

# Electrical Impedance Tomography: Applications and Perspectives

BioEM 2014  
Cape Town, South Africa  
11 June 2014

Andy Adler

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

## Outline:

### Electrical Impedance

## Outline:

### Electrical Impedance

Stimulate with current  
measure voltage  
Hz – kHz

## Outline:

Electrical Impedance

Stimulate with current  
measure voltage  
Hz – kHz

Tomography

## Outline:

Electrical Impedance

Stimulate with current  
measure voltage  
Hz – kHz

Tomography

“Seeing within” (Imaging)

## Outline:

Electrical Impedance

Stimulate with current  
measure voltage  
Hz – kHz

Tomography

“Seeing within” (Imaging)

Applications

# Outline:

Electrical Impedance

Stimulate with current  
measure voltage  
Hz – kHz

Tomography

“Seeing within” (Imaging)

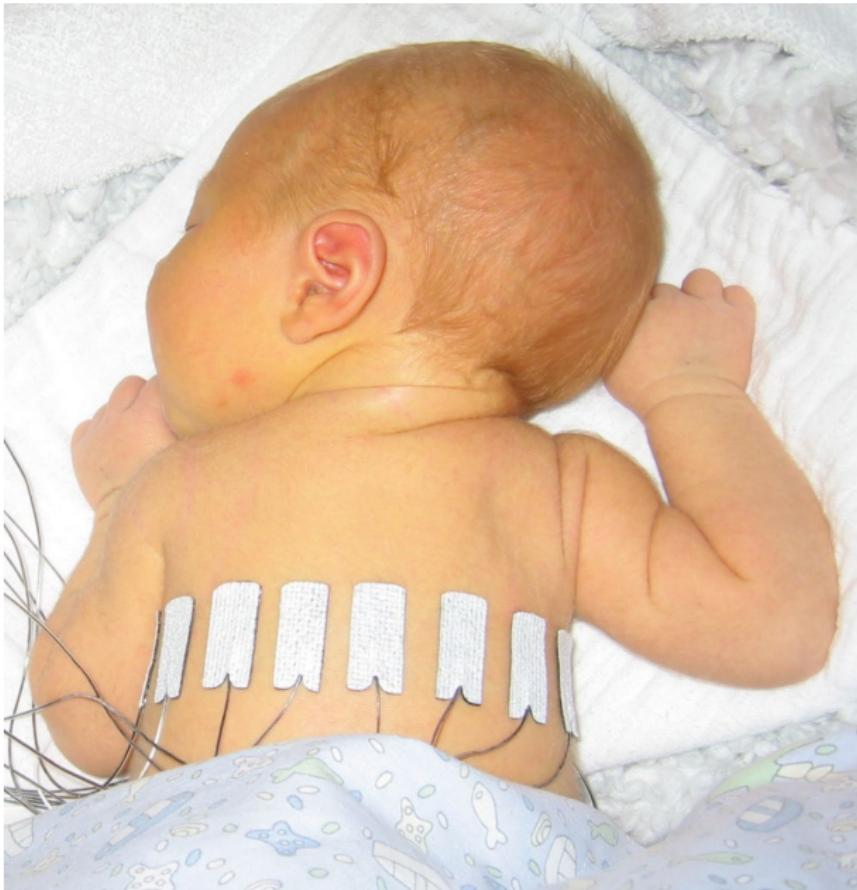
Applications

Perspectives

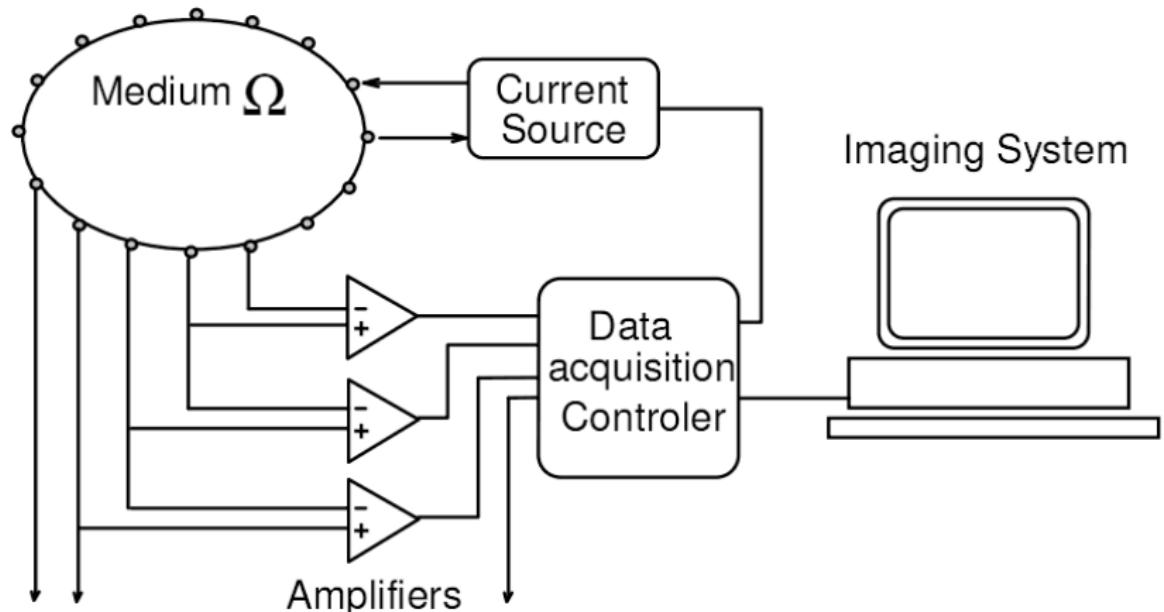
# Electrical Impedance Tomography

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 slice at heart

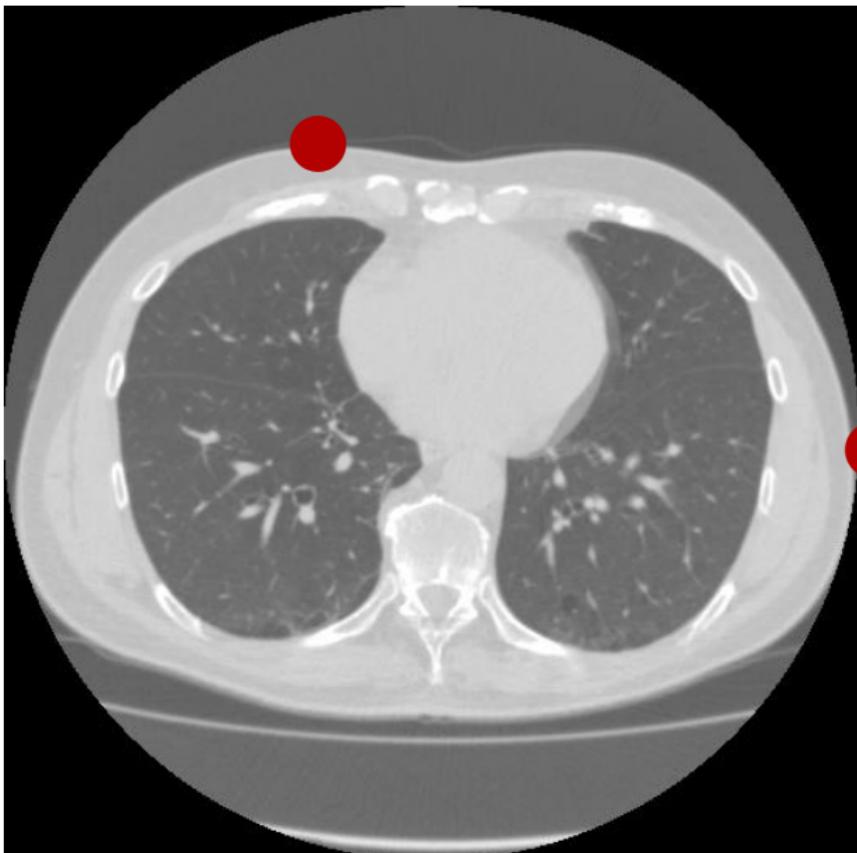
Source: ei-  
[dors3d.sf.net/tutorial/netgen/extrusion](http://dors3d.sf.net/tutorial/netgen/extrusion)



# Current Propagation

Healthy Adult Male  
CT slide at heart

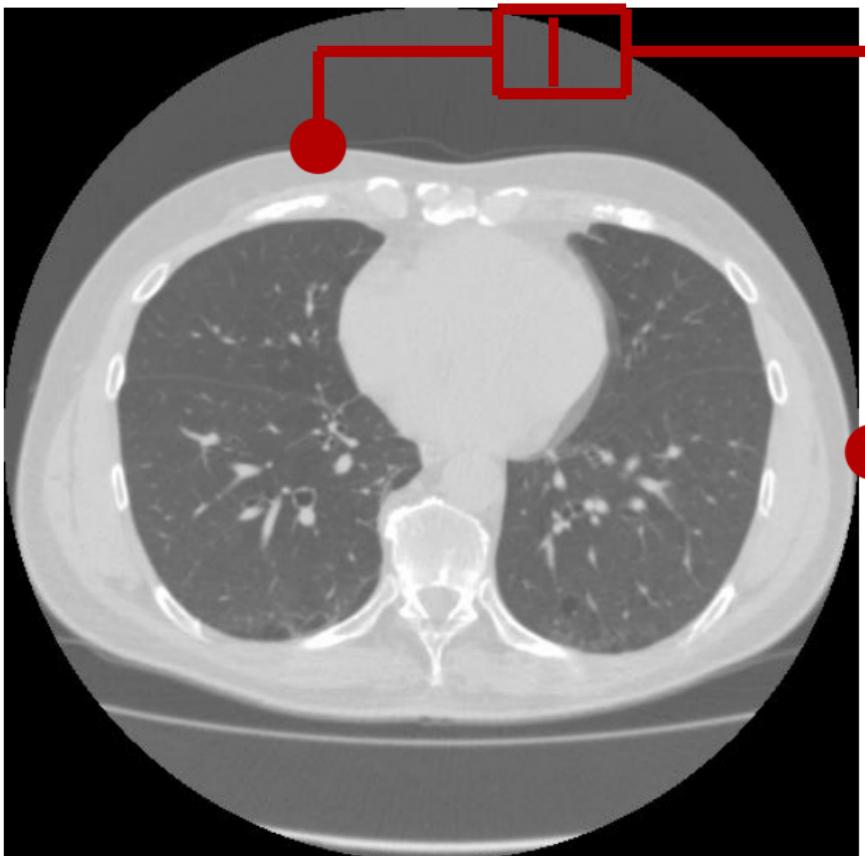
Source: ei-  
[dors3d.sf.net/tutorial/netgen/extrusion](http://dors3d.sf.net/tutorial/netgen/extrusion)



# Current Propagation

Healthy Adult Male  
CT slide at heart

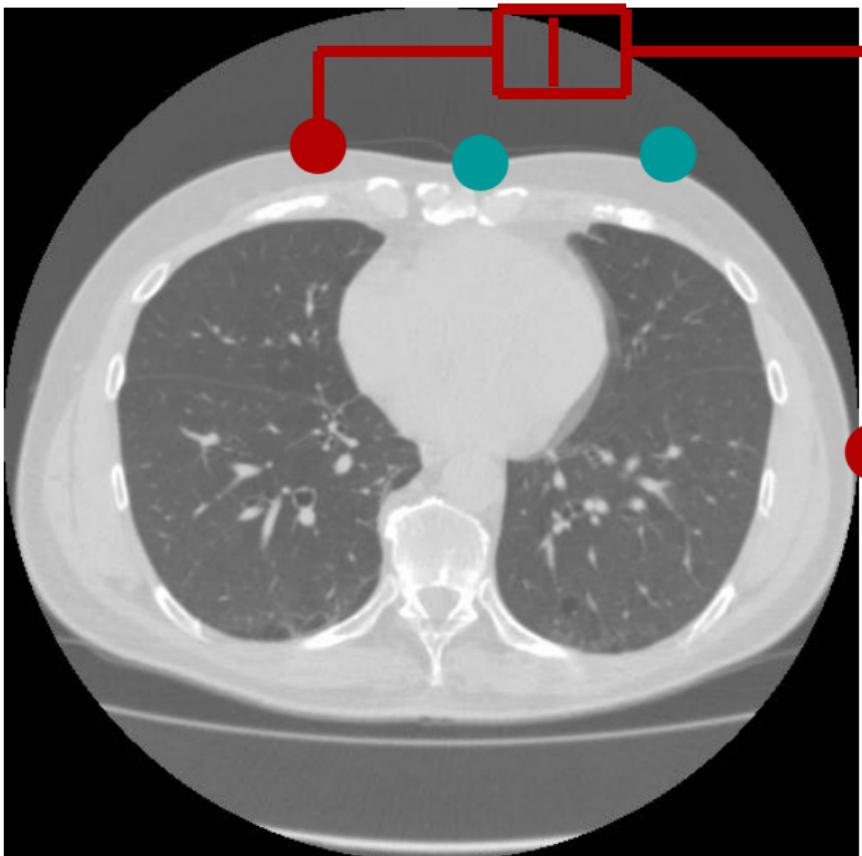
Source: ei-  
[dors3d.sf.net/tutorial/netgen/extrusion](http://dors3d.sf.net/tutorial/netgen/extrusion)



# Current Propagation

Healthy Adult Male  
CT slide at heart

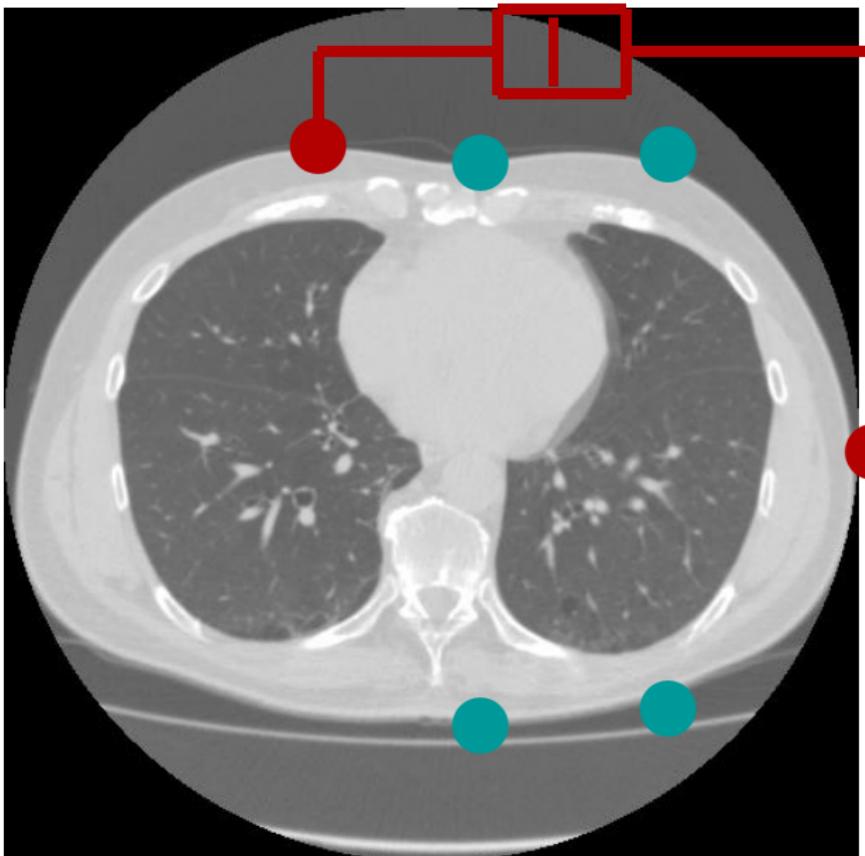
Source: ei-  
[dors3d.sf.net/tutorial/netgen/extrusion](http://dors3d.sf.net/tutorial/netgen/extrusion)



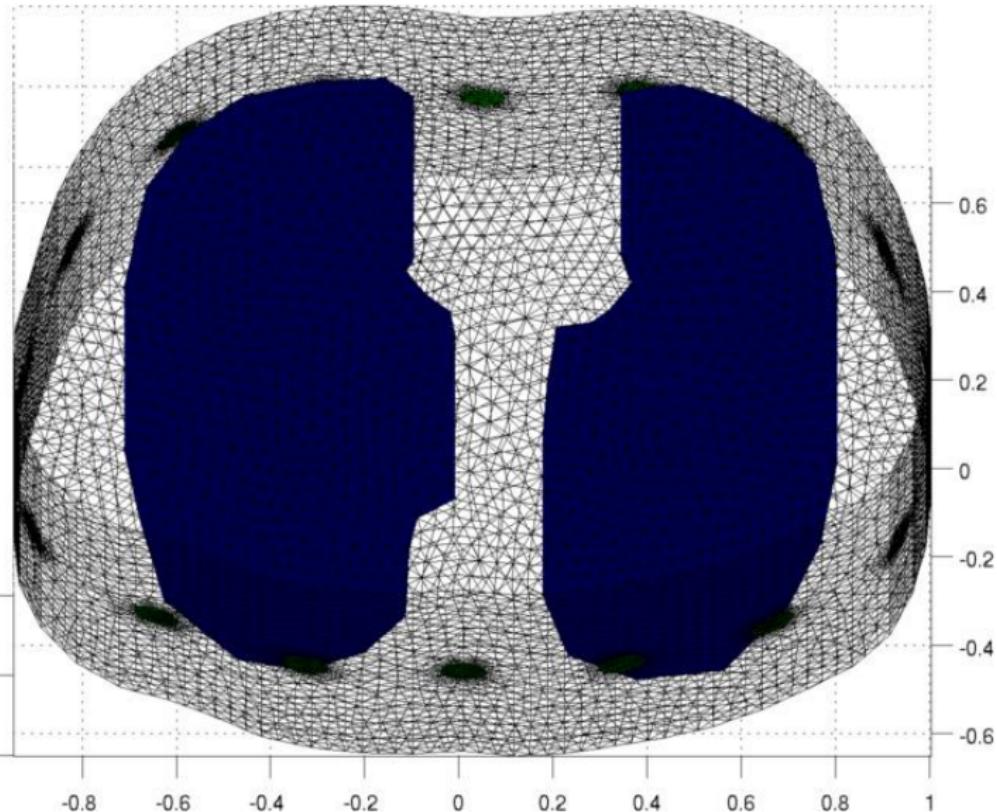
# Current Propagation

Healthy Adult Male  
CT slide at heart

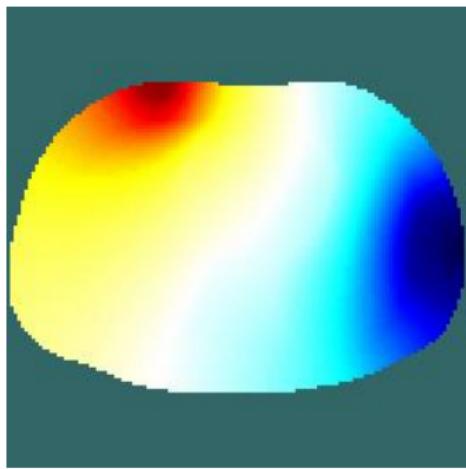
Source: ei-  
[dors3d.sf.net/tutorial/netgen/extrusion](http://dors3d.sf.net/tutorial/netgen/extrusion)



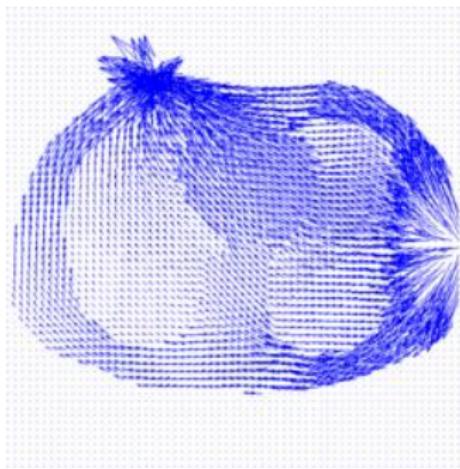
# Finite Element Modelling



# Finite Element Modelling



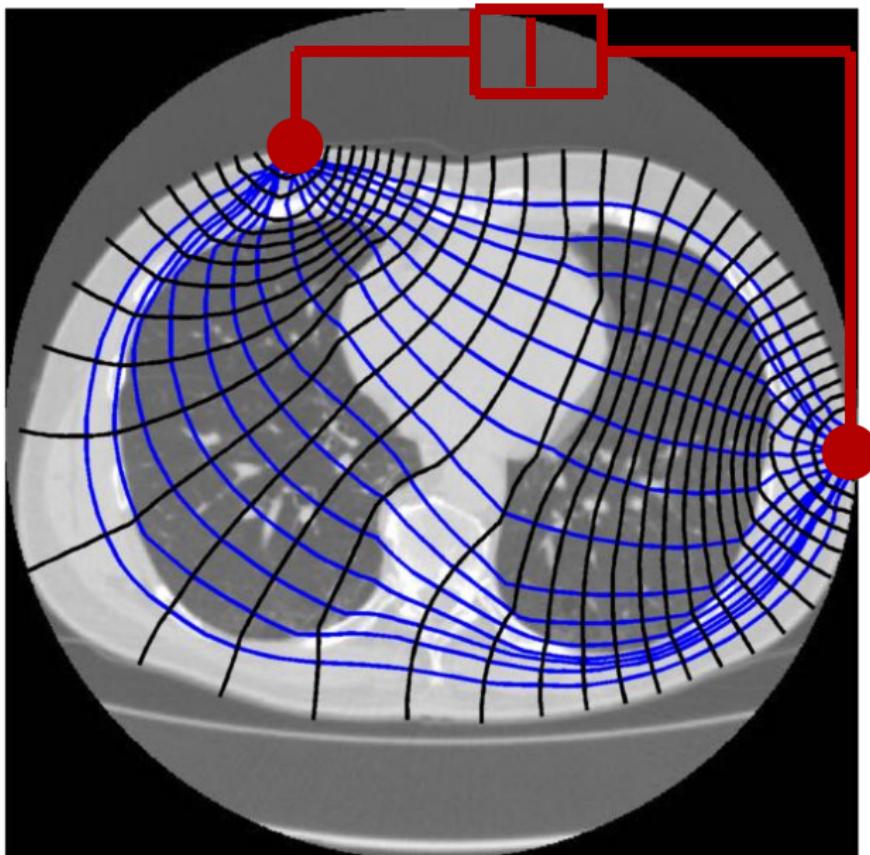
Simulated Voltages



Voxel Currents

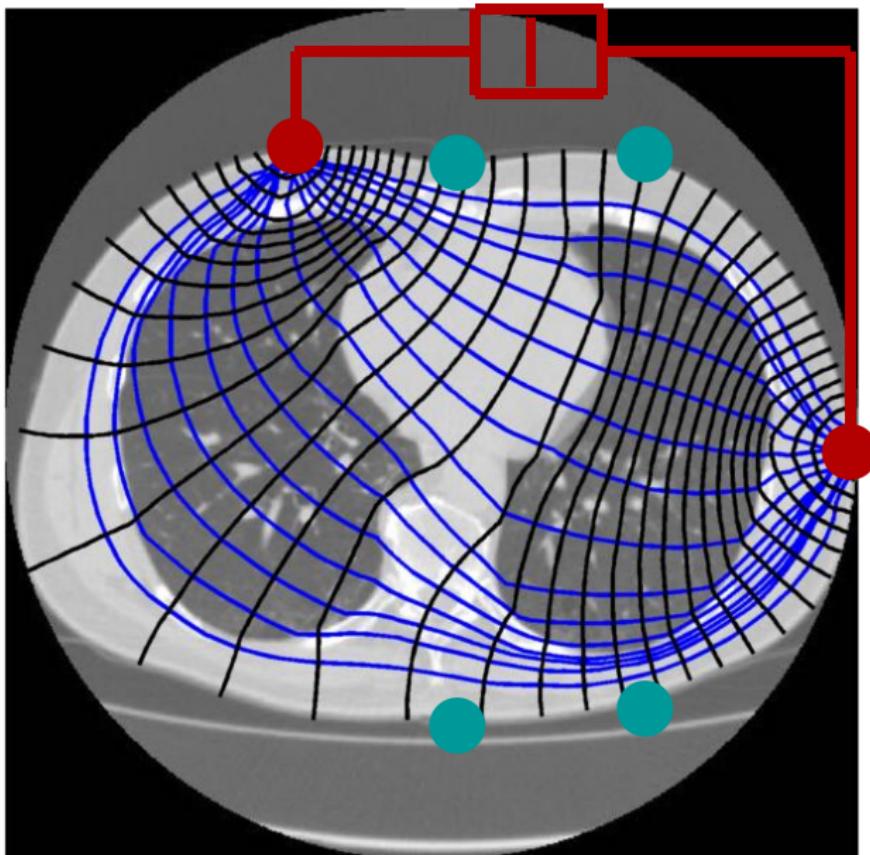
## Thorax Propagation

CT Slice with  
simulated current  
streamlines and  
voltage  
equipotentials



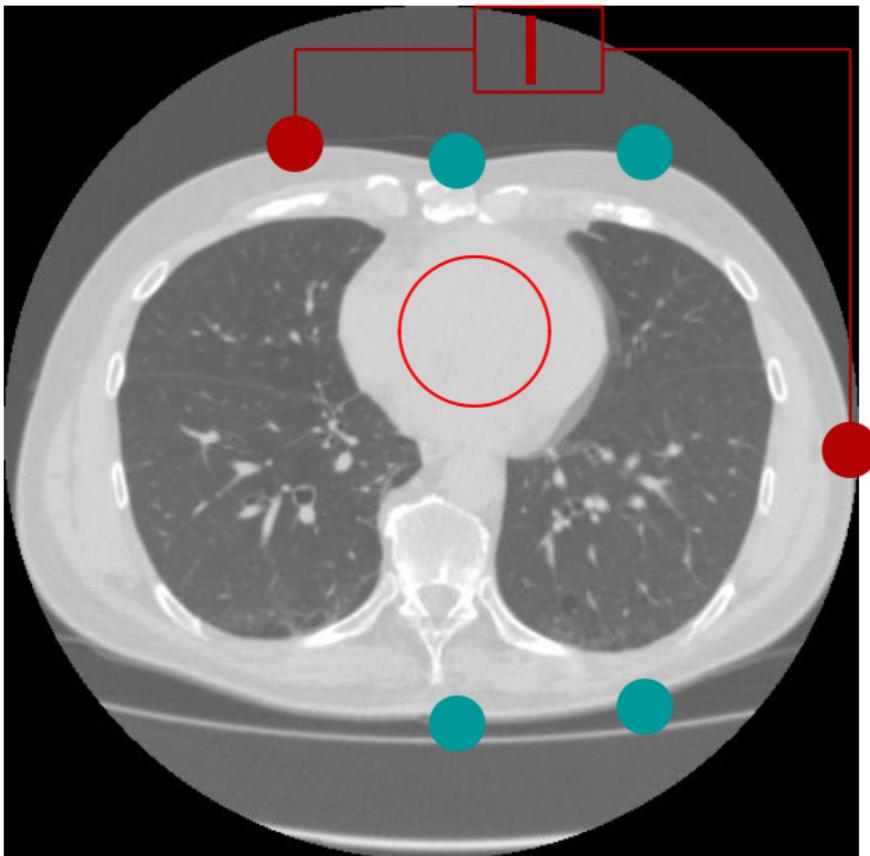
# Thorax Propagation

CT Slice with  
simulated current  
streamlines and  
voltage  
equipotentials



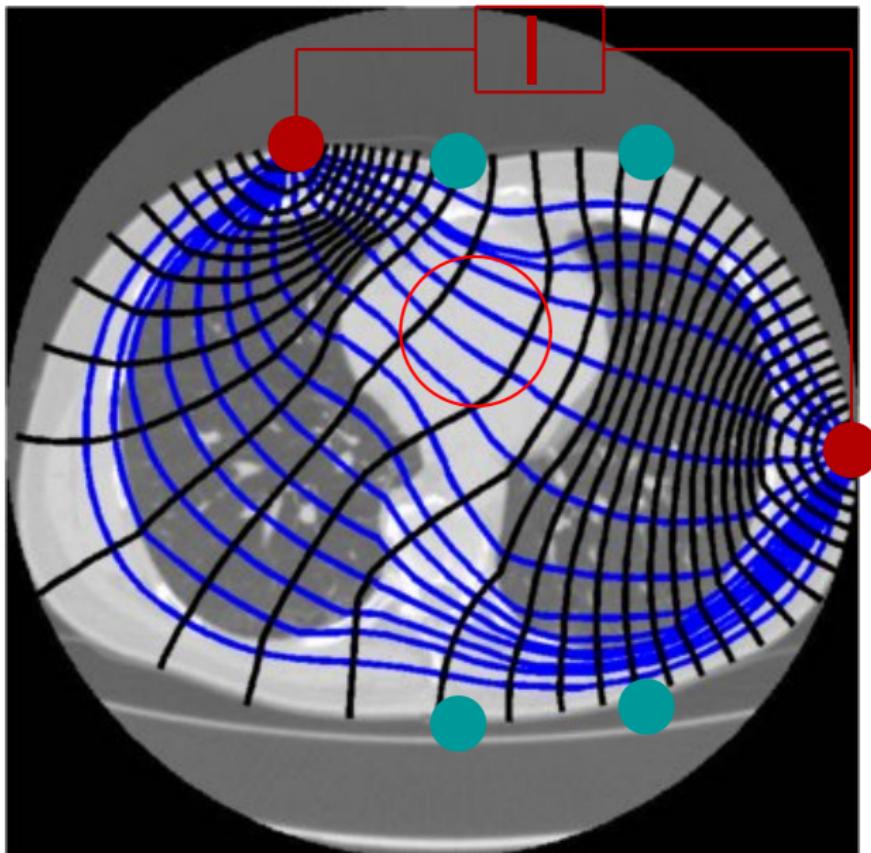
# Changing Conductivity

Heart receives blood (diastole) and is more conductive

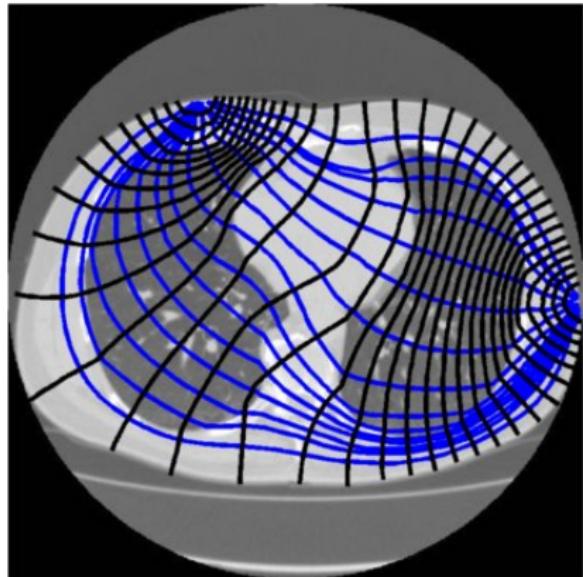
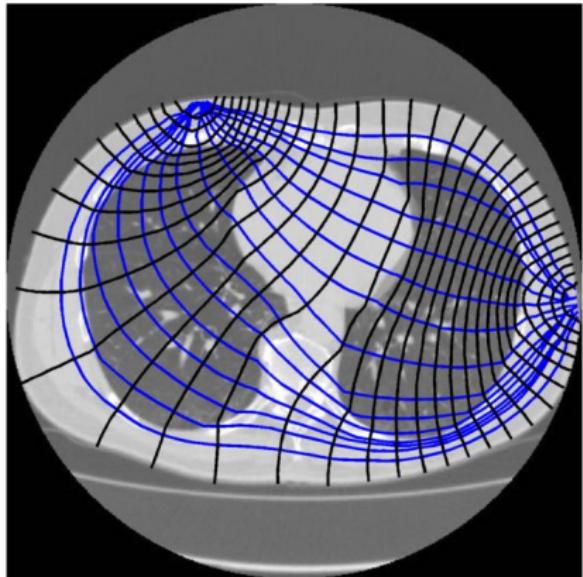


# Changing Conductivity

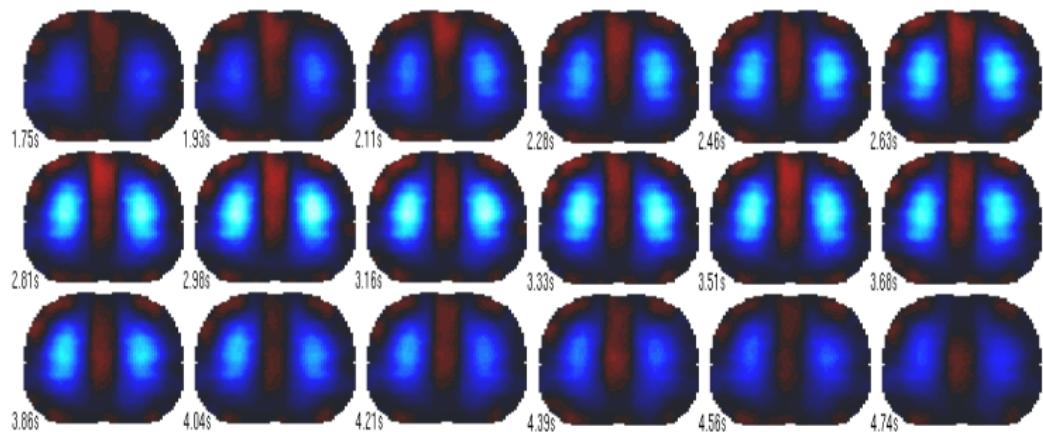
Heart receives blood (diastole) and is more conductive



# Changing Conductivity

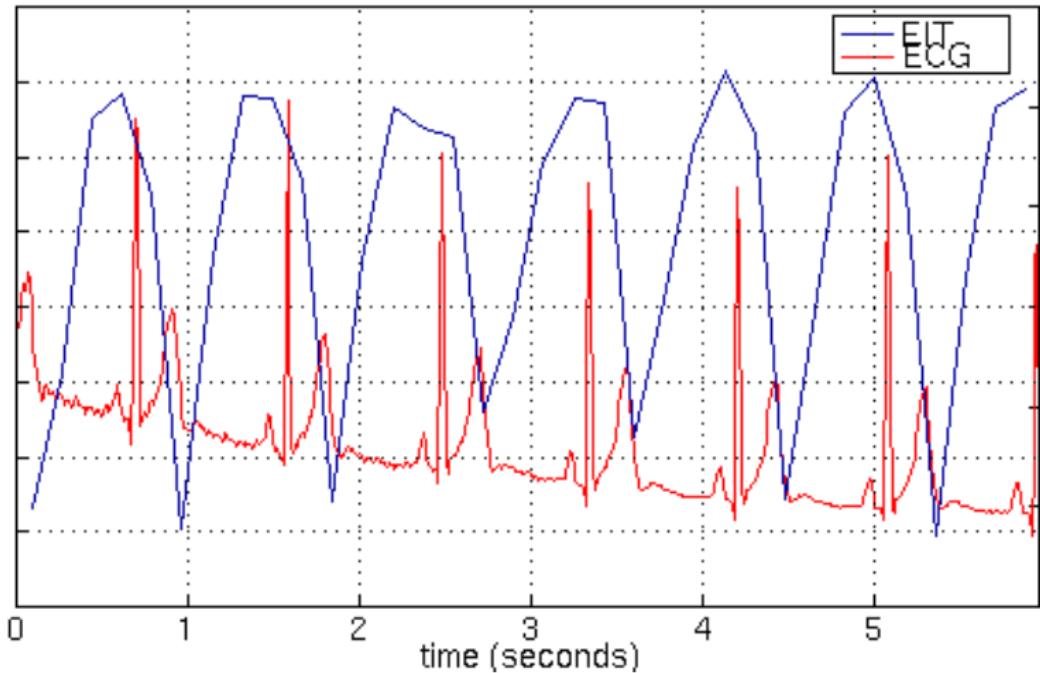


## Application: Breathing



Chest images of tidal breathing in healthy adult

## Application: Heart



EIT Signal in ROI around heart (and ECG)

## 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

## 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

### Treatment

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

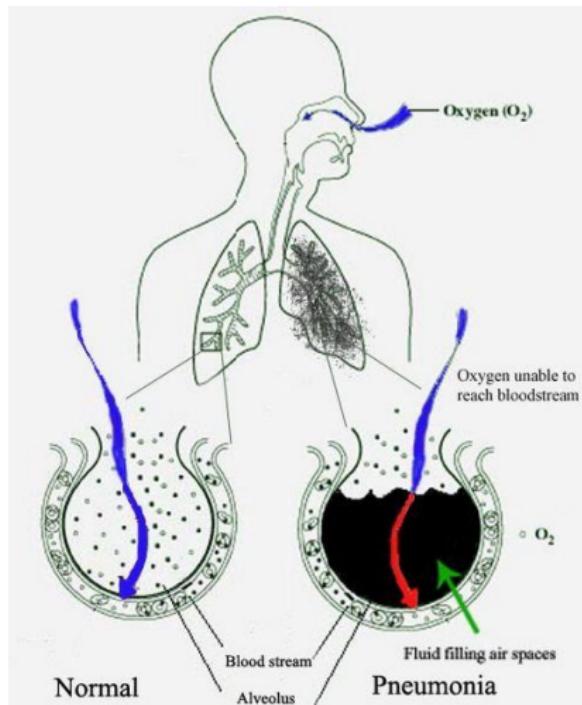
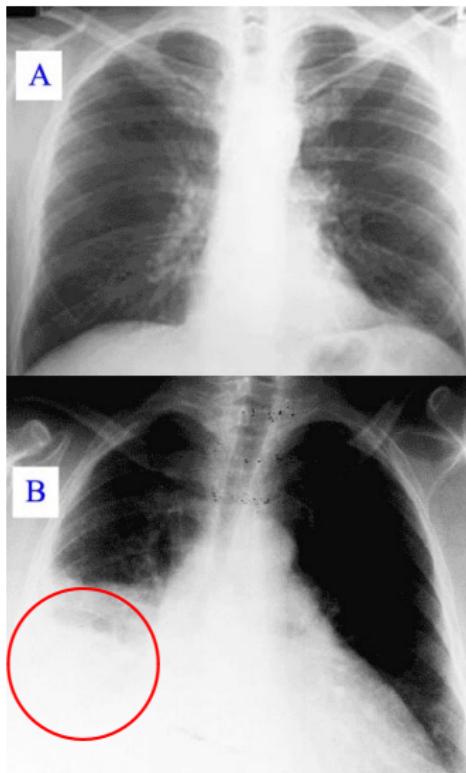
# Mechanical Ventilation



Mechanical Ventilator with EIT monitor

Source: [Swisstom.com](http://Swisstom.com)

# Why image lungs? Example: Pneumonia

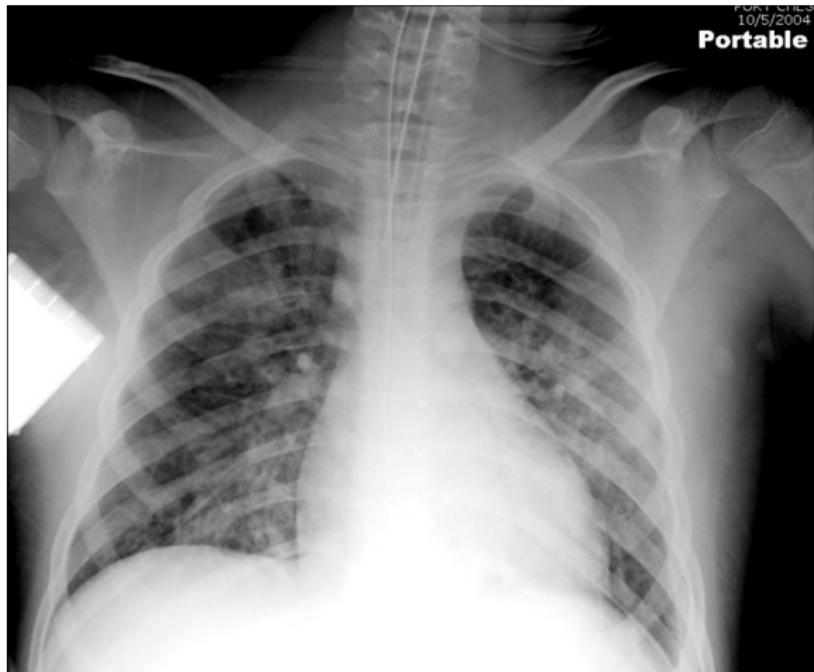


B: fluid in right lung

# Acute Respiratory Distress Syndrome (ARDS)

Chest X-ray of  
paediatric patient

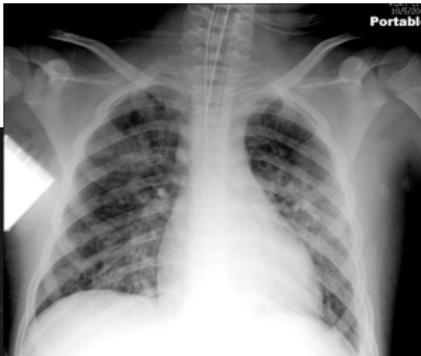
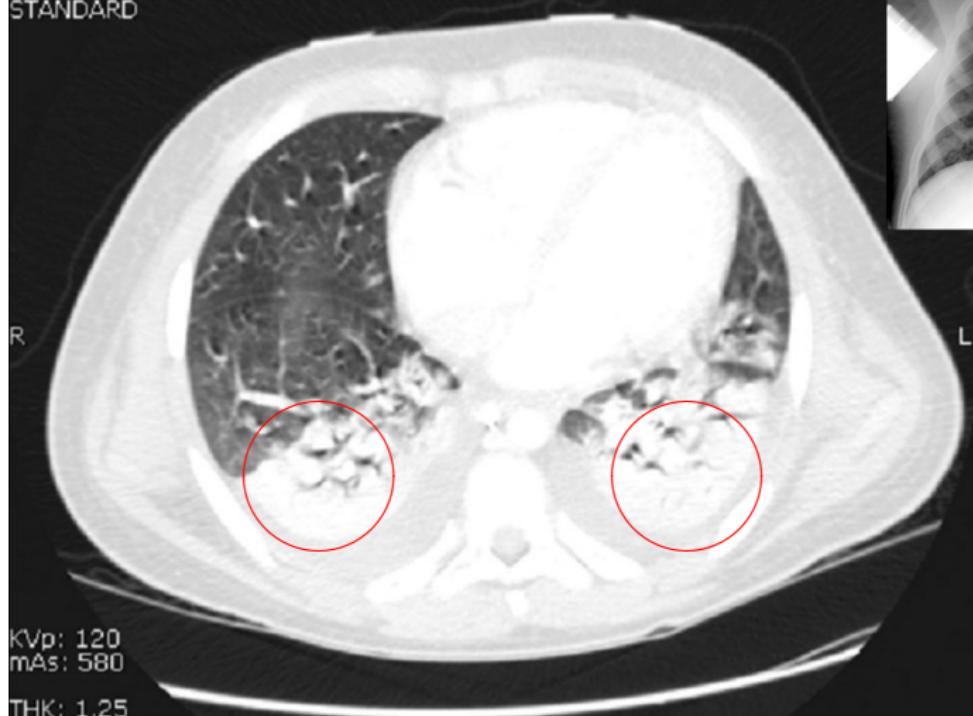
Source: Wolf GK, Arnold JH, in



*Yearbook of Intensive Care and  
Emergency Medicine, 2005*

# Acute Respiratory Distress Syndrome (ARDS)

STANDARD



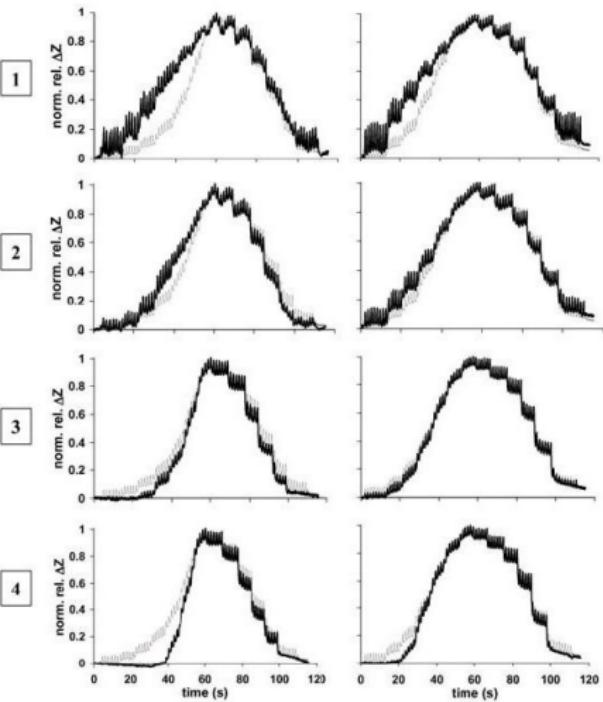
# Regional Ventilation

Electrical impedance tomography

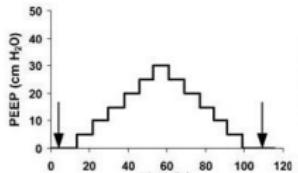
Acute lung injury

Surfactant treatment

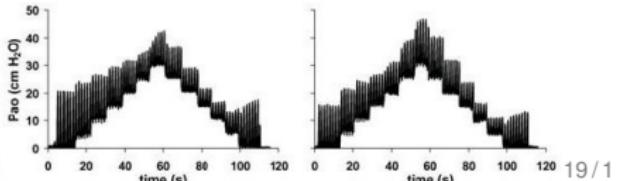
Regions of interest



Ventilatory manoeuvre



Airway pressure

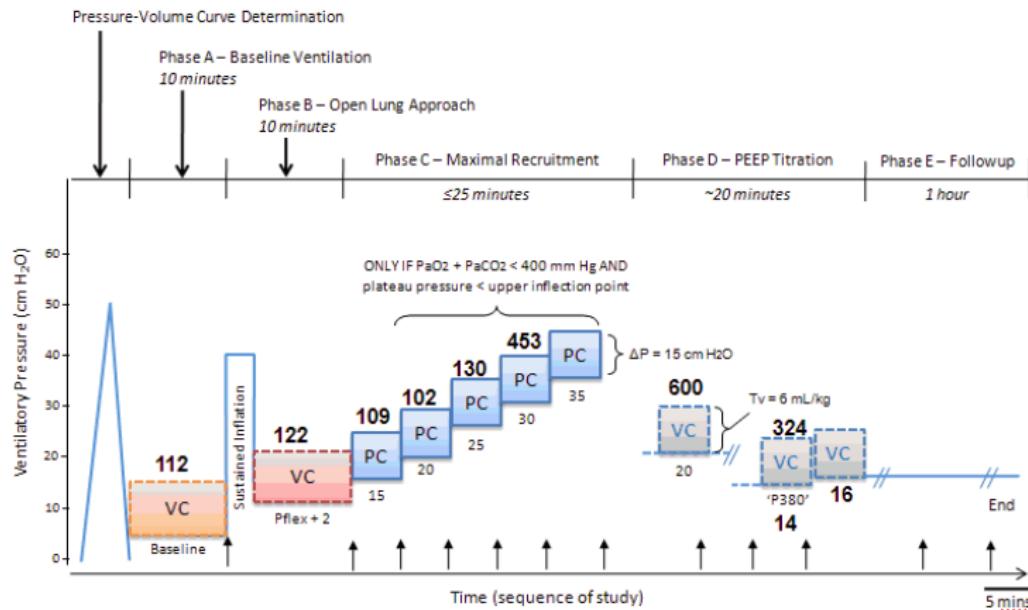


Source: Frerichs *et al*,  
Intensive Care Med,  
2003

[eidors3d.sf.net/tutorial/lung\\_EIT/if.c](http://eidors3d.sf.net/tutorial/lung_EIT/if.c)

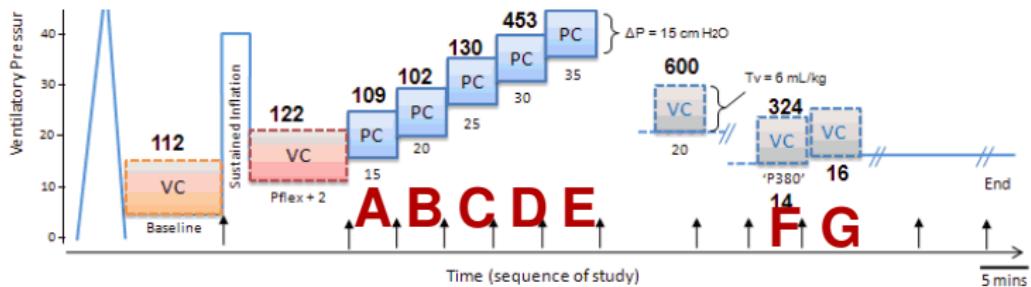
# EIT in ARDS

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

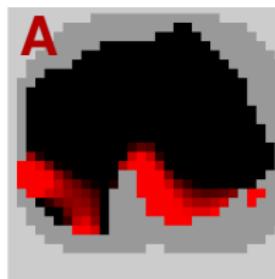
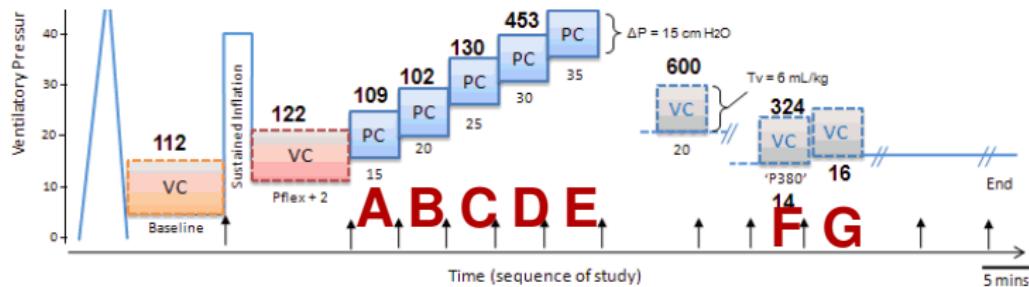


Lung recruitment protocol (Patient: F, 5.9 years, 20 kg, ARDS triggered by parainfluenza pneumonia).

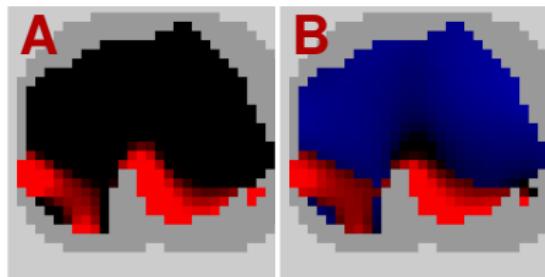
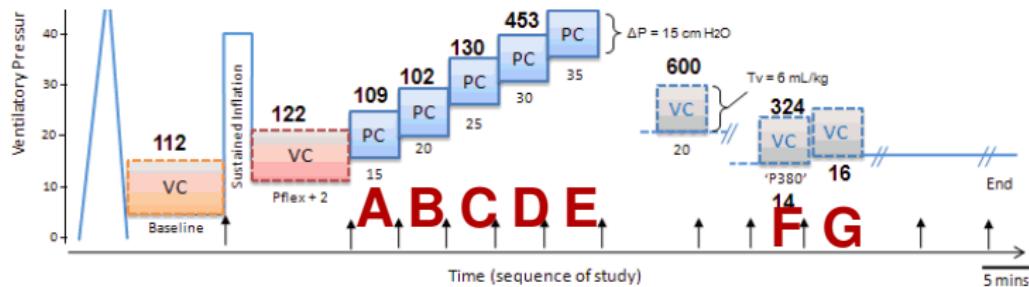
# EIT + Lung State



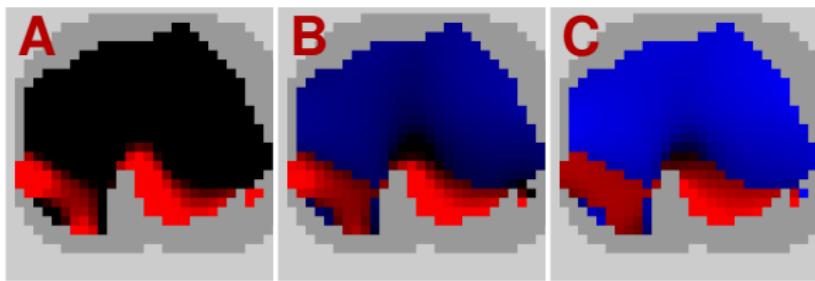
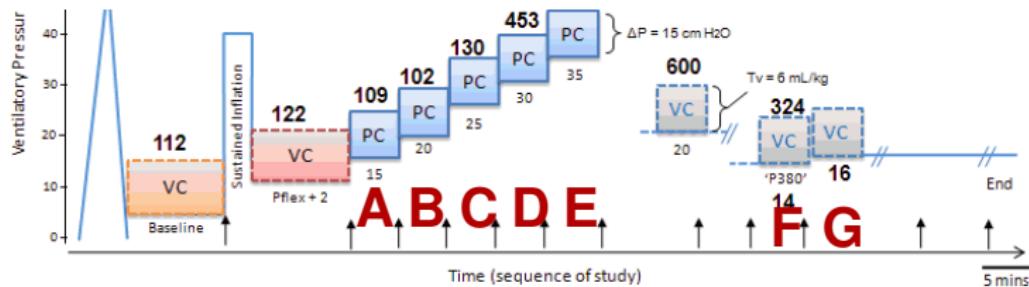
# EIT + Lung State



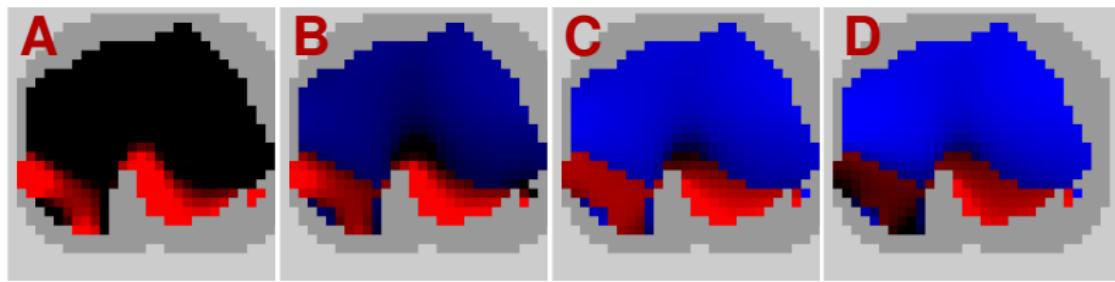
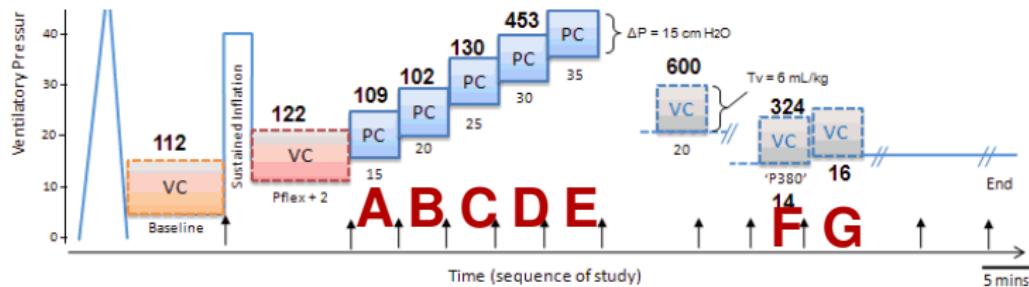
# EIT + Lung State



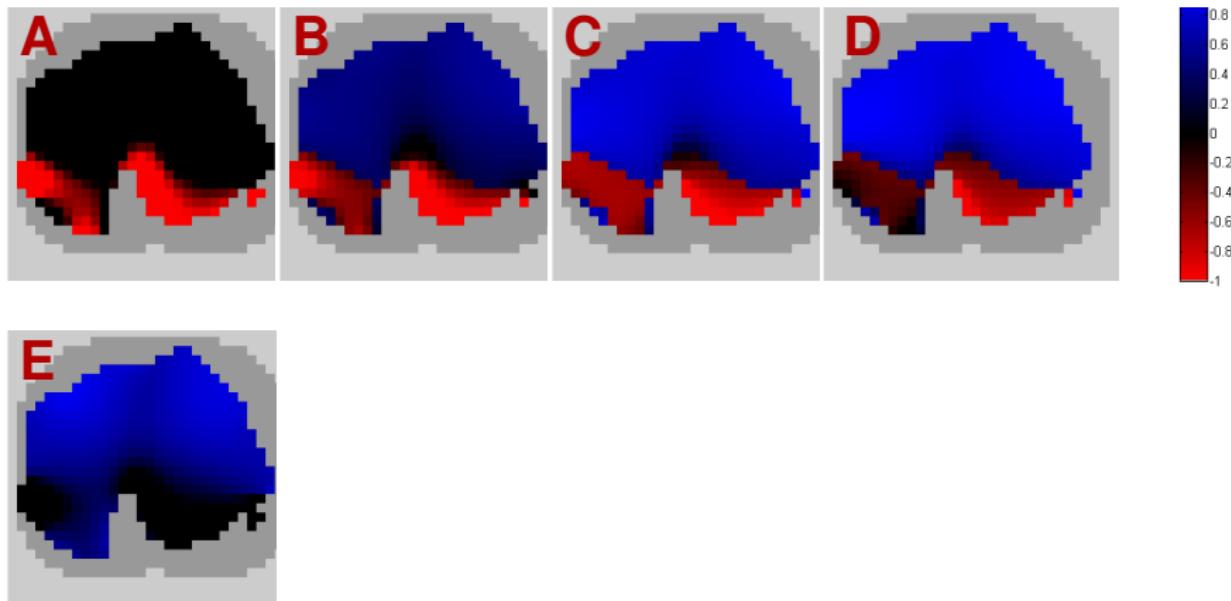
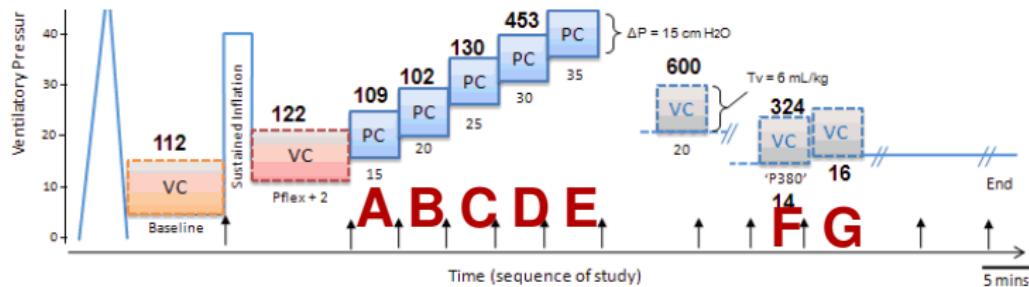
# EIT + Lung State



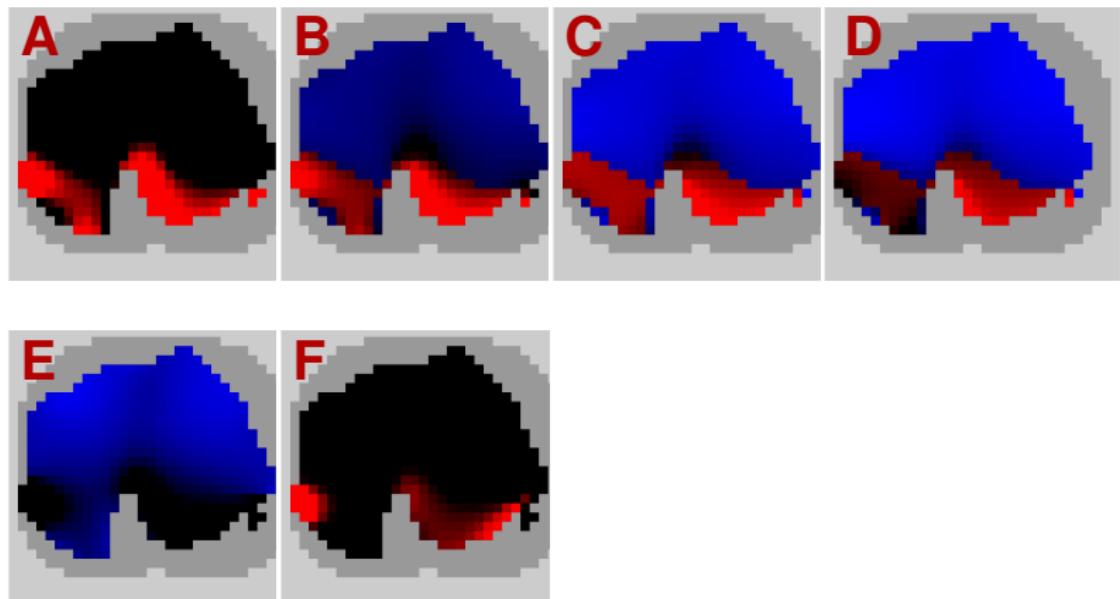
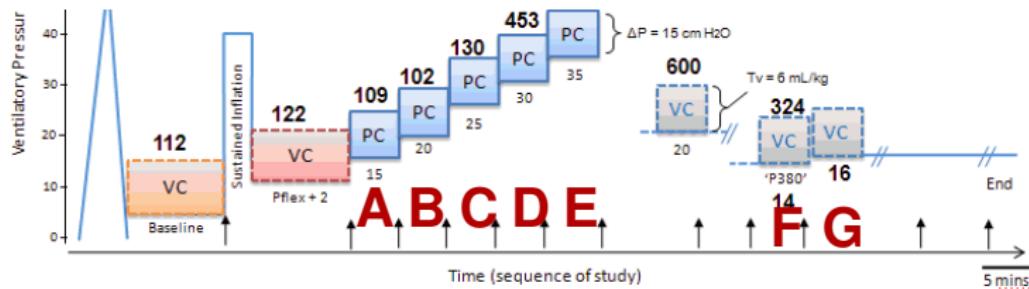
# EIT + Lung State



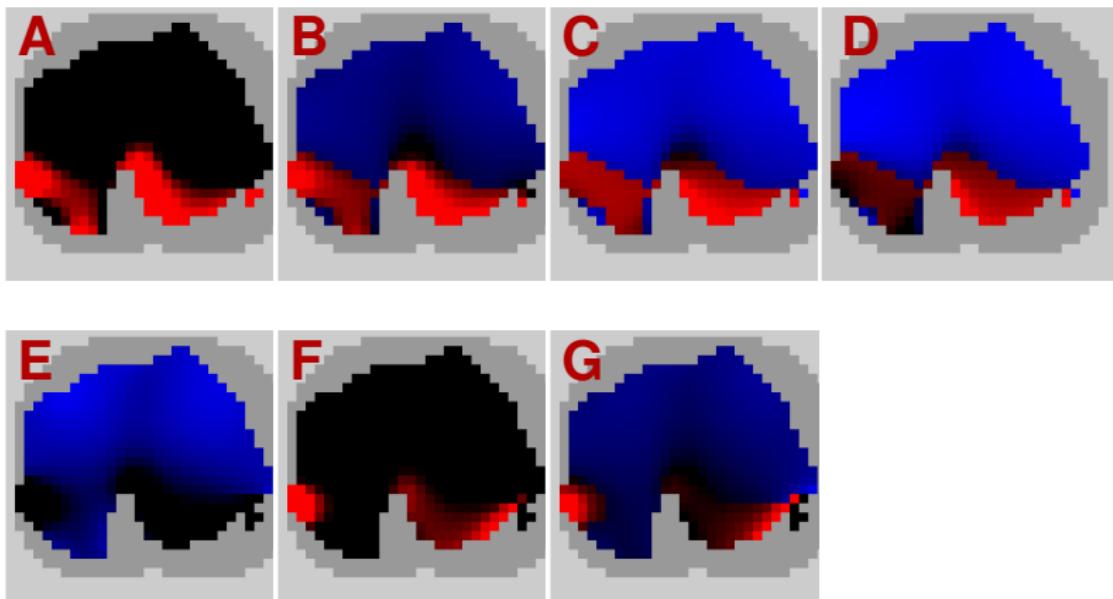
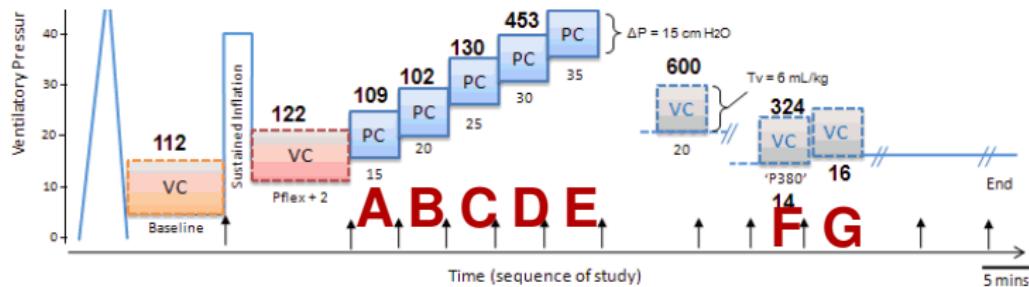
# EIT + Lung State



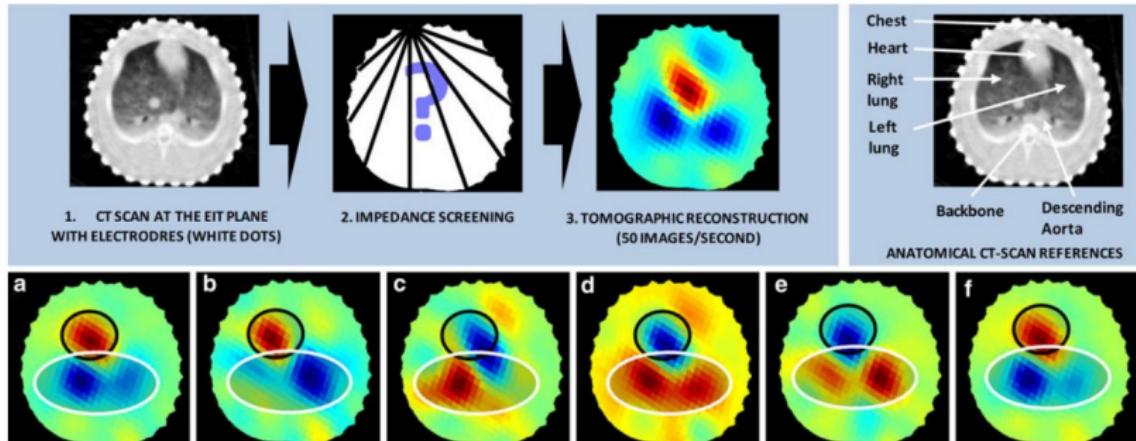
# EIT + Lung State



# EIT + Lung State



# EIT for Non-Invasive Blood Pressure



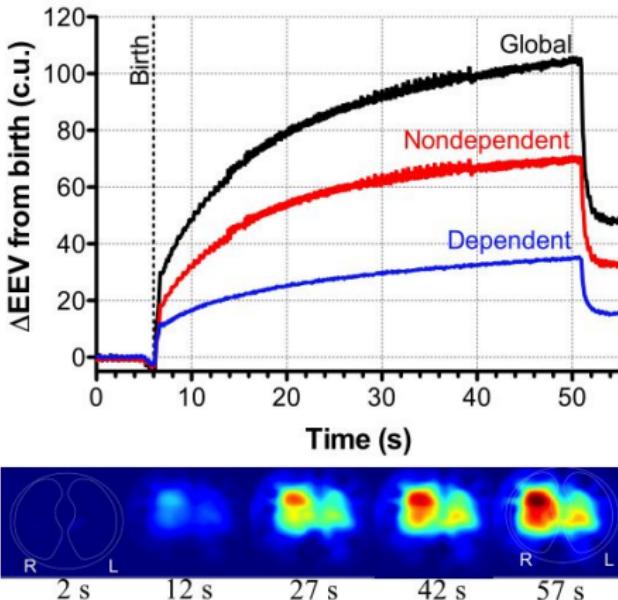
**Fig. 1** Tracking the propagation of arterial pressure pulses by EIT:  
After placing several electrodes around the chest (1), impedance measurements are performed for each electrode pair (2) and used to construct a tomographic impedance image (3). A CT-scan of pig chest is provided as anatomical reference.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

# 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

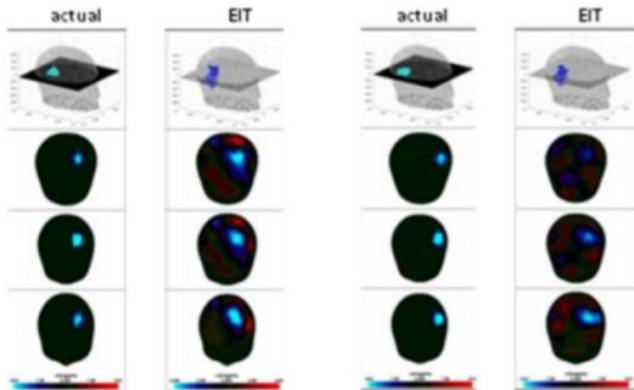
# EIT for Brain Imaging

## Applications:

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



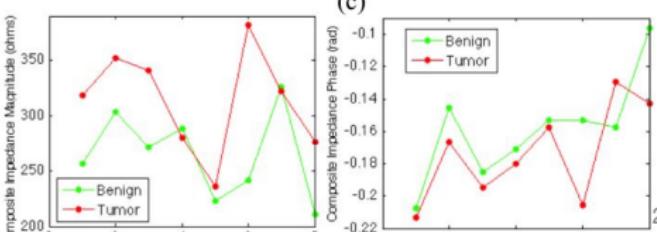
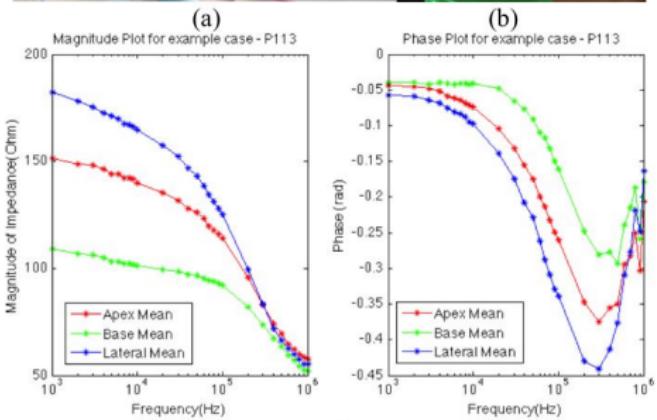
Fig. 2. Left : Finite element of the head used to produce images. Right: Example of EIT images produced in a saline filled tank



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

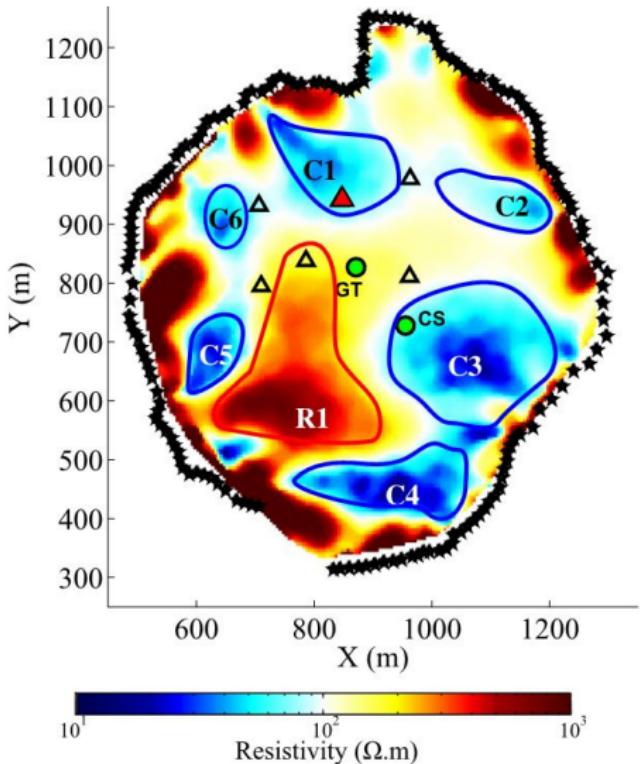


Figure shows resistivity in a cross-section of La Soufrière de Guadeloupe volcano.

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)" is combined with "noise" to produce the final output.

# Reconstruction in Pictures

- Forward Problem

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

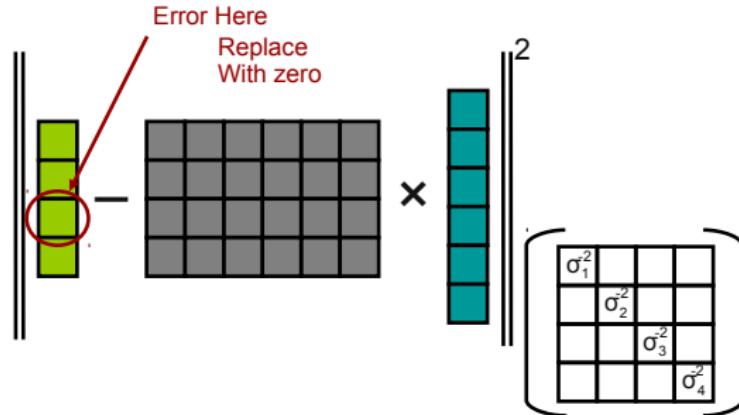
- Linear Solution: Minimize norm

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

Norm weighted by measurement accuracy

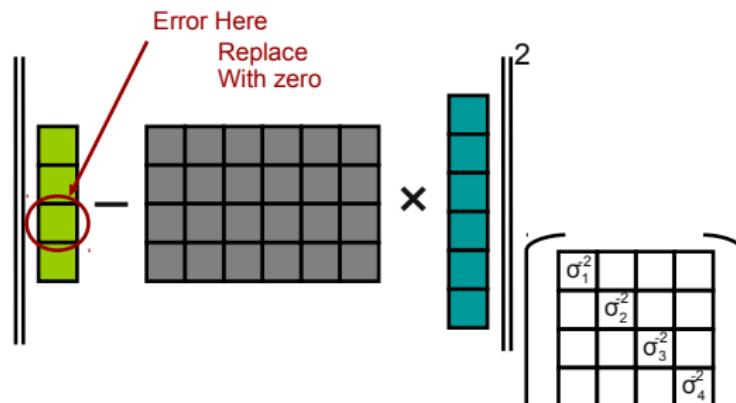
# Idea #1: Reconstruction with Data Errors

“Traditional”  
Solution

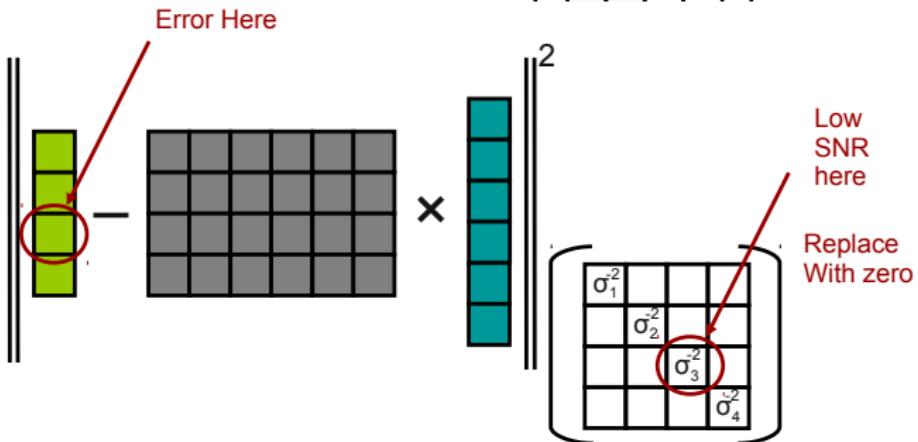


# Idea #1: Reconstruction with Data Errors

“Traditional”  
Solution

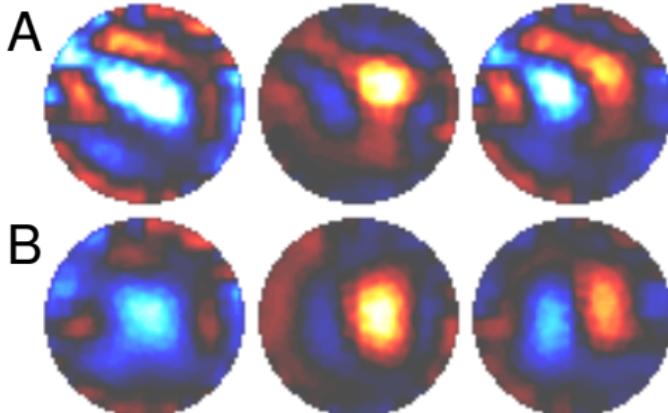


Error Model  
Solution



## 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

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

Jacobian now includes measurement change due to movement

"image" now includes x,y sensor movement

The diagram illustrates a mathematical model for sensor movement. On the left, a vertical bar composed of three green squares is followed by an equals sign. To the right of the equals sign is a gray grid divided into a 3x5 matrix of smaller squares. To the right of the grid is a multiplication sign. To the right of the multiplication sign is another vertical bar composed of three squares, where the top two are blue and the bottom one is light blue. To the right of this bar is a plus sign and the word "noise". Below the grid, red text states "Jacobian now includes measurement change due to movement" with a red arrow pointing to the grid. Below the second vertical bar, red text states "'image' now includes x,y sensor movement" with a red arrow pointing to the second vertical bar.

## Idea #2: Electrode movement

Sensitivity to  
sensor  
movement

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

Jacobian now includes  
measurement change  
due to movement

"image" now includes  
x,y sensor movement

Adapted  
penalty  
function

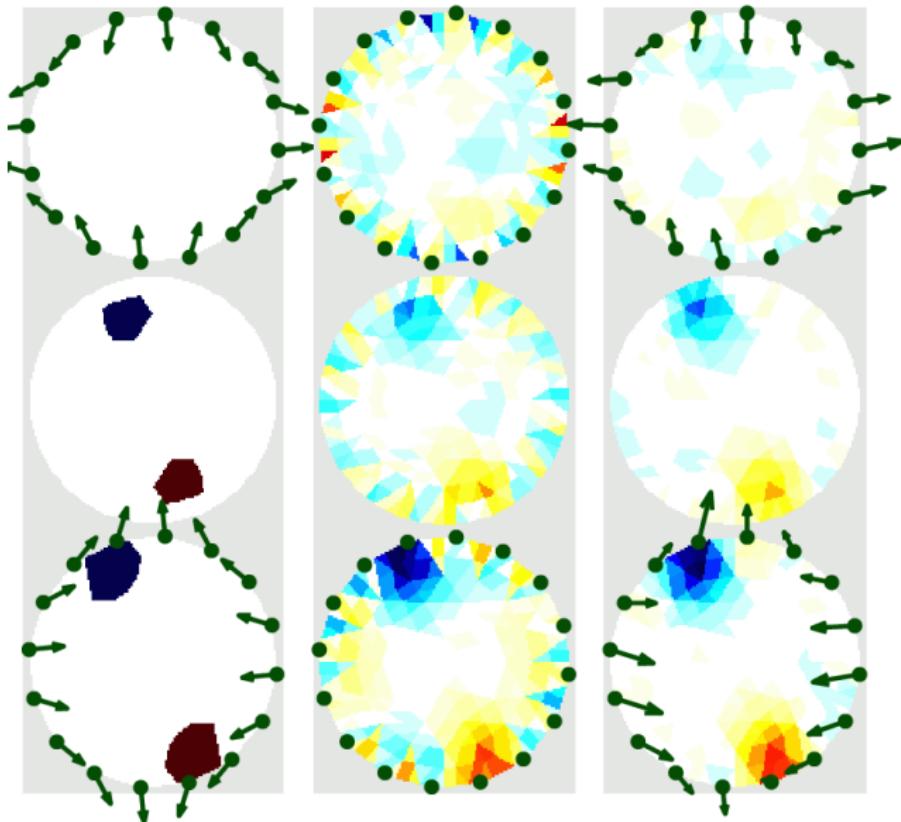
$$\left\| \begin{matrix} \text{blue bar} \\ - \end{matrix} \begin{matrix} \text{Expected image} \\ \text{---} \\ \text{Expected movement} \end{matrix} \right\|^2$$

*Unlikelyhood* of movement and image co-variance

*Unlikelyhood* of movement

1	$-\frac{1}{2}$		
$-\frac{1}{2}$	1	$-\frac{1}{2}$	
$-\frac{1}{2}$	1	$-\frac{1}{2}$	
$-\frac{1}{2}$	1	$-\frac{1}{2}$	
$-\frac{1}{2}$	1	$-\frac{1}{2}$	
$-\frac{1}{2}$	1	$-\frac{1}{2}$	
$-\frac{1}{2}$	1	$-\frac{1}{2}$	
$-\frac{1}{2}$	1	$-\frac{1}{2}$	

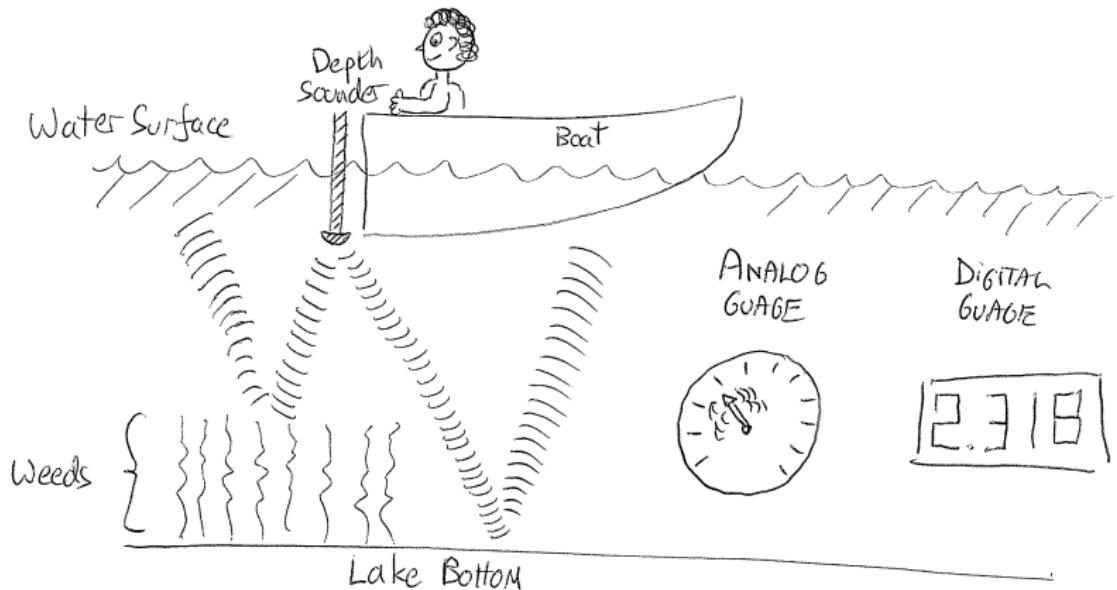
## Electrode movement compensation



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?

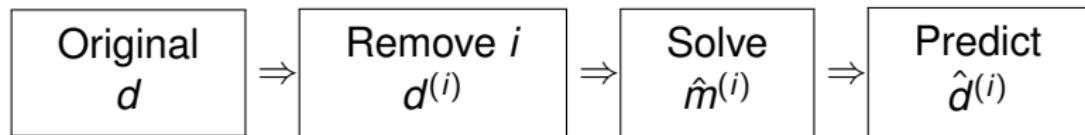
With strong priors and complex algorithms, algorithms give us pretty pictures, even when they are irrelevant.

*Question:*

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

# Data Quality Measure: Concept

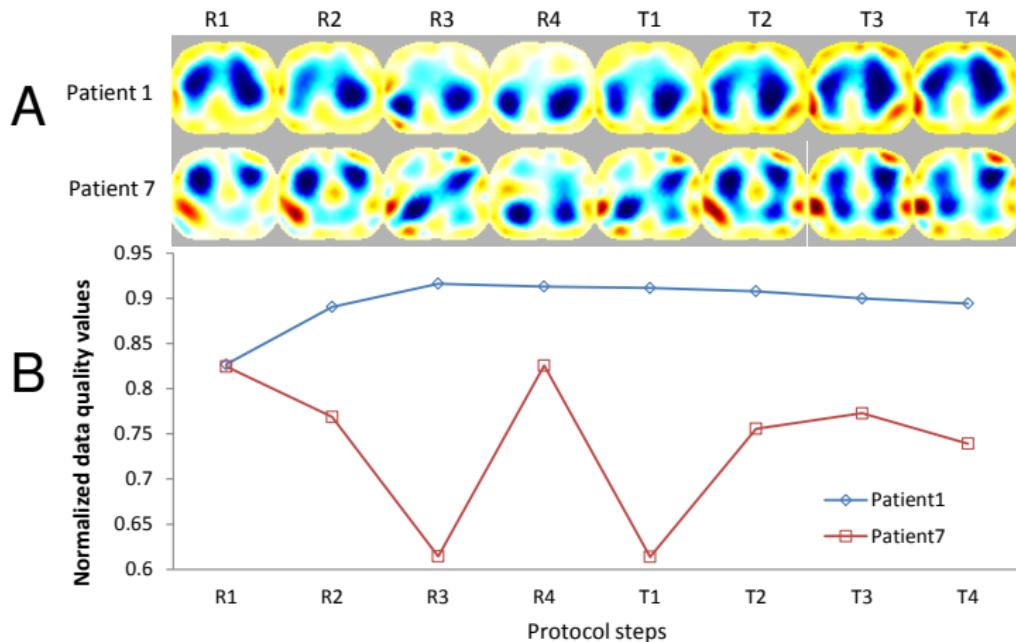
- *Concept:* High Quality Data is Consistent
- *Idea:* Use IP to predict each data point from all others



- Calculate error

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

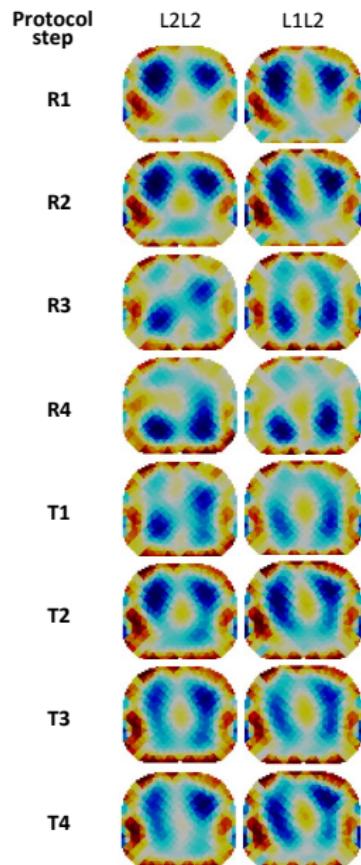
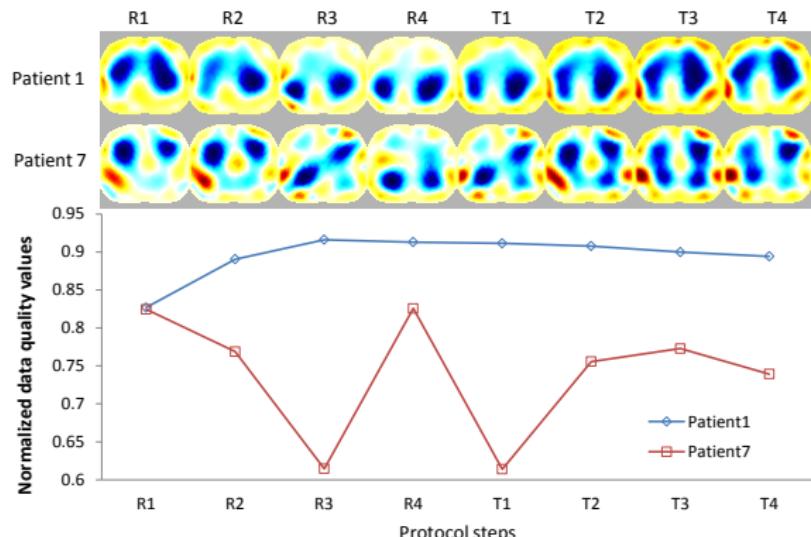
## Example: Data quality measures



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?

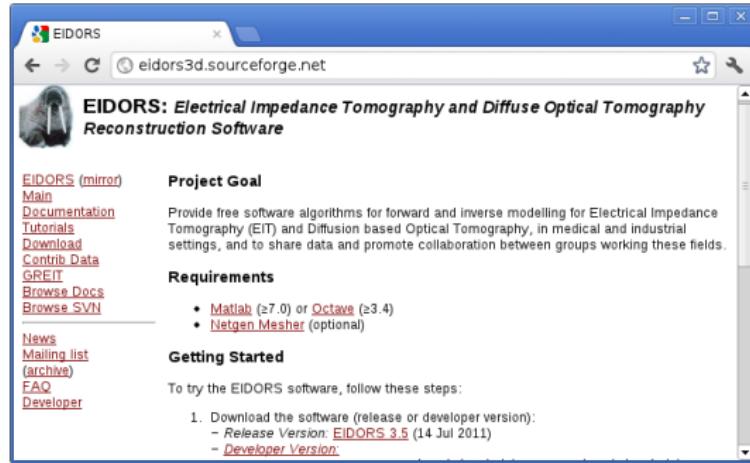


Thus, we need

- Open Data
- Open source analysis

For EIT ...

# For EIT ...



The screenshot shows a Microsoft Internet Explorer window displaying the EIDORS website at [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 to "EIDORS (mirror)", "Main", "Documentation", "Tutorials", "Download", "Contrib Data", "GREIT", "Browse Docs", and "Browse SVN". Below this is a news section with links to "News", "Mailing list (archive)", "FAQ", and "Developer". The main content area has sections for "Project Goal" (describing free software for EIT and DOT), "Requirements" (listing Matlab/Octave and Netgen Meshes), and "Getting Started" (instructions to download the software). A sidebar on the right contains a search bar and navigation links.

EIDORS (mirror)

Main

Documentation

Tutorials

Download

Contrib Data

GREIT

Browse Docs

Browse SVN

---

News

Mailing list (archive)

FAQ

Developer

**EIDORS: Electrical Impedance Tomography and Diffuse Optical Tomography Reconstruction Software**

**Project Goal**

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.

**Requirements**

- [Matlab](#) ( $\geq 7.0$ ) or [Octave](#) ( $\geq 3.4$ )
- [Netgen Meshes](#) (optional)

**Getting Started**

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](#):

# 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.

**License:** Creative Commons Artistic License (with Attribution)

**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:**



# Thank you



Traffic jam near my university