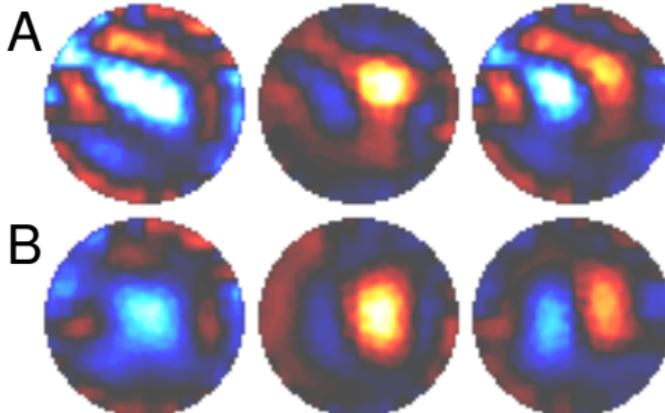


Error Model
Solution



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

$$\begin{matrix} \text{Sensitivity to sensor movement} \\ = \end{matrix} \begin{matrix} \text{Jacobian now includes measurement change due to movement} \\ \times \end{matrix} \begin{matrix} \text{"image" now includes x,y sensor movement} \\ + \text{noise} \end{matrix}$$

The diagram illustrates the effect of electrode movement on a system. On the left, a vertical vector of three green squares is labeled "Sensitivity to sensor movement". An equals sign follows, leading to a 3x3 grid of gray squares. To the right of the grid is a multiplication sign. To the right of the multiplication sign is another vertical vector consisting of three teal squares at the top and one light blue square at the bottom. This second vector is labeled "+ noise". Red arrows point from the text "Jacobian now includes measurement change due to movement" to the 3x3 grid and from the text "'image' now includes x,y sensor movement" to the bottom row of the second vector.

Idea #2: Electrode movement

Sensitivity to
sensor
movement

$$\begin{matrix} \text{green} \\ \text{green} \\ \text{green} \end{matrix} = \begin{matrix} \text{grid} & \times \end{matrix} \begin{matrix} \text{teal} \\ \text{teal} \\ \text{teal} \\ \text{light blue} \end{matrix} + \text{noise}$$

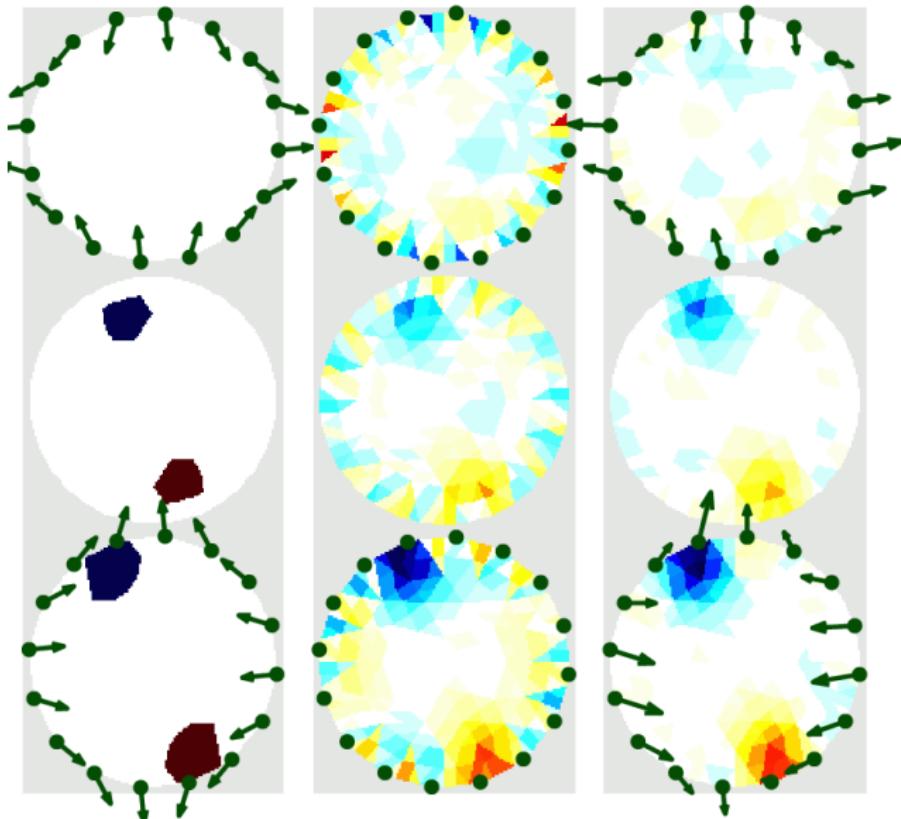
Jacobian now includes measurement change due to movement

"image" now in x,y sensor move

Adapted penalty function

The diagram illustrates the computation of movement co-variance in a convolutional neural network layer. It shows a vertical stack of four colored squares (red, green, blue, yellow) representing the input image. To its right, a bracket labeled "Expected image" groups the first two squares. A dashed line separates them from the next two squares, which are grouped by a bracket labeled "Expected movement". An arrow points from the input stack to a 2x2 input receptive field. This field is overlaid on a 5x5 kernel matrix. The matrix contains values 1 and -½ at various positions. Red arrows point from the text "Unlikelyhood of movement and image co-variance" to the bottom-right corner of the matrix and to the bottom-right square of the 5x5 kernel, which is circled in red.

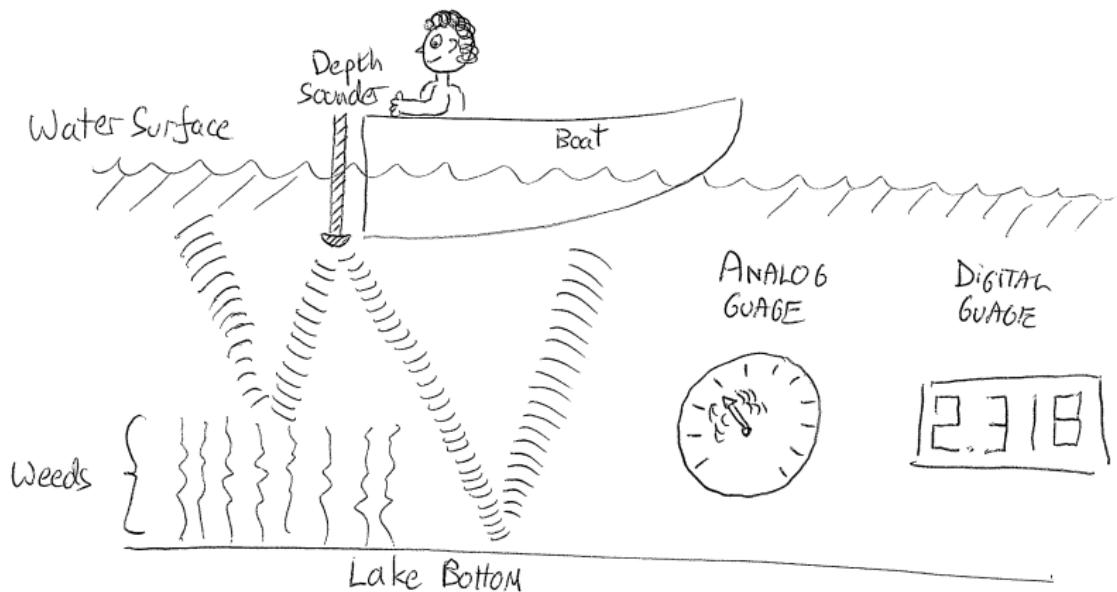
Electrode movement compensation



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?

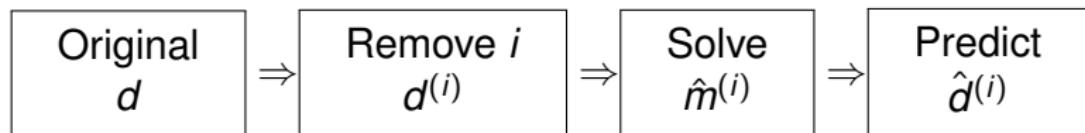
With strong priors and complex algorithms, algorithms give us pretty pictures, even when they are irrelevant.

Question:

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

Data Quality Measure: Concept

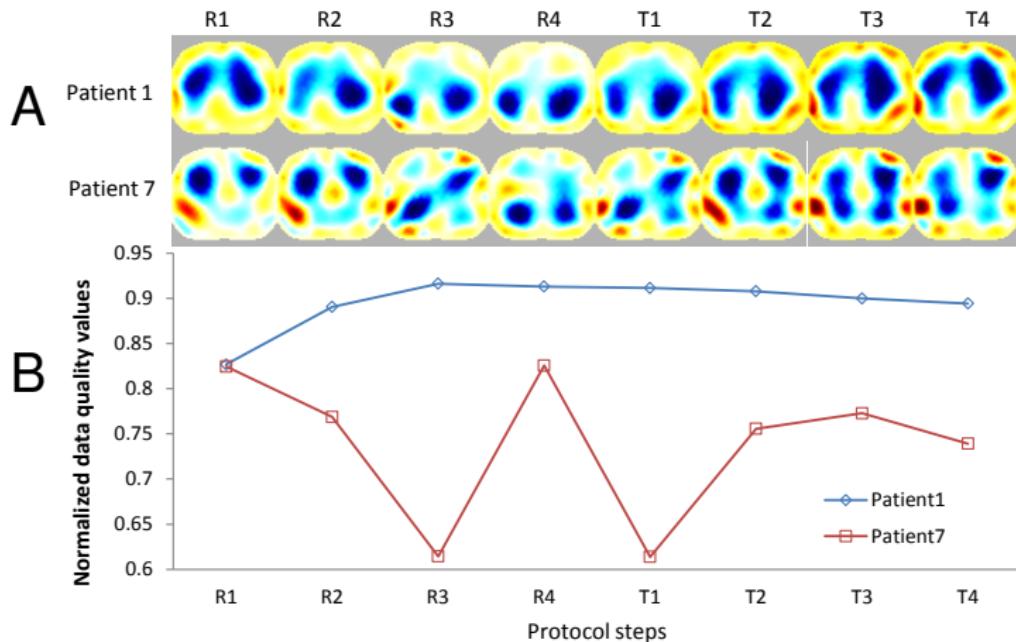
- *Concept:* High Quality Data is Consistent
- *Idea:* Use IP to predict each data point from all others



- Calculate error

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

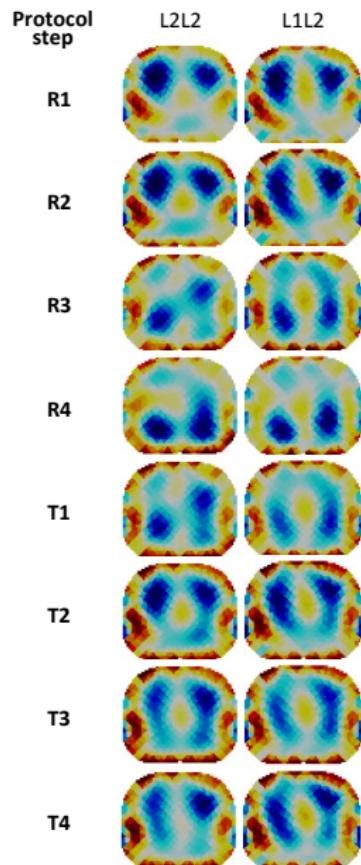
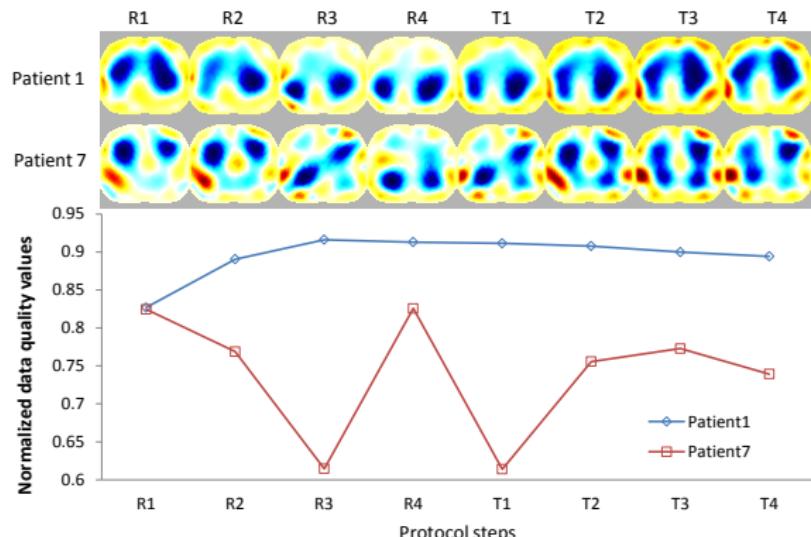
Example: Data quality measures



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?

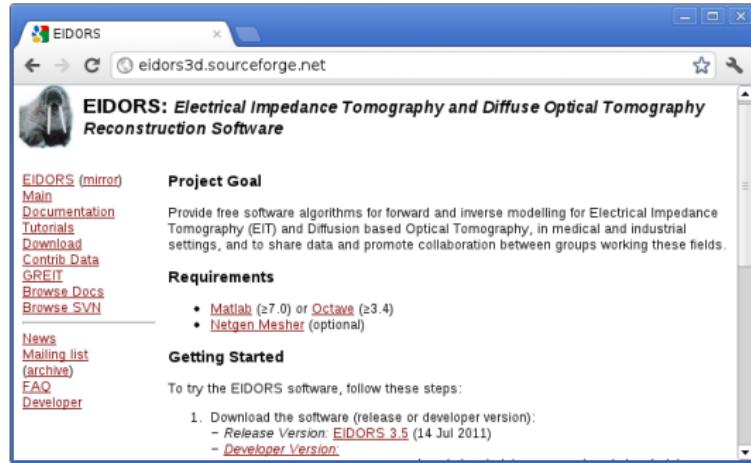


Thus, we need

- 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

EIDORS (mirror)

Main Documentation Tutorials Download Contrib Data GREIT Browse Docs Browse SVN

News Mailing list (archive) FAQ Developer

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 [Developer Version](#))
 - 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

Brief 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