

# *Impedance Imaging of the Thorax:* Why it's difficult, and what we are doing about it?

Biomedical Engineering Research Centre (BIRC)  
Western University, London, ON, 6 May 2015

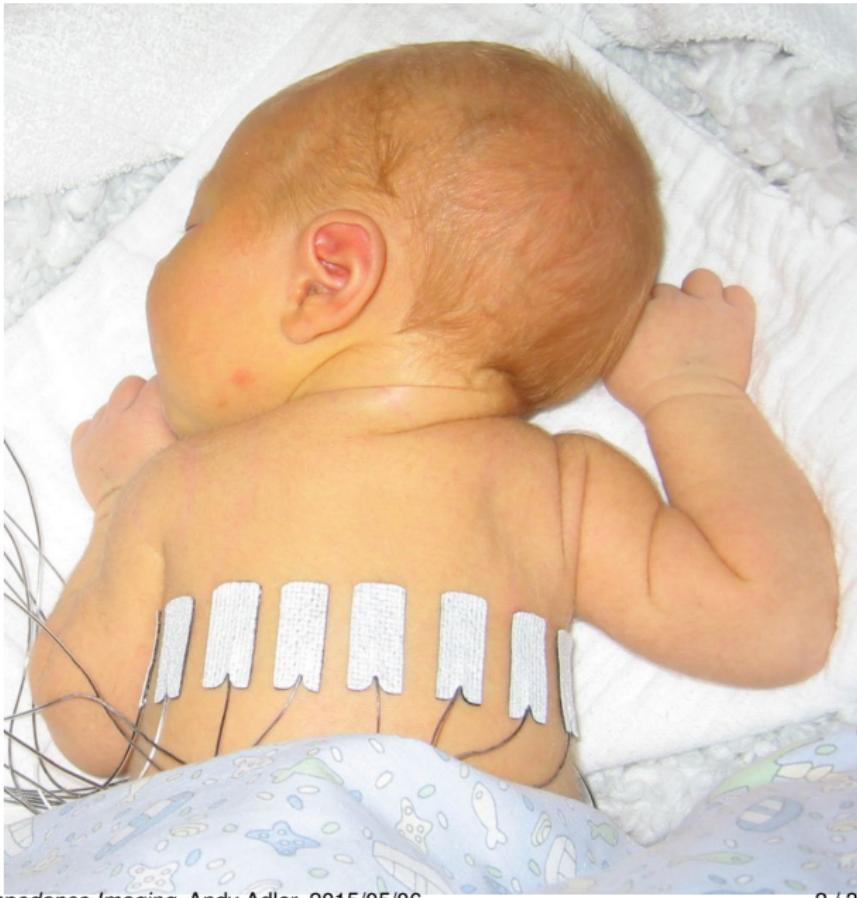
Andy Adler

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

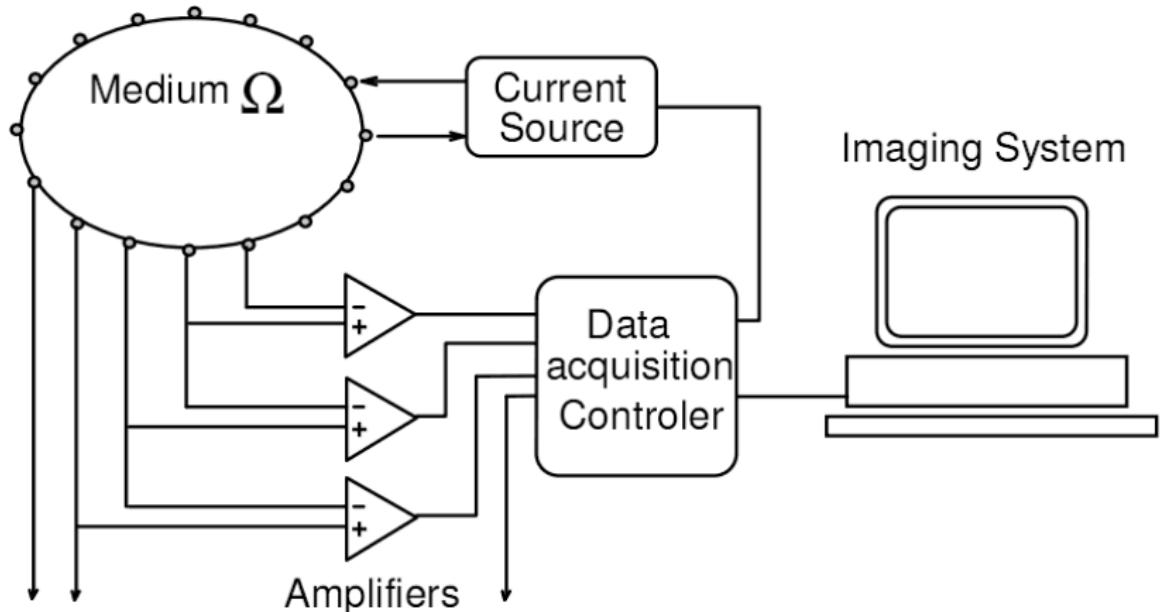
# Electrical Impedance Tomography

10-day old healthy  
baby with EIT  
electrodes

Source:  
[eidors3d.sf.net/data\\_contrib/if-neonate-spontaneous](http://eidors3d.sf.net/data_contrib/if-neonate-spontaneous)



# Electronics – Block Diagram



# Current Propagation

Healthy Adult Male  
CT slide at heart

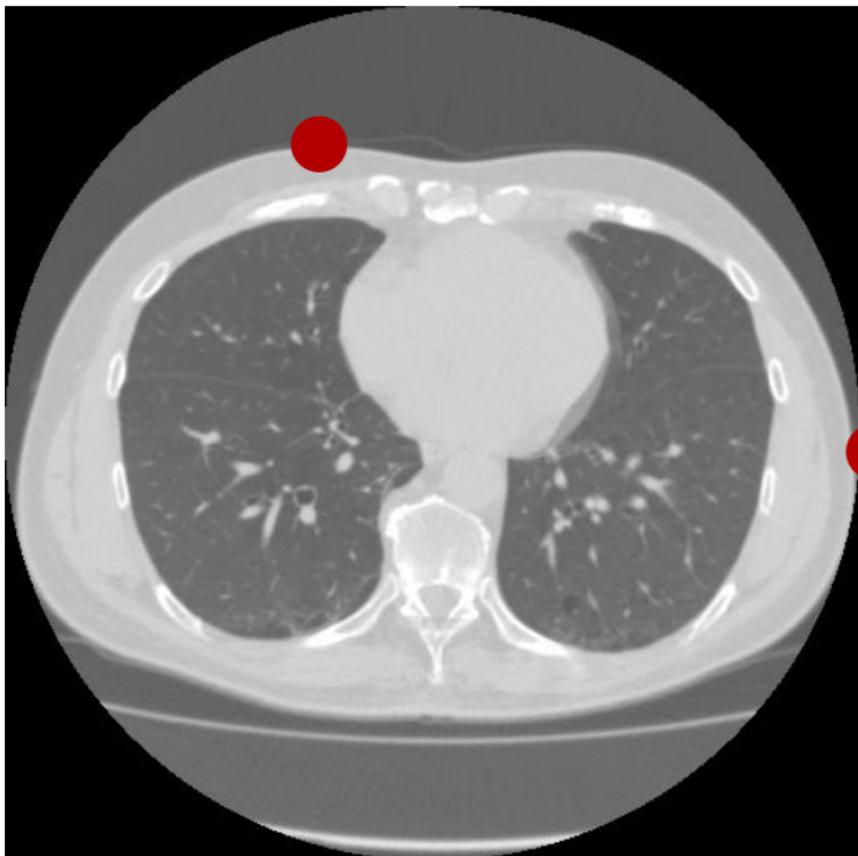
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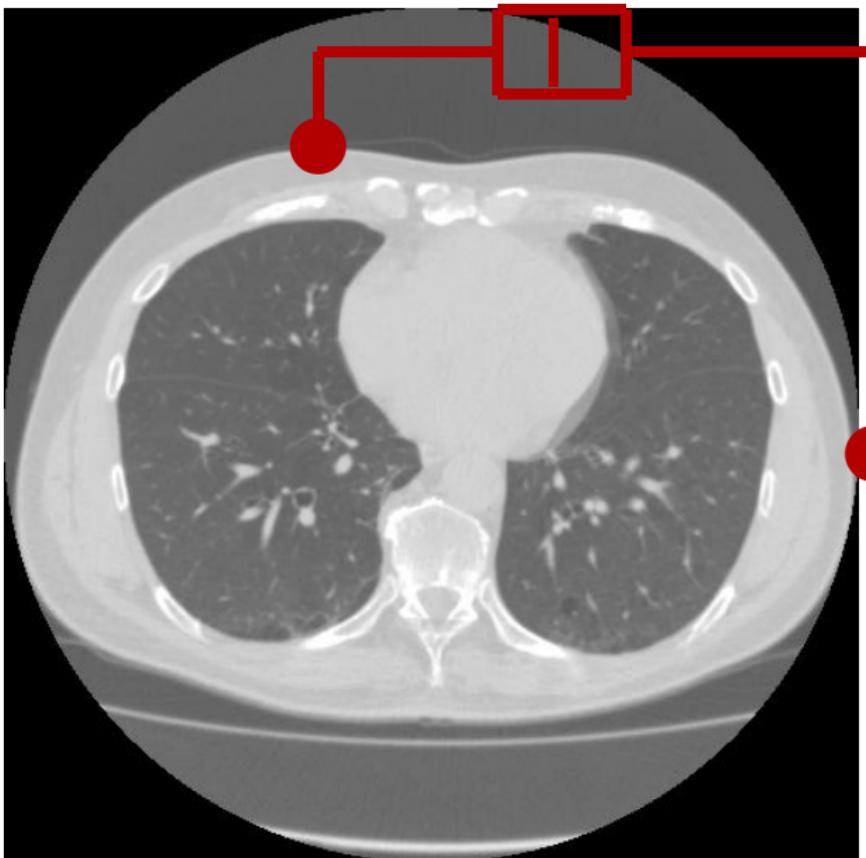
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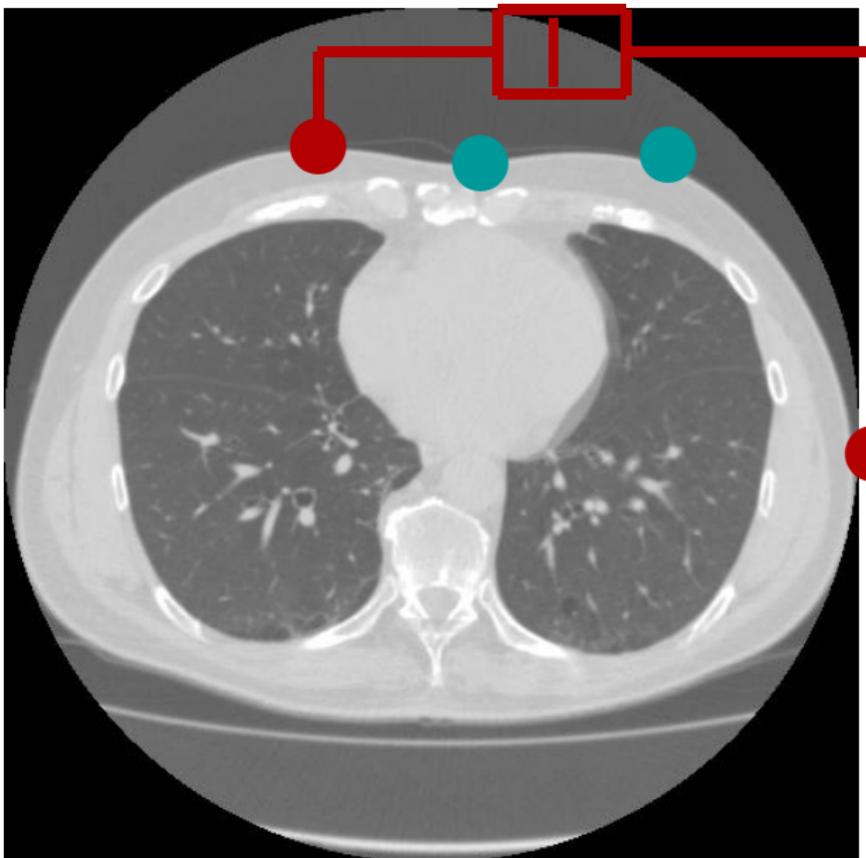
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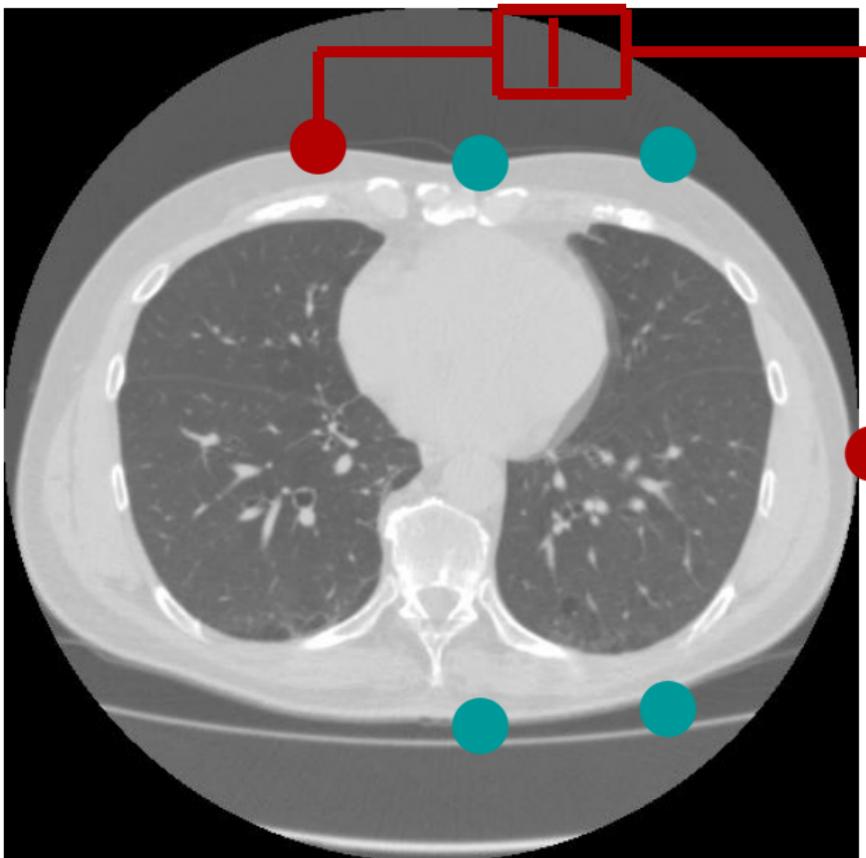
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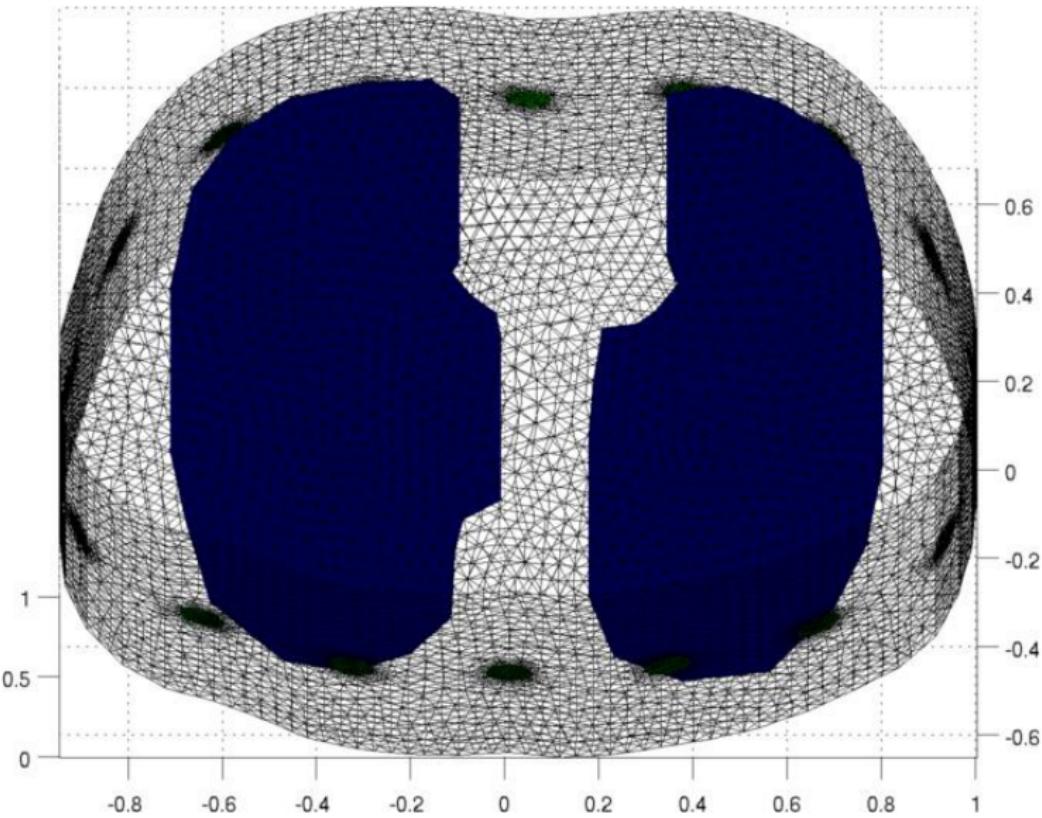
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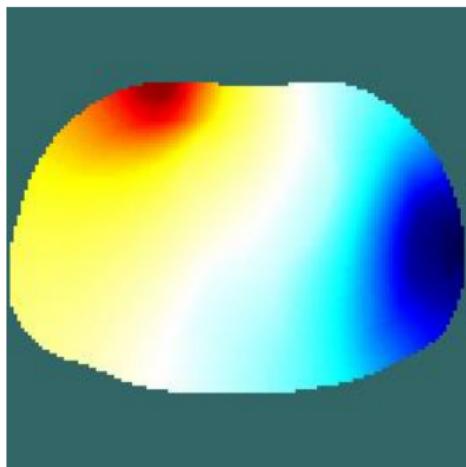
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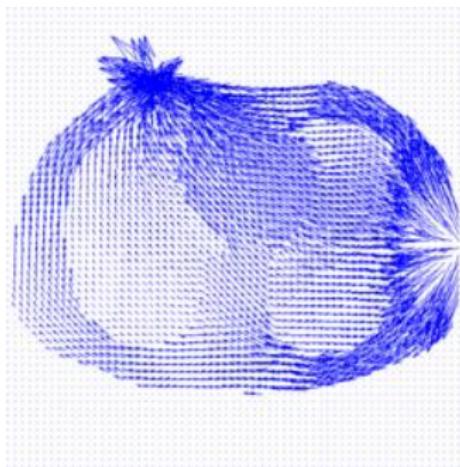
# Finite Element Modelling



# Finite Element Modelling



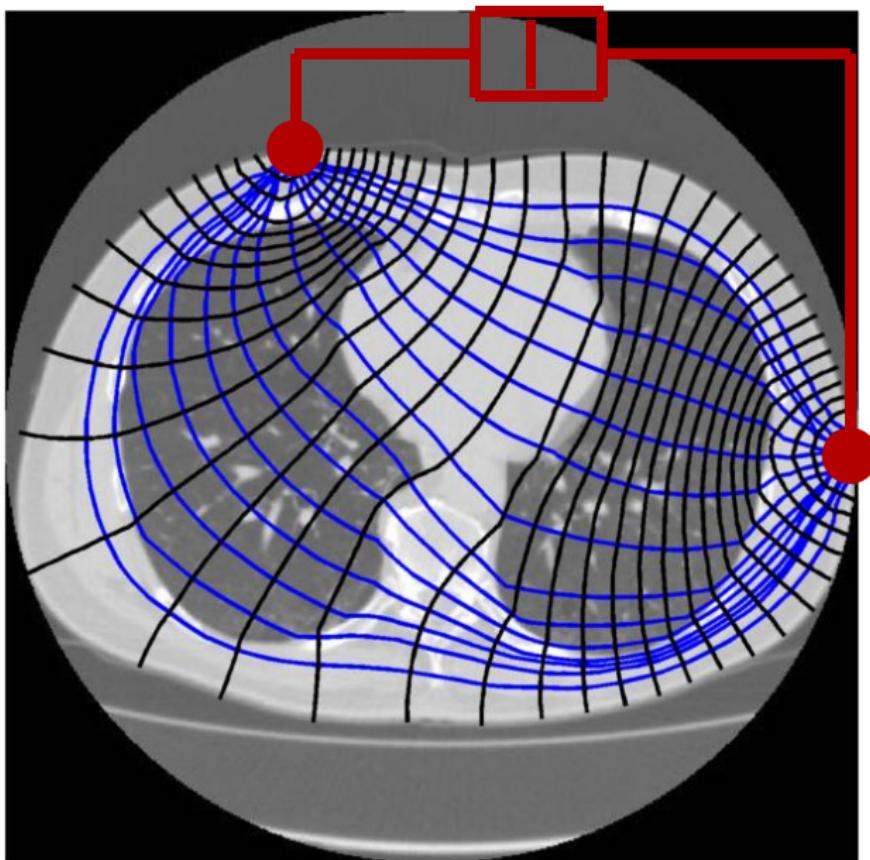
Simulated Voltages



Voxel Currents

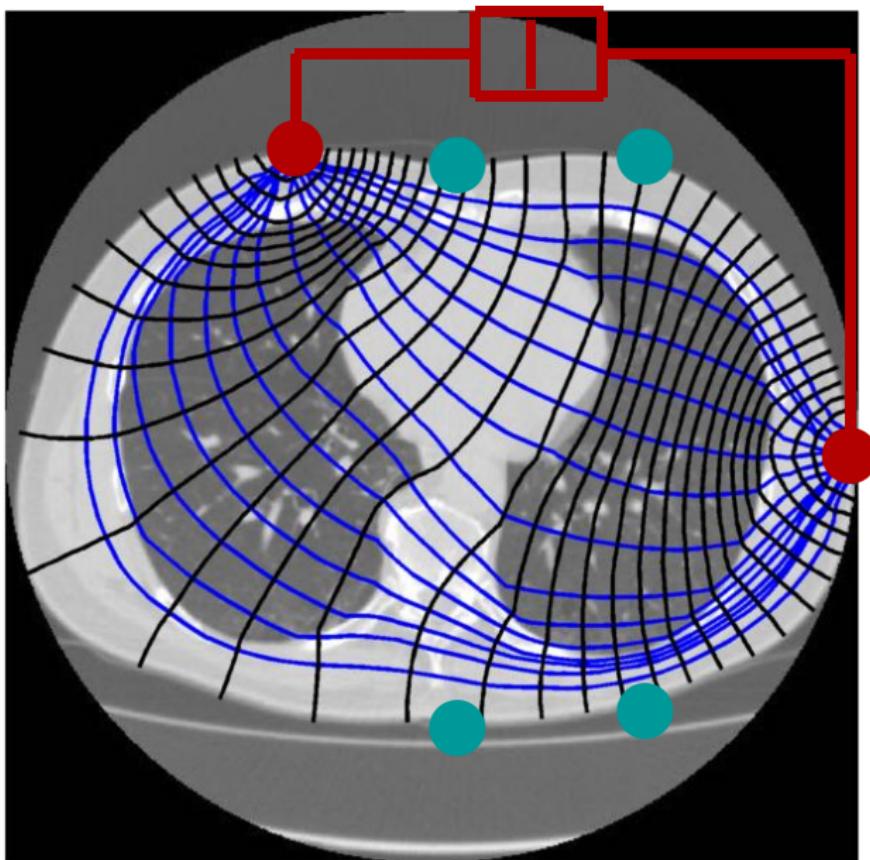
# Thorax Propagation

CT Slice with simulated current streamlines and voltage equipotentials



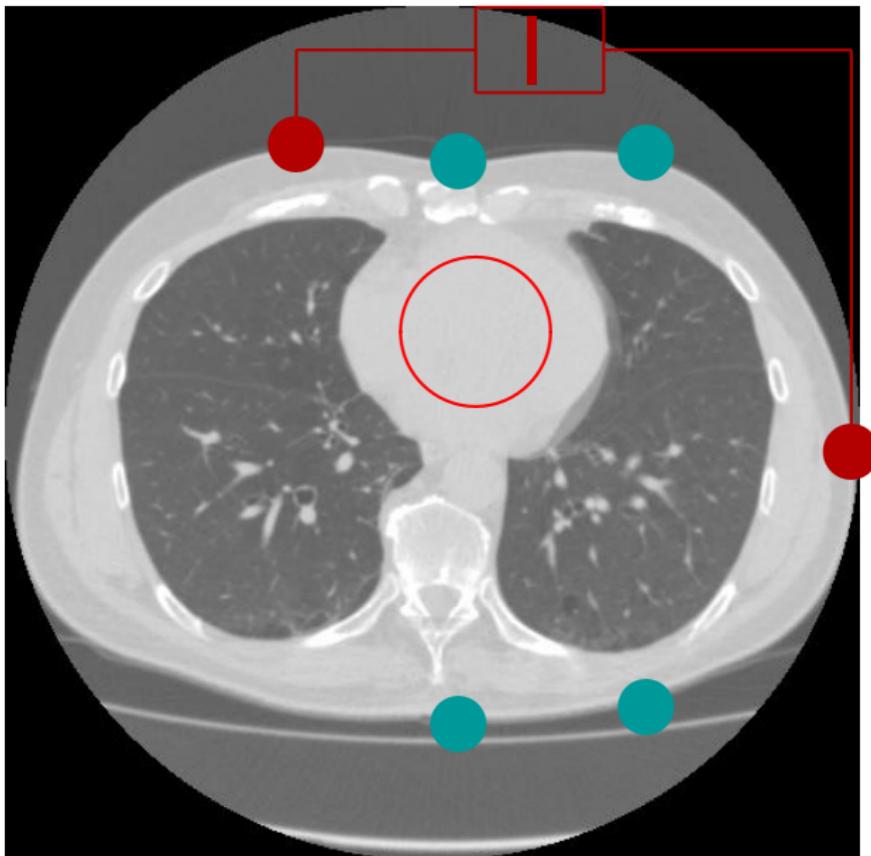
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CT Slice with simulated current streamlines and voltage equipotentials



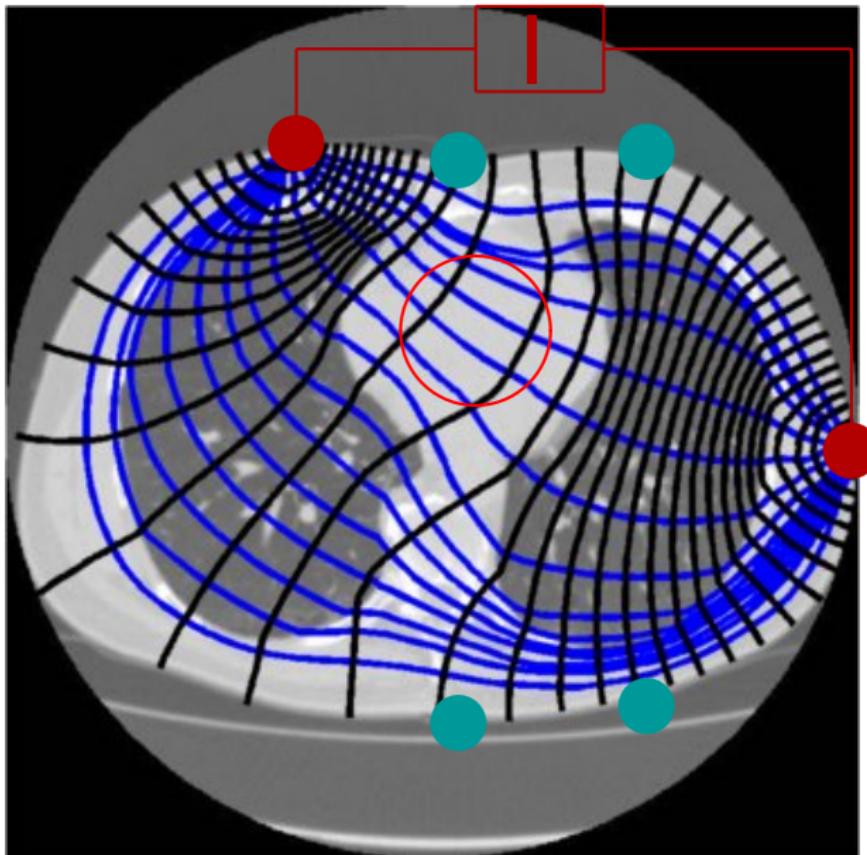
# Changing Conductivity

Heart receives blood (diastole) and is more conductive

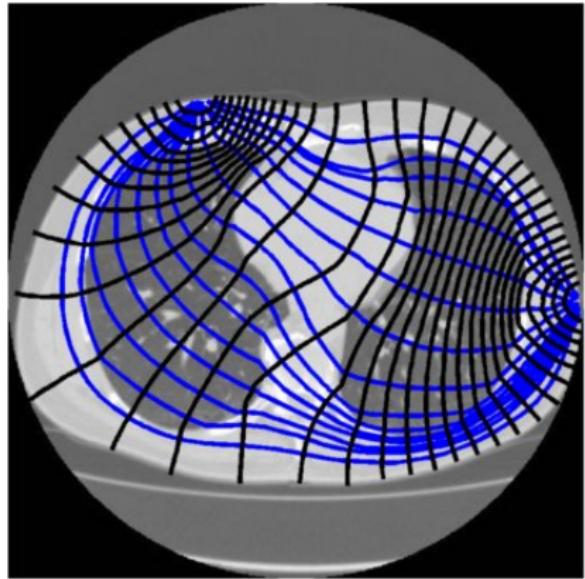
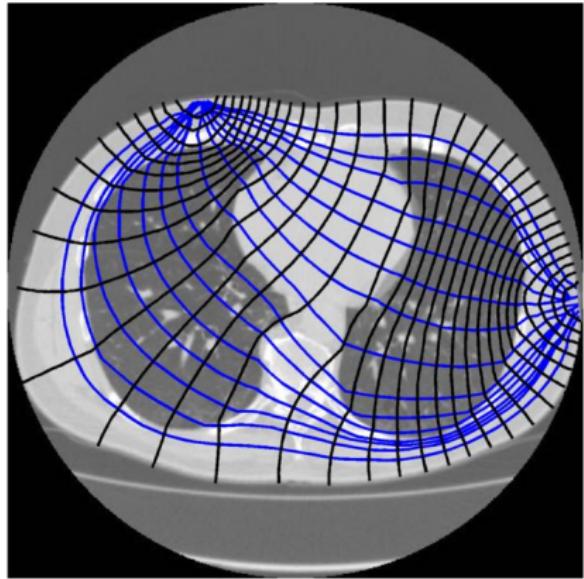


# Changing Conductivity

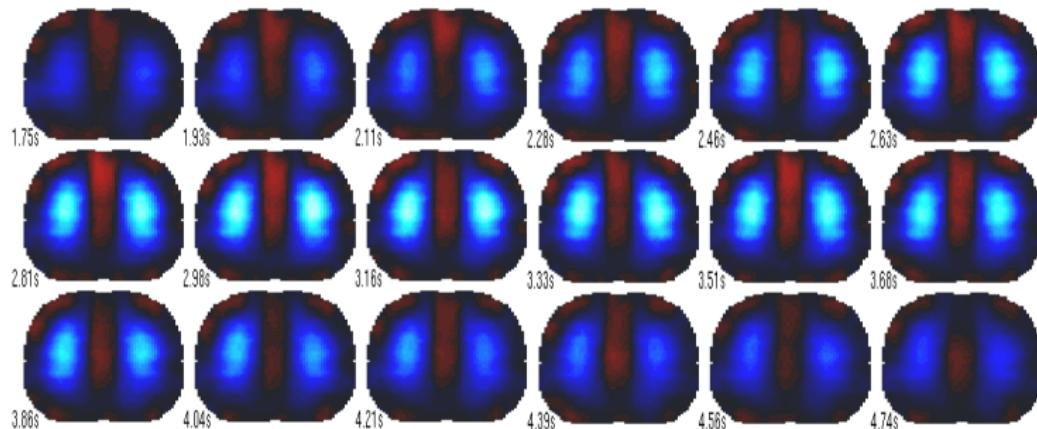
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# Changing Conductivity

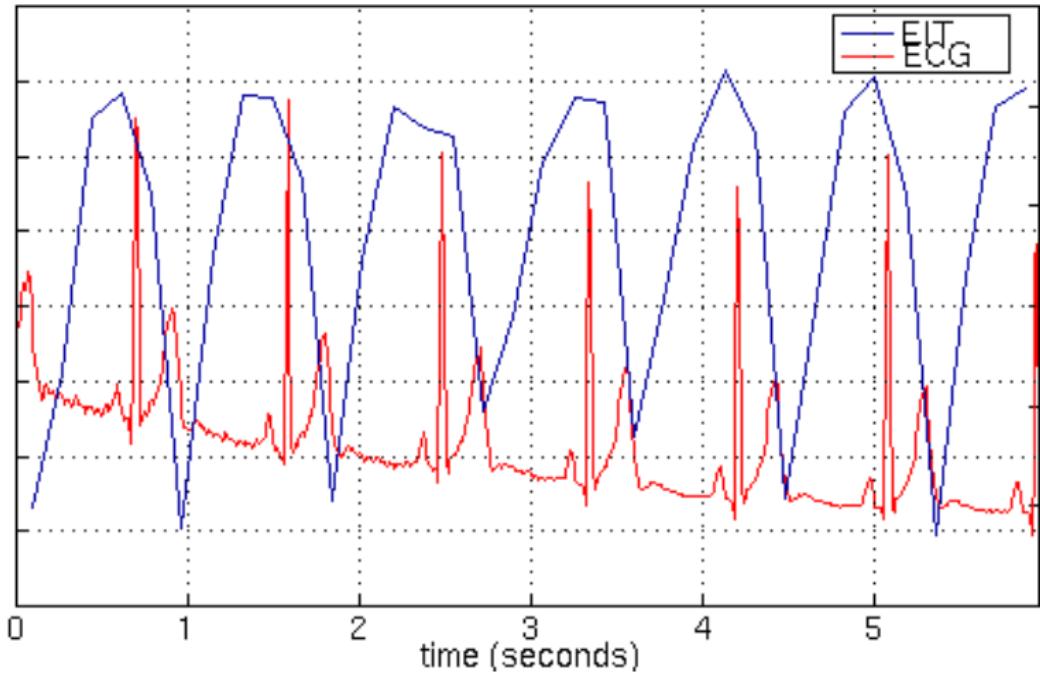


# Application: Breathing



Chest images of tidal breathing in healthy adult

## Application: Heart



EIT Signal in ROI around heart (and ECG)

# Mechanical Ventilation

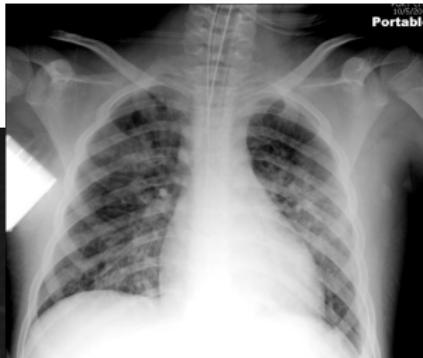
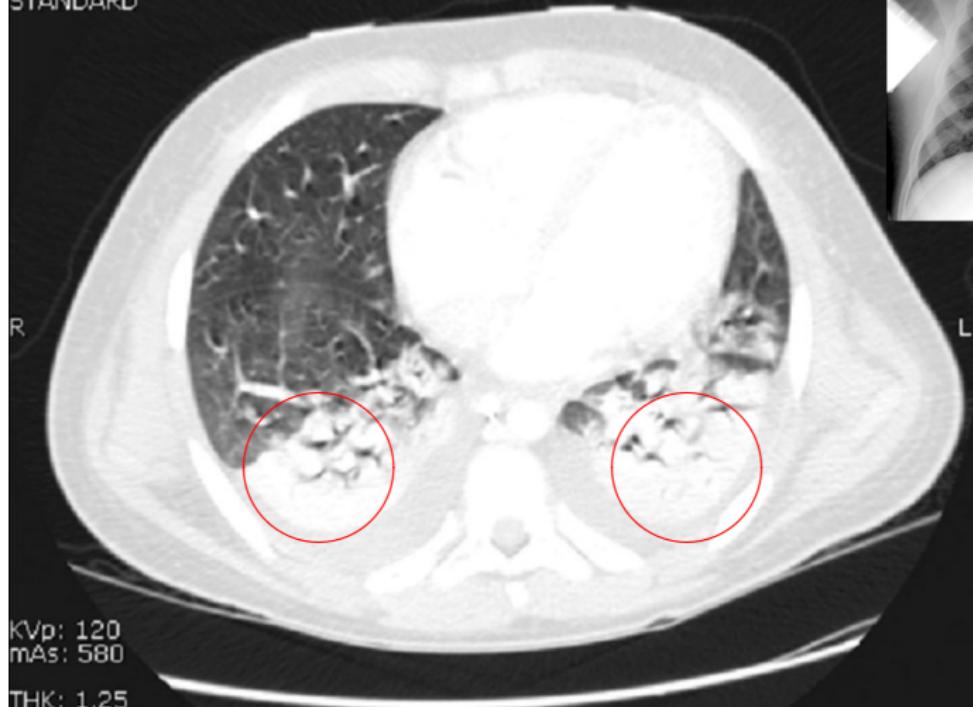


Mechanical Ventilator with EIT monitor

Source: Swisstom.com

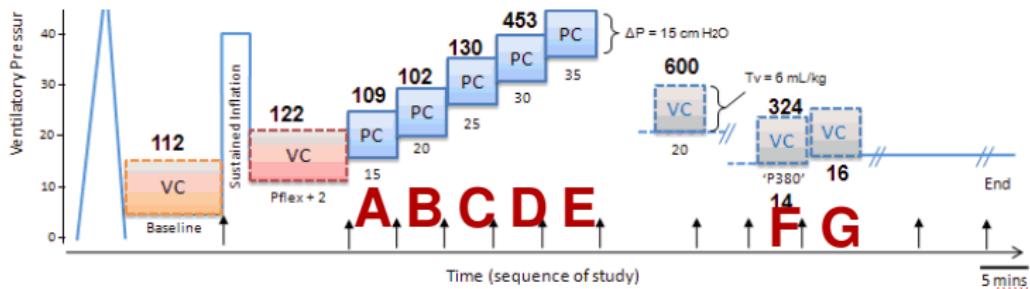
# Acute Respiratory Distress Syndrome (ARDS)

STANDARD

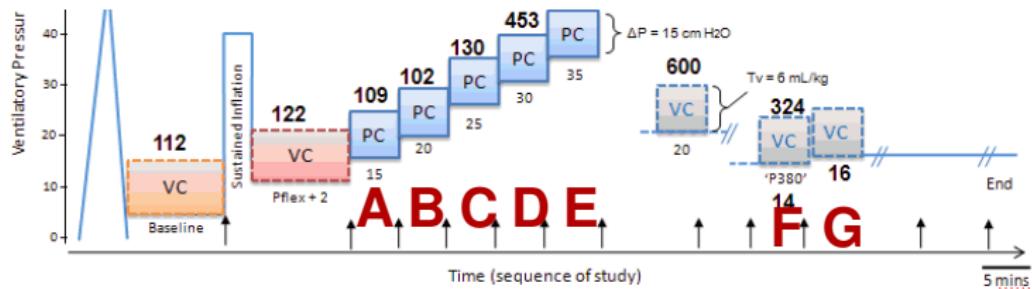


KVP: 120  
mAs: 580  
THK: 1.25

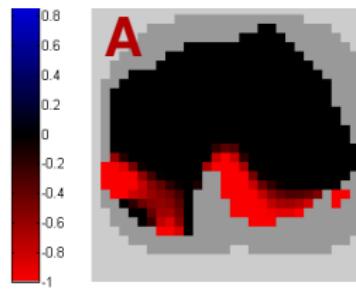
# EIT + Lung State



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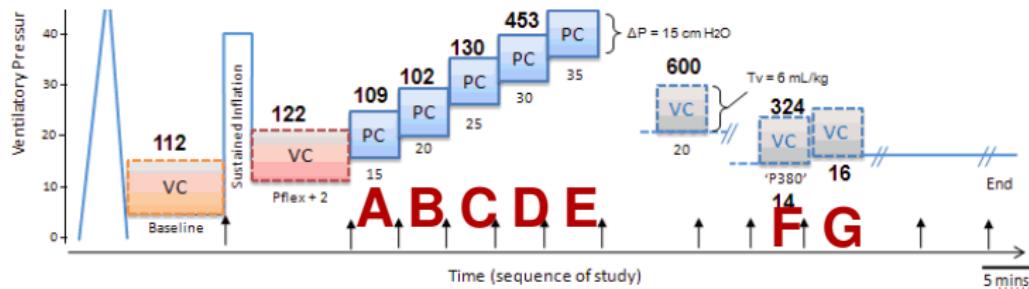


Overdistension

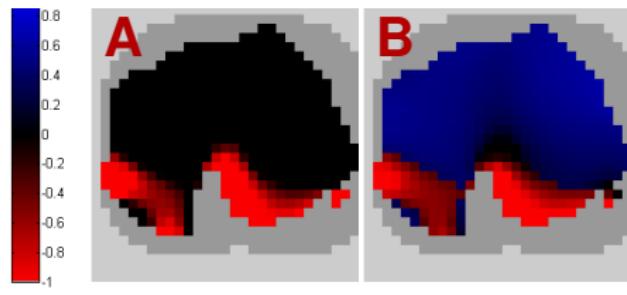


Collapse

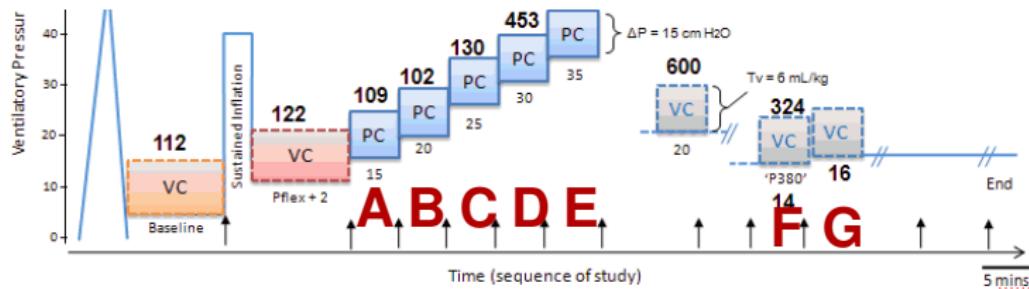
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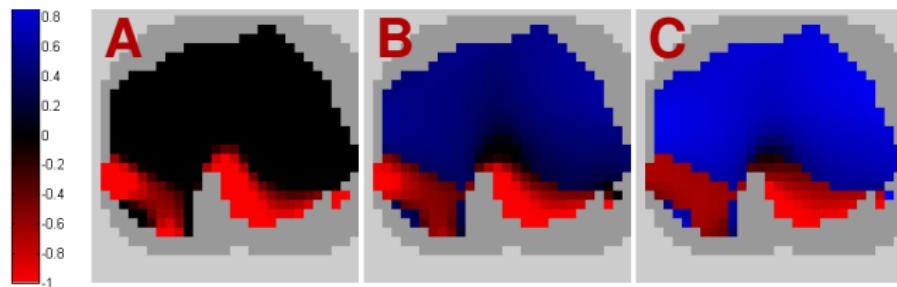
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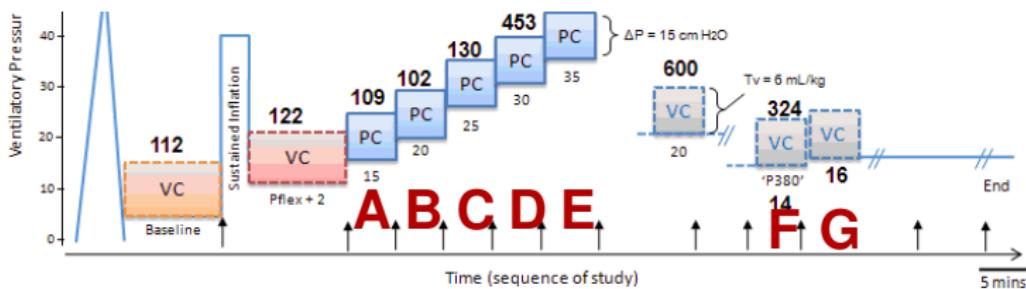
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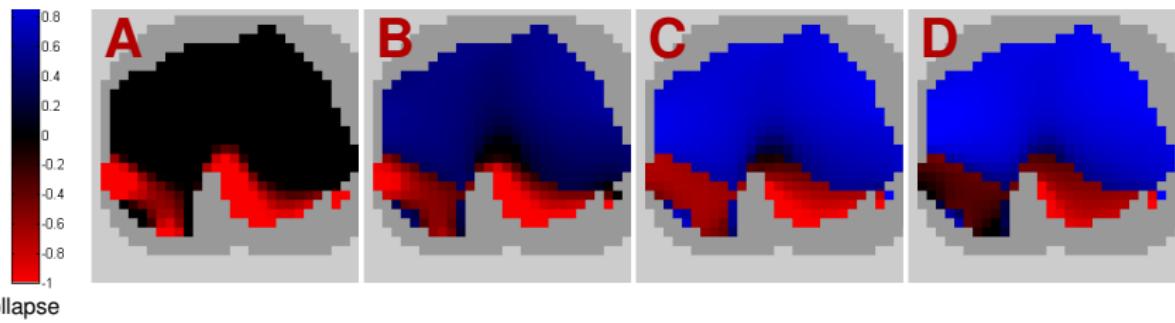
Overdistension



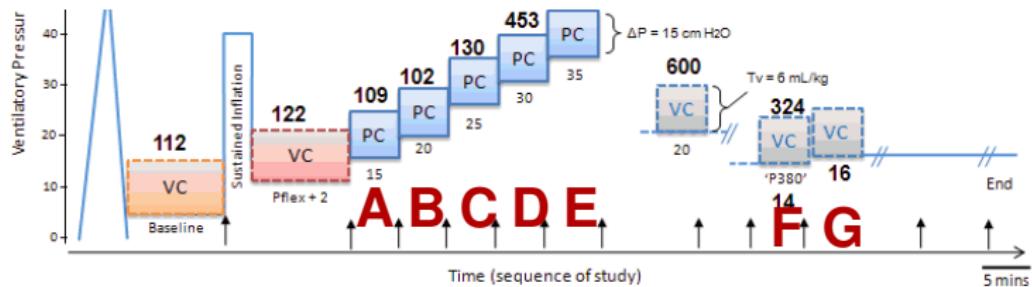
EIT +  
Lung  
State



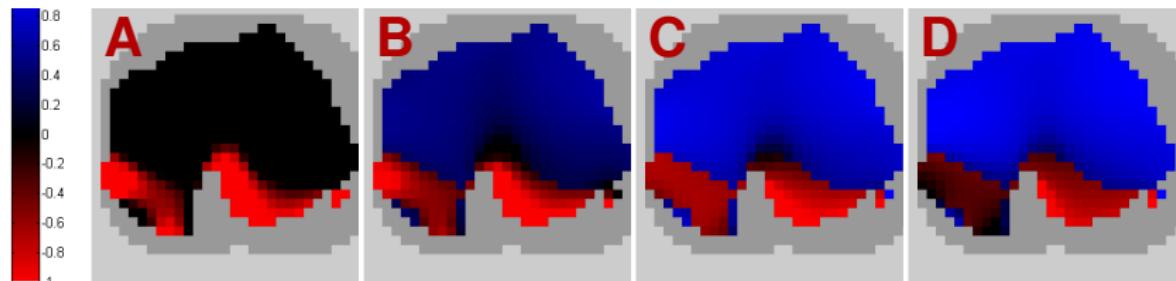
### Overdistension



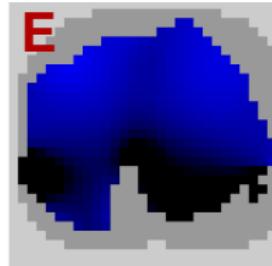
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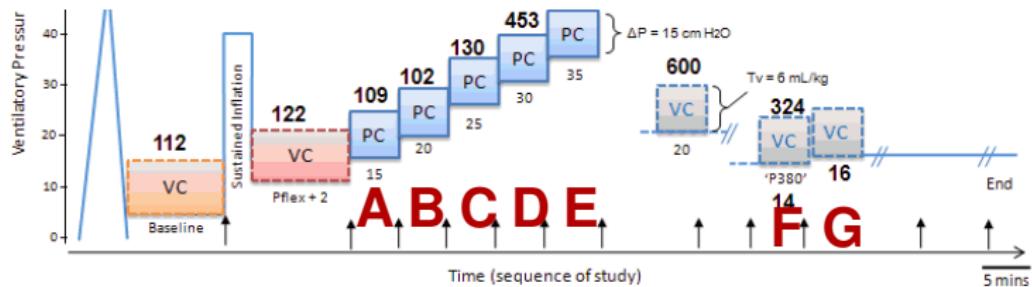
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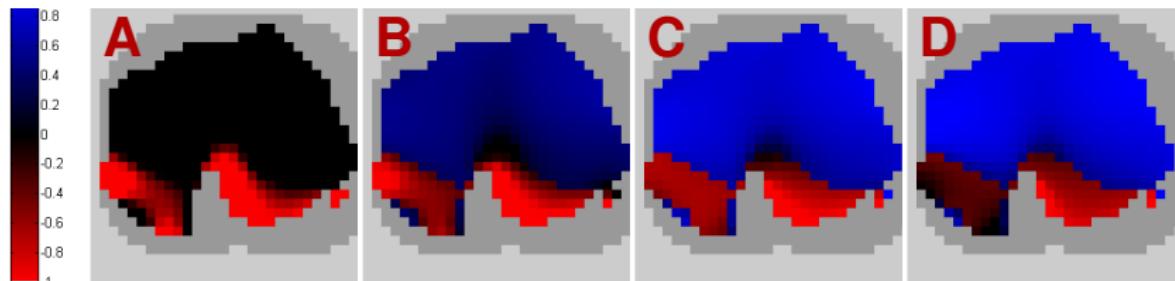
Collapse



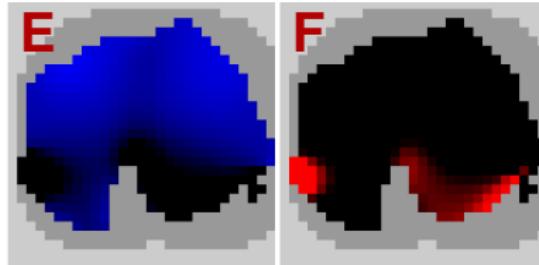
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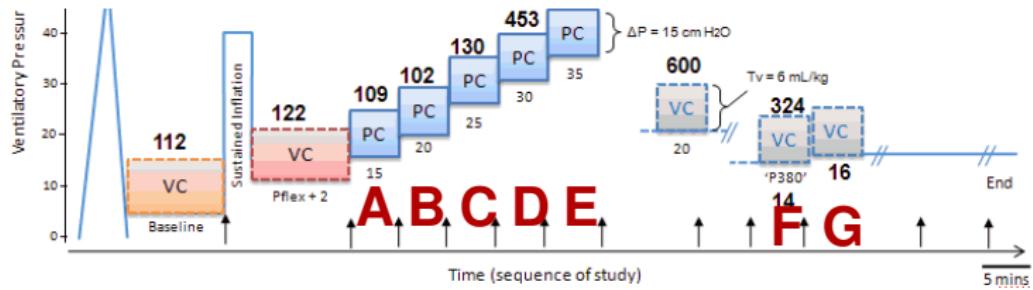
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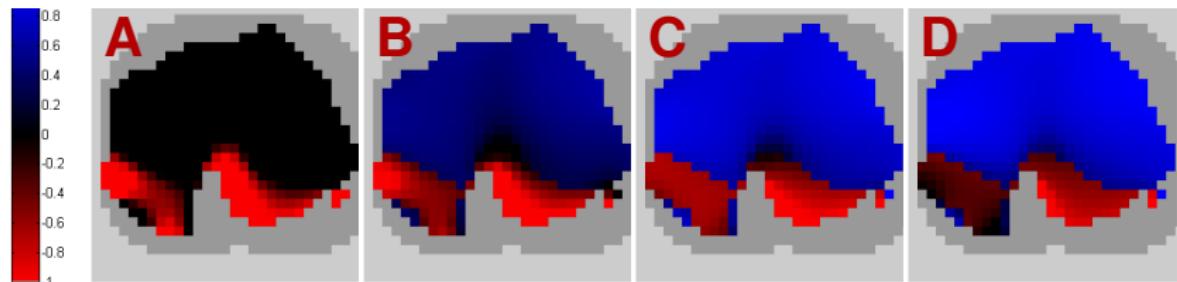
Collapse



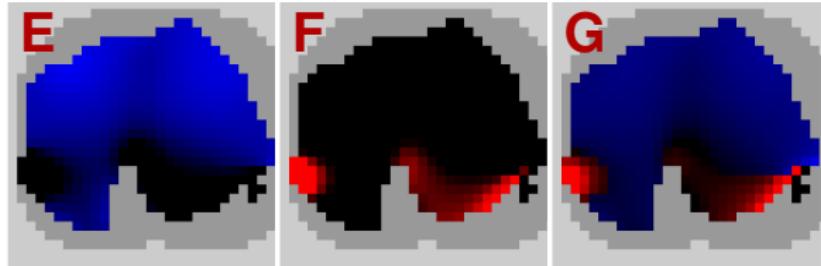
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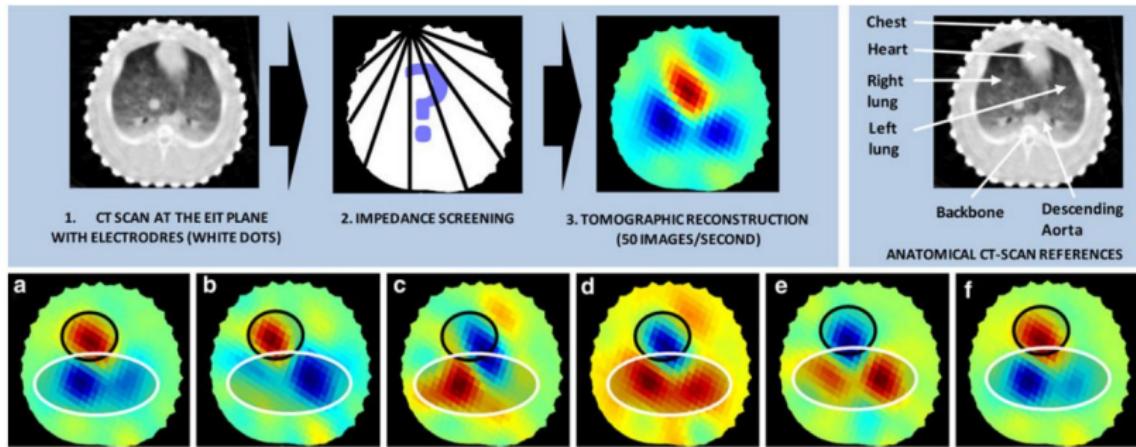
Overdistension



Collapse



# 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

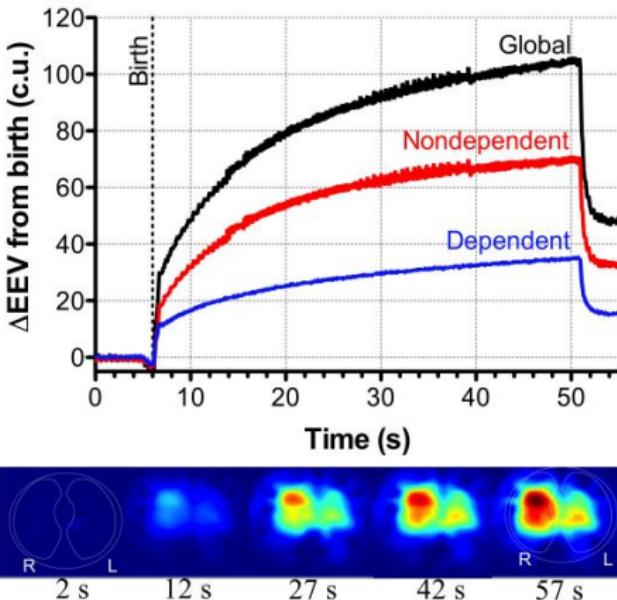
of pulse propagation during an entire cardiac cycle: a and b the filling of the heart is observed (black ROI). c The heart empties while the right lung (here on the left hand side) is starting to be perfused with conductive blood. d and e Both lungs are perfused (white ROI). Finally, f the cardiac cycle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

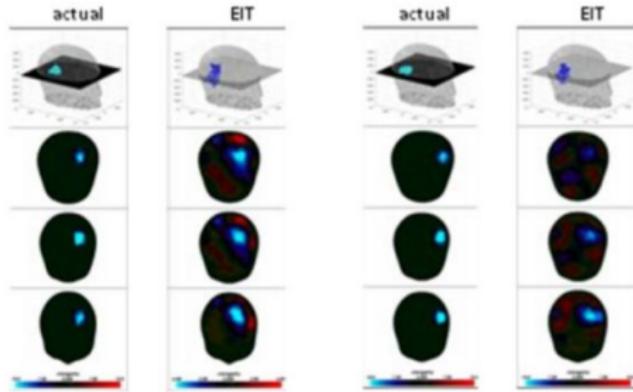
# EIT for Brain Imaging

## Applications:

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



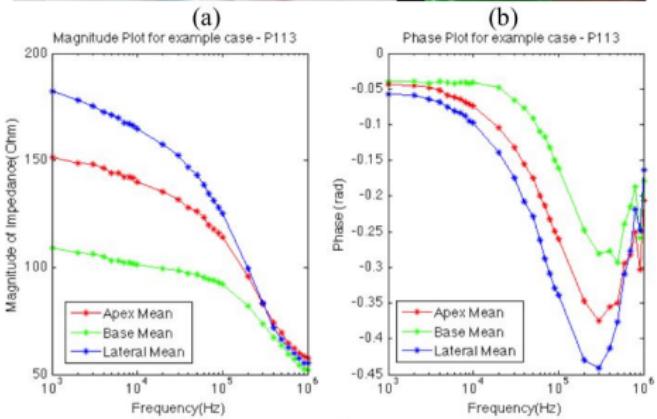
Fig. 2. Left : Finite element of the head used to produce images. Right: Example of EIT images produced in a saline filled tank



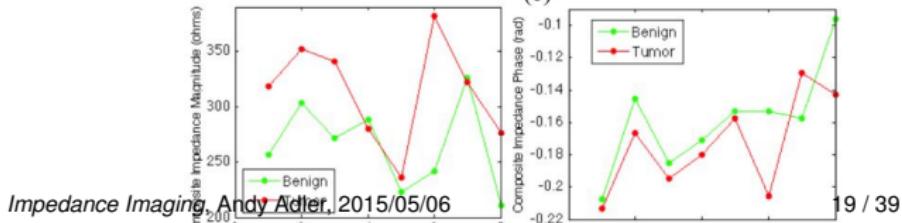
Source: Holder, [www.ucl.ac.uk/medphys/research/eit/pubs/brain\\_EIT\\_overview.pdf](http://www.ucl.ac.uk/medphys/research/eit/pubs/brain_EIT_overview.pdf)

# 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

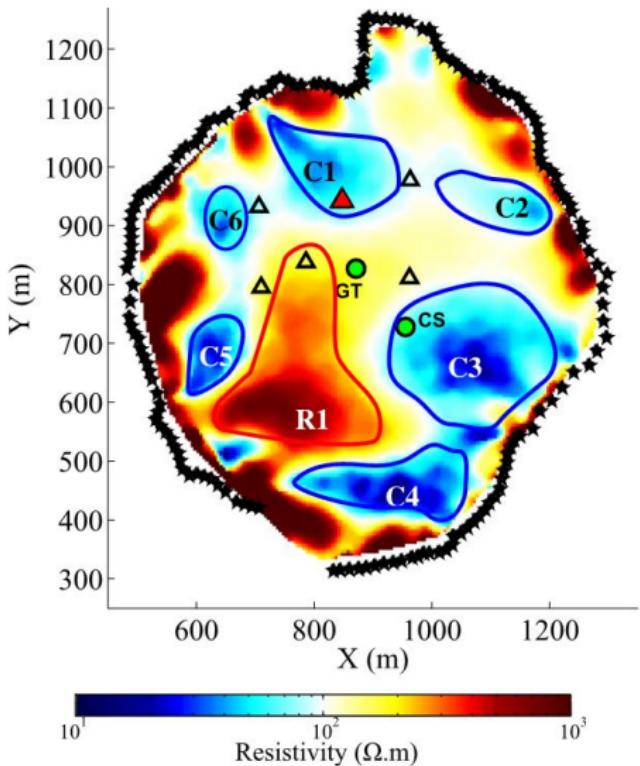


Figure shows resistivity in a cross-section of La Soufrière de Guadeloupe volcano.

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

# Why is EIT hard?

# Inverse Problems ... *Plato's cave*



## *Plato's cave ... Shadows on the wall*



Source: iamcriselleeee.files.wordpress.com/2013/11/cave-2.jpg

# Inverse Problems

Forward Problem:  $Forms \Rightarrow Shadows$

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Inverse Problem:  $Shadows \Rightarrow Forms$

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- Ill-conditioned
- Sensitivity to some movements is low

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Forward Problem:  $Forms \Rightarrow Shadows$

Inverse Problem:  $Shadows \Rightarrow Forms$

- Ill-conditioned  
Sensitivity to some movements is low
- Ill-posed  
Some movements don't change shadows

# Inverse Problems

Forward Problem:  $Forms \Rightarrow Shadows$

Inverse Problem:  $Shadows \Rightarrow Forms$

- Ill-conditioned  
Sensitivity to some movements is low
- Ill-posed  
Some movements don't change shadows
- Noisy  
Flickering light

# Inverse Problems

Techniques: to calculate stable & meaningful parameters in the presence of inversion difficulties

## Examples

- Image deblurring / restoration
- Medical imaging
- Geophysical imaging
- Model parameter fitting
- Reconstruction with incomplete/noisy data

# Reconstruction in Pictures

- Forward Problem

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

+ noise

Jacobian

# 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 column of three green squares is labeled "Measurements (difference)". An equals sign follows. To the right of the equals sign is a gray 3x5 grid labeled "Jacobian". To the right of the grid is a times sign. To the right of the times sign is a vertical column of four teal squares labeled "Image (difference)". A plus sign follows, and the word "noise" is written next to it.

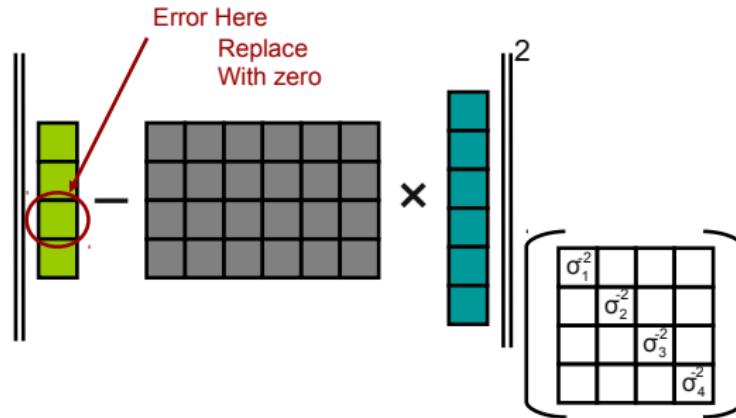
- Linear Solution: Minimize norm

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

The diagram illustrates the linear solution for reconstruction. It shows the difference between the measured data and the model's prediction, weighted by the inverse of the measurement error variance. This difference is squared and summed to form the first term of the cost function. The second term is a "Penalty Function" applied to the image, represented by a vertical column of four teal squares enclosed in a bracket. A red arrow points from the text "Norm weighted by measurement accuracy" to this bracket.

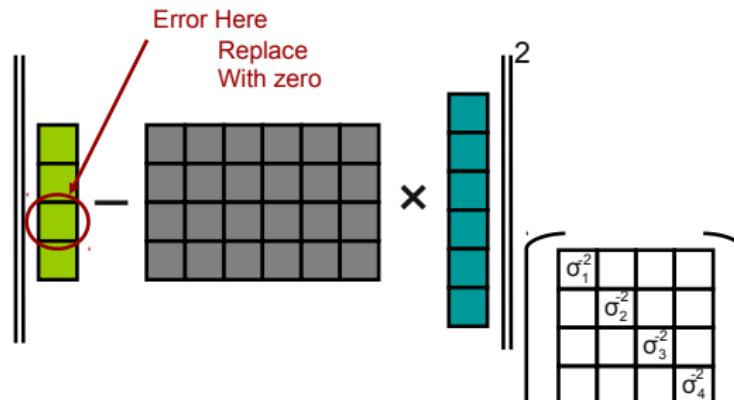
# Idea #1: Reconstruction with Data Errors

“Traditional”  
Solution

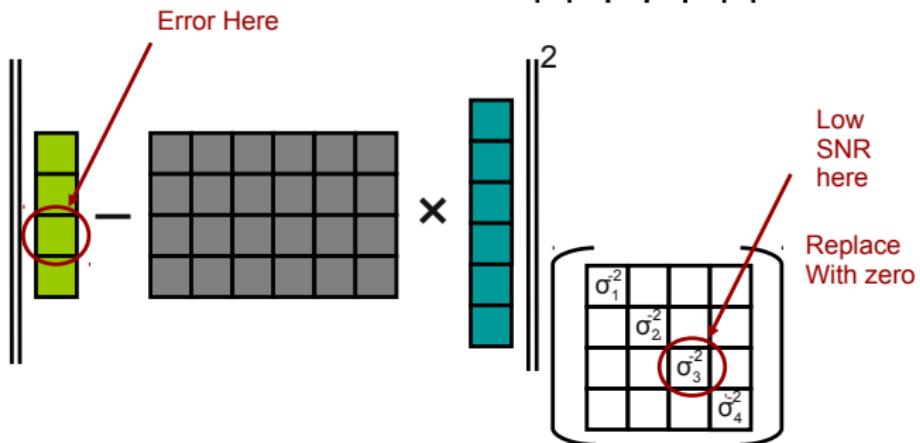


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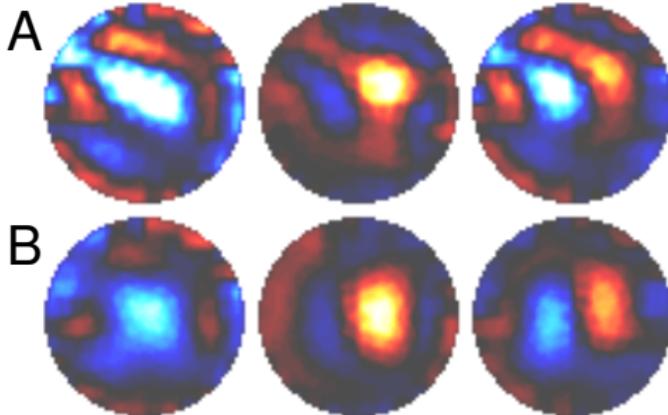


Error Model  
Solution



## 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

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

## Idea #2: Electrode movement

Sensitivity to  
sensor  
movement

$$\begin{matrix} \text{green} \\ \text{green} \\ \text{green} \end{matrix} = \begin{matrix} \text{grey} & \text{grey} & \dots & \text{grey} \\ \text{grey} & \text{grey} & \dots & \text{grey} \\ \vdots & \vdots & \ddots & \vdots \\ \text{grey} & \text{grey} & \dots & \text{grey} \end{matrix} \times \begin{matrix} \text{cyan} \\ \text{cyan} \\ \text{cyan} \\ \text{cyan} \end{matrix} + \text{noise}$$

Jacobian now includes  
measurement change  
due to movement

Adapted  
penalty  
function

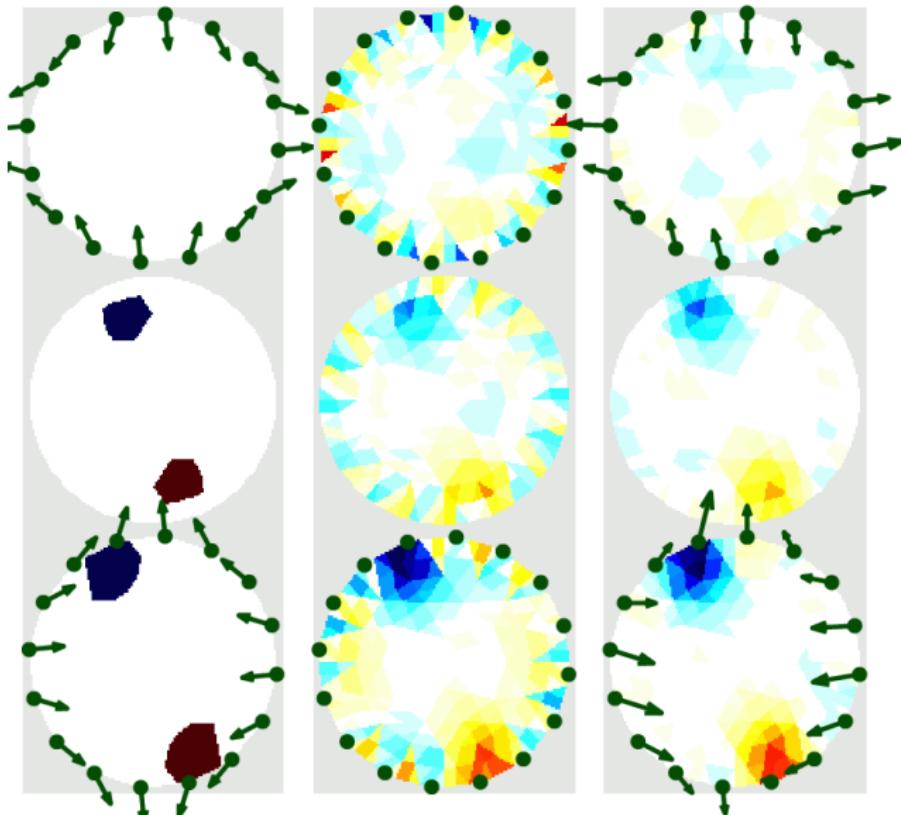
$$\left\| \begin{matrix} \text{cyan} \\ \text{cyan} \\ \text{cyan} \\ \text{cyan} \end{matrix} - \left( \begin{matrix} \text{Expected} \\ \text{image} \\ \hline \text{Expected} \\ \text{movement} \end{matrix} \right) \right\|^2$$

"Unlikelyhood"  
of movement  
and image  
co-variance

"Unlikelyhood"  
of movement

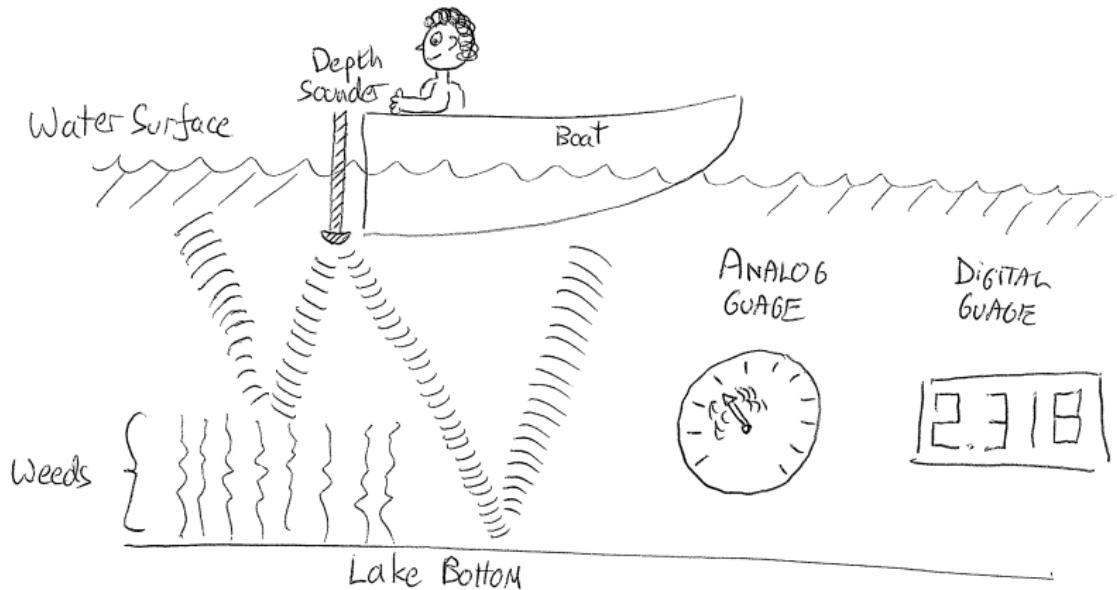
"Unlikelyhood"  
of movement

# Electrode movement compensation



## Idea #3: Data Quality

## Idea #3: Data Quality



Depth Sounder – with analog and digital guages

## What's the problem?

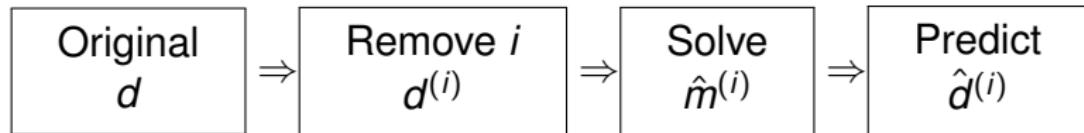
With strong priors and complex algorithms, algorithms give us pretty pictures, even when they are irrelevant.

*Question:*

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

# Data Quality Measure: Concept

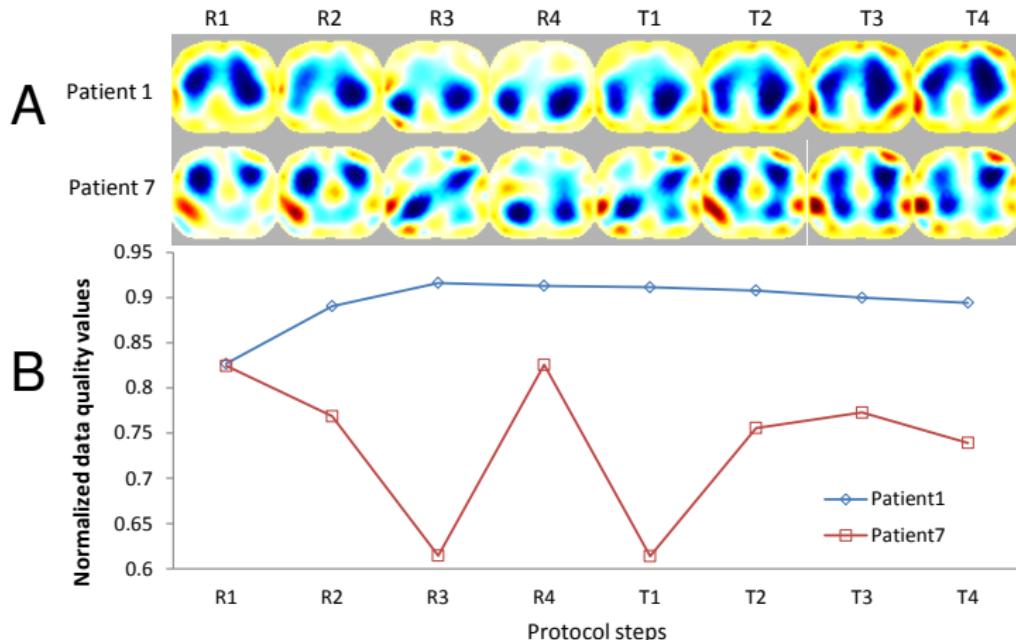
- *Concept:* High Quality Data are Consistent
- *Idea:* Use IP to predict each data point from all others



- 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.

# 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?

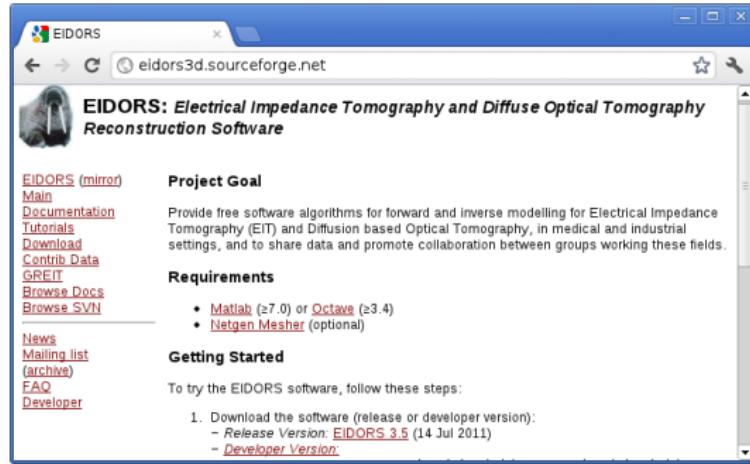


Thus, we need

- Open Data
- Open source analysis

For EIT ...

# For EIT ...

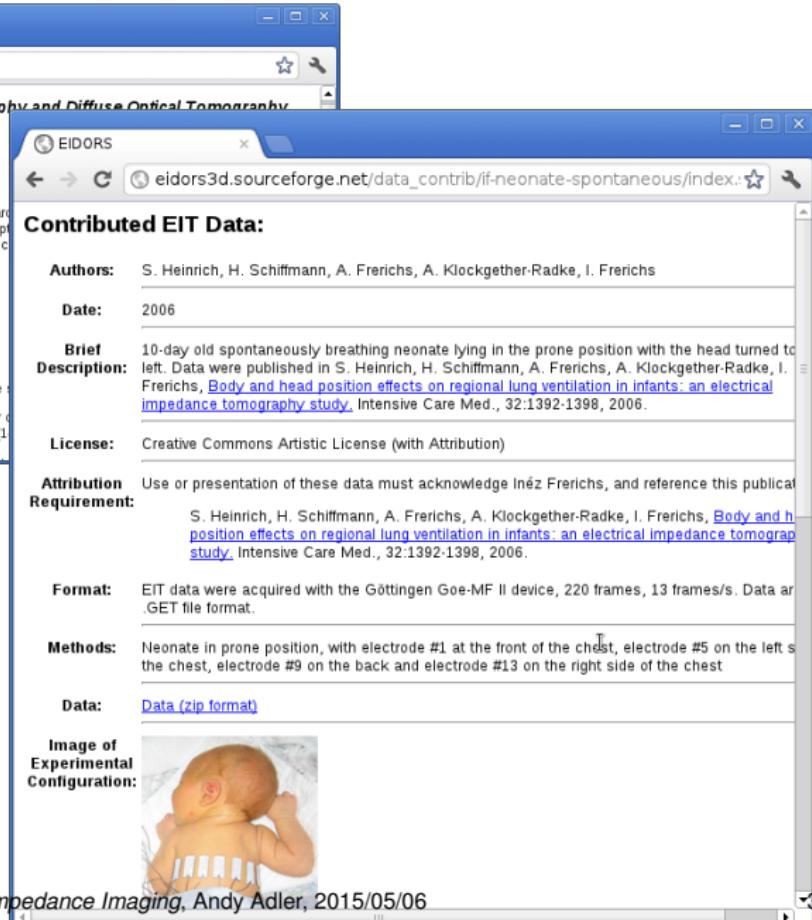


The screenshot shows a web browser window with the URL [eidors3d.sourceforge.net](http://eidors3d.sourceforge.net). The page title is "EIDORS: Electrical Impedance Tomography and Diffuse Optical Tomography Reconstruction Software". On the left, there is a sidebar with links: EIDORS (mirror), Main, Documentation, 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)  
• 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](#)".

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The screenshot shows the EIDORS website at [eidors3d.sourceforge.net](http://eidors3d.sourceforge.net). The page features a logo of a hand holding a probe, followed by the text "EIDORS: Electrical Impedance Tomography and Diffuse Optical Tomography Reconstruction Software". A sidebar on the left contains links for "EIDORS (mirror)", "Main", "Documentation", "Tutorials", "Download", "Contrib Data", "GREIT", "Browse Docs", and "Browse SVN". Below this are links for "News", "Mailing list (archive)", "FAQ", and "Developer". The main content area has sections for "Project Goal", "Requirements" (listing Matlab, Octave, and Netgen Mesh), and "Getting Started" (with instructions to download the software). A numbered list provides download options: 1. Download the software (release or developer version).



The screenshot shows a page titled "Contributed EIT Data:" from the same website. It lists the following details:

<b>Authors:</b>	S. Heinrich, H. Schiffmann, A. Frerichs, A. Klockgether-Radke, I. Frerichs
<b>Date:</b>	2006
<b>Brief Description:</b>	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, <a href="#">Body and head position effects on regional lung ventilation in infants: an electrical impedance tomography study</a> , Intensive Care Med., 32:1392-1398, 2006.
<b>License:</b>	Creative Commons Artistic License (with Attribution)
<b>Attribution Requirement:</b>	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, <a href="#">Body and head position effects on regional lung ventilation in infants: an electrical impedance tomography study</a> , Intensive Care Med., 32:1392-1398, 2006.
<b>Format:</b>	EIT data were acquired with the Göttingen Goe-MF II device, 220 frames, 13 frames/s. Data are .GET file format.
<b>Methods:</b>	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
<b>Data:</b>	<a href="#">Data (zip format)</a>
<b>Image of Experimental Configuration:</b>	



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*Traffic jam on the way to Carleton*

## Abstract for talk:

### Impedance Imaging of the Thorax: Why its difficult and what we are doing about it

*Abstract:* Electrical impedance tomography (EIT) uses body surface electrical current stimulation and measurements to generate images of the internal tissue electrical impedance. Currently, the most successful application of EIT is for imaging the thorax, where the movement on conductivity contrasting air and blood can be imaged over time. The generation of EIT images requires solving an inverse problem, which is ill-conditioned because of the diffuse nature of current propagation. The technology is thus sensitive to electrode properties, data quality, and patient movement. To address these issues, several innovative strategies to analyze and interpret these data have been developed. This talk will explain our recent progress in imaging the chest with EIT, and the image generation and interpretation strategies that are required.