# Electrical Impedance Tomography: Image Algorithms and Applications

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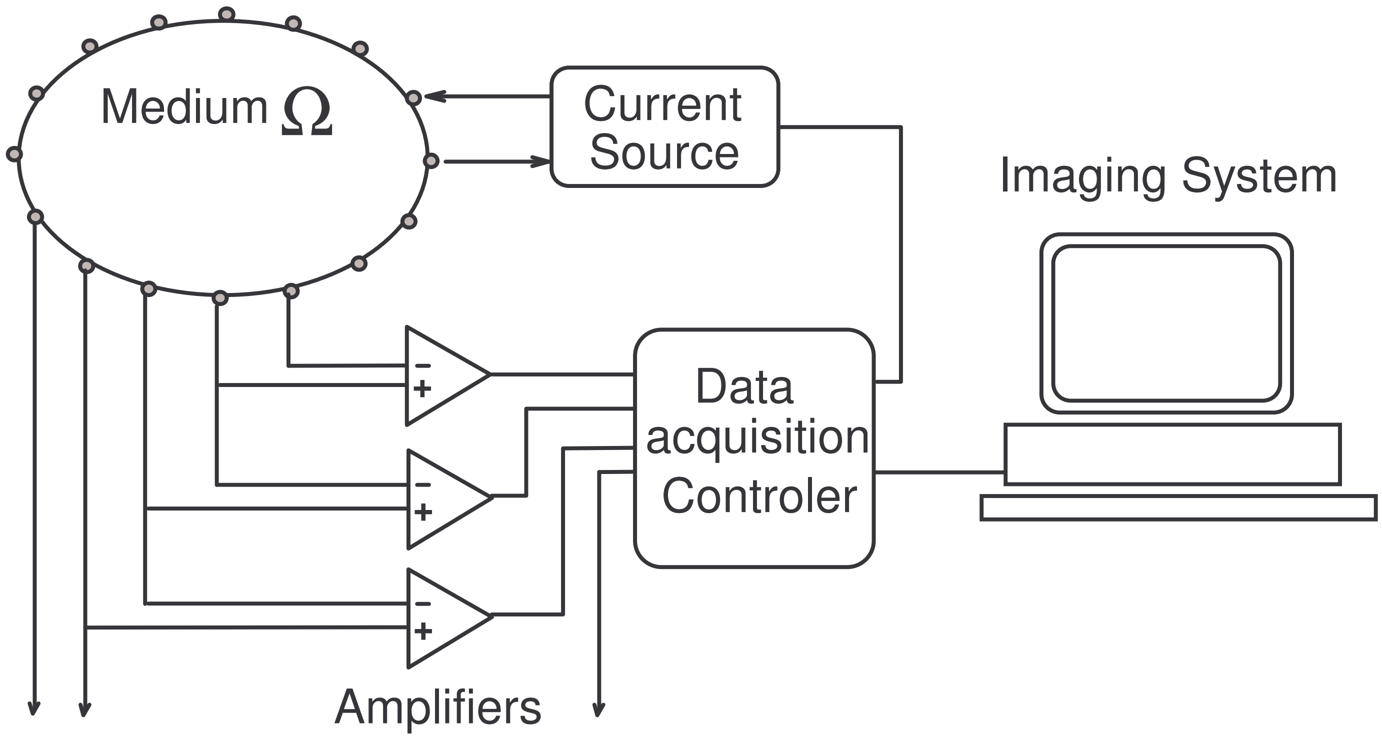
# Outline

- Electrical Impedance Tomography
- Physics
- Image Reconstruction
- Applications
- Future Work

# Electrical Impedance Tomography

- Relatively new medical imaging technique (early 1990's)
- Body Surface Electrodes apply current patterns and measure the resulting voltages
- Distribution of conductivity is calculated

# EIT: Block Diagram



# EIT: Applications

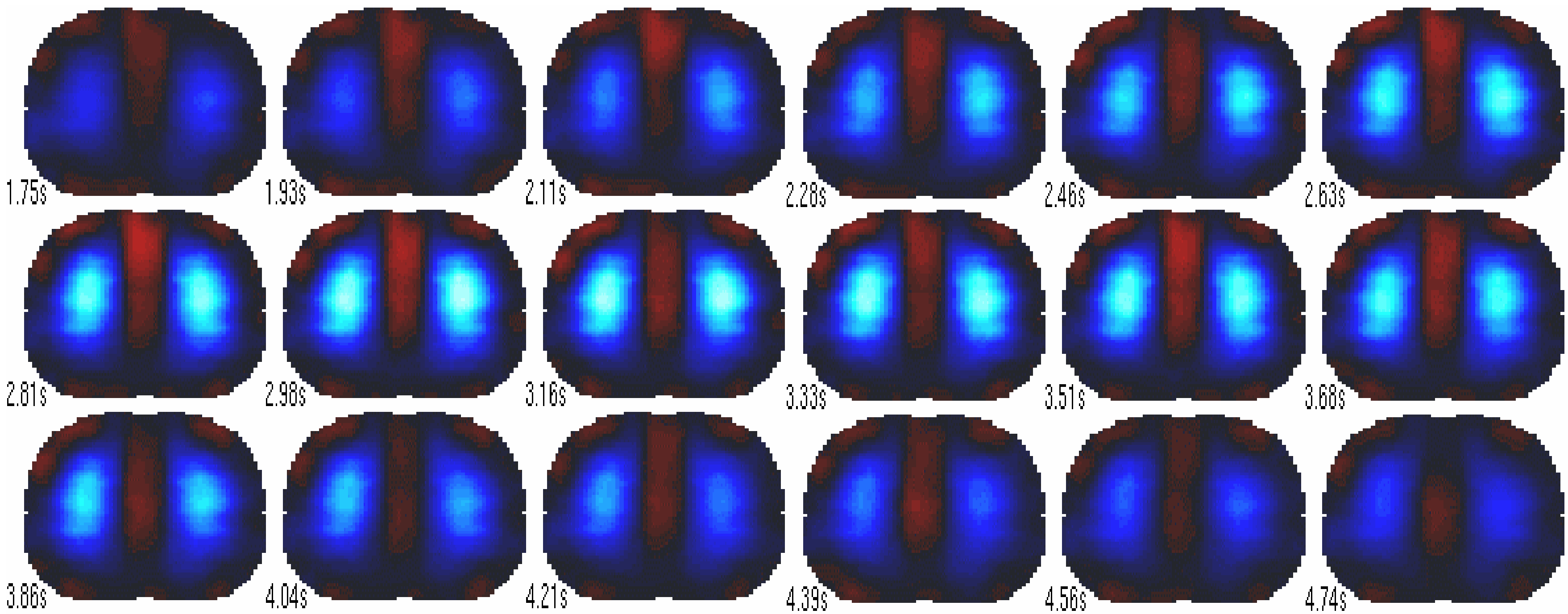
- EIT can image physiological processes involving movement of conductive fluids and gasses
- Lungs
- Heart / perfusion
- GI tract
- Brain
- Breast

# EIT: Advantages

EIT is a relatively low resolution imaging modality, *but*

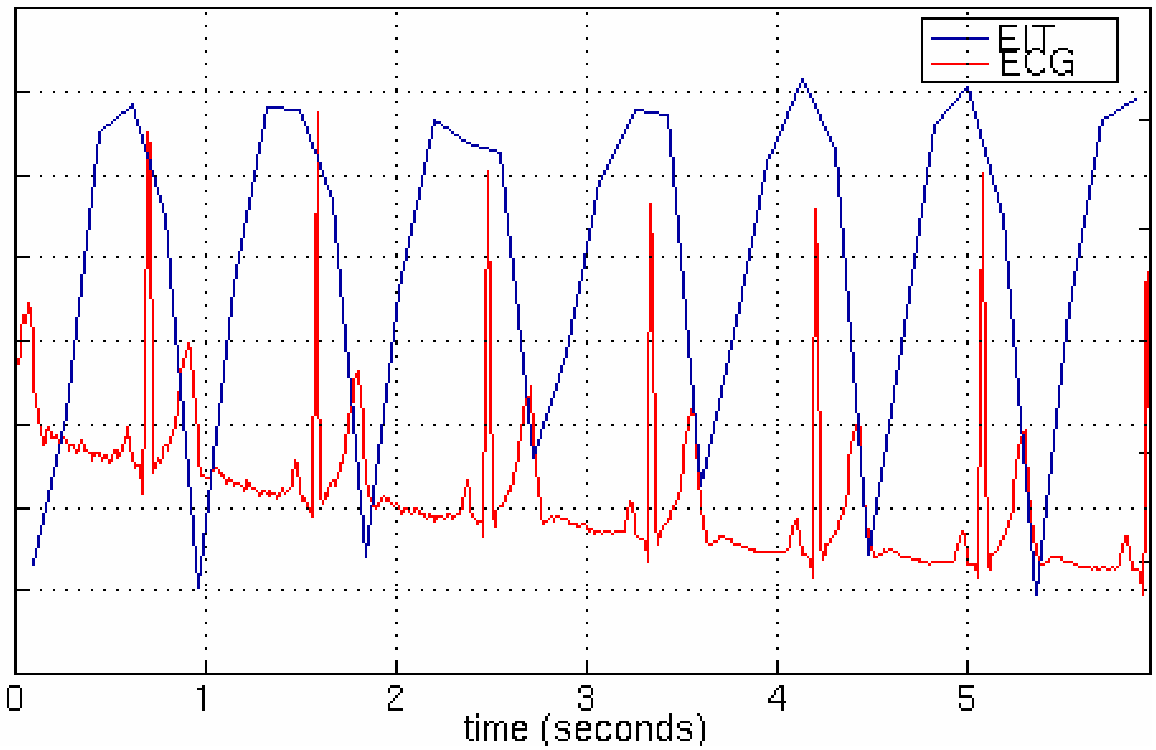
- Non-invasive
- Non-cumbersome
- Suitable for monitoring
- Underlying technology is low cost

# Application: Breathing



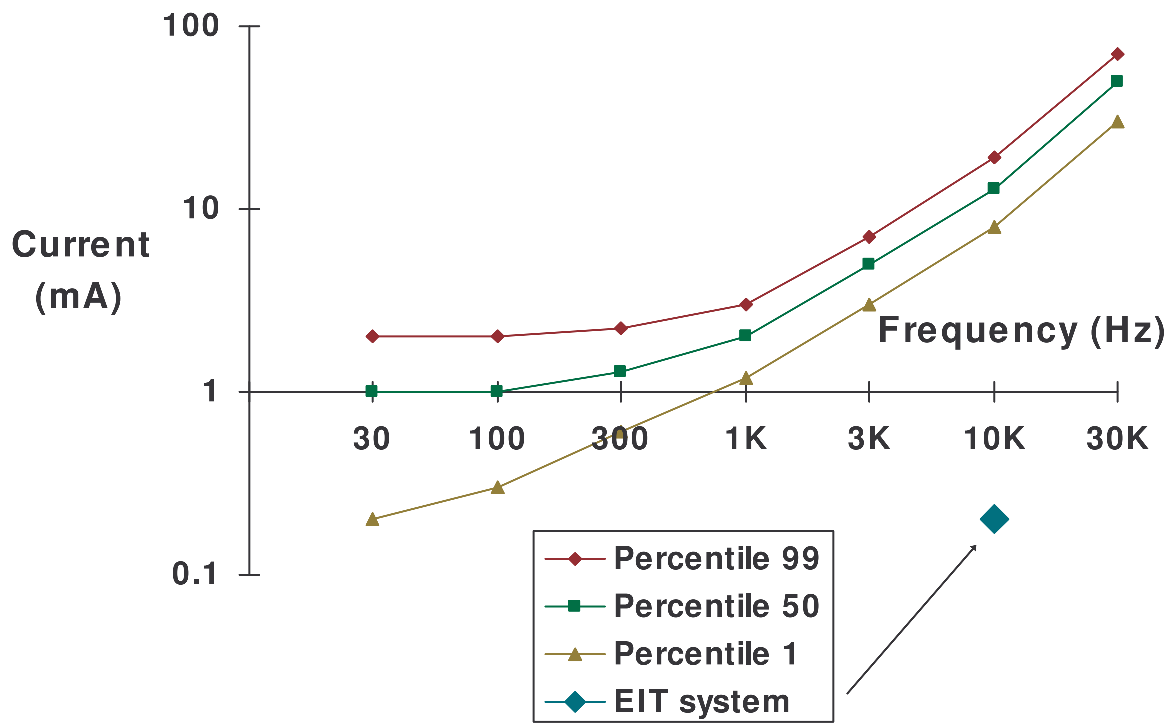

Chest images of tidal breathing in normal

# Application: Heart Beat




EIT signal in ROI around heart and ECG

# Non-invasive




Thresholds for cutaneous perception of electric current vs. frequency and EIT system

# EIT: Physics

- Within medium Ω there is **E** and **J**.
- $$J_c = \sigma E$$

$$J_d = \varepsilon \varepsilon_o \frac{dE}{dt}$$

$$\mathbf{J} = \left( \sigma - j\omega \varepsilon \varepsilon_o \right) \mathbf{E}$$

# EIT: Physics

In the absence of magnetic fields

$$\mathrm{E} = -\nabla V$$

No charge build up in conductive medium

$$\nabla \bullet \mathrm{J} = -\frac{\partial \rho}{\partial t} = 0$$

We have

$$\nabla \bullet \left( \sigma - j\omega\varepsilon\varepsilon_o \right) \nabla V = 0 \qquad \text{in } \Omega$$

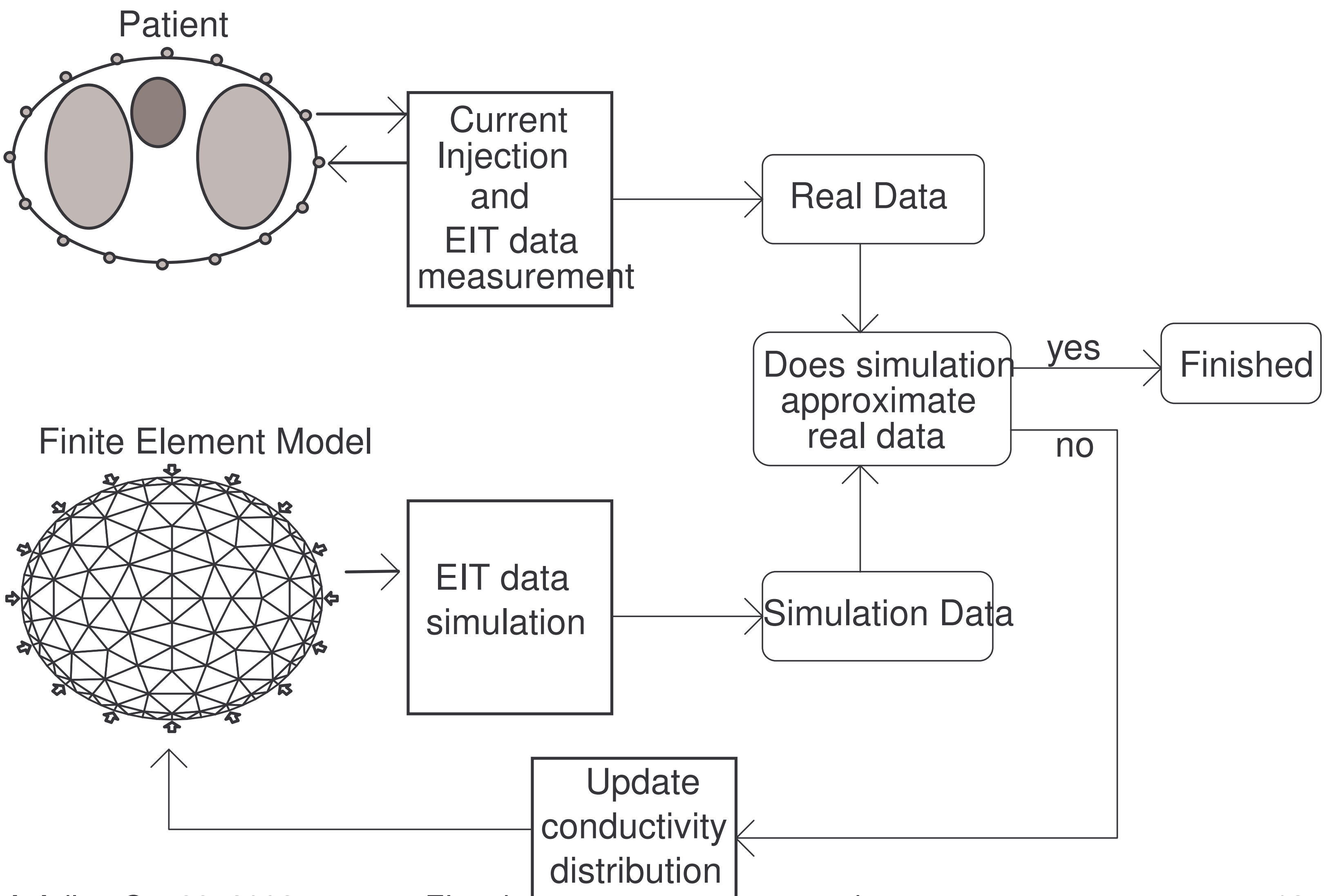
# Image Reconstruction: Static Imaging

*Static imaging* reconstructs the absolute conductivity from measurements.

Algorithms:

- Iterative (Newton-Raphson)
- Layer Stripping

# Block Diagram of Iterative Algorithm



# Static Imaging Difficulties

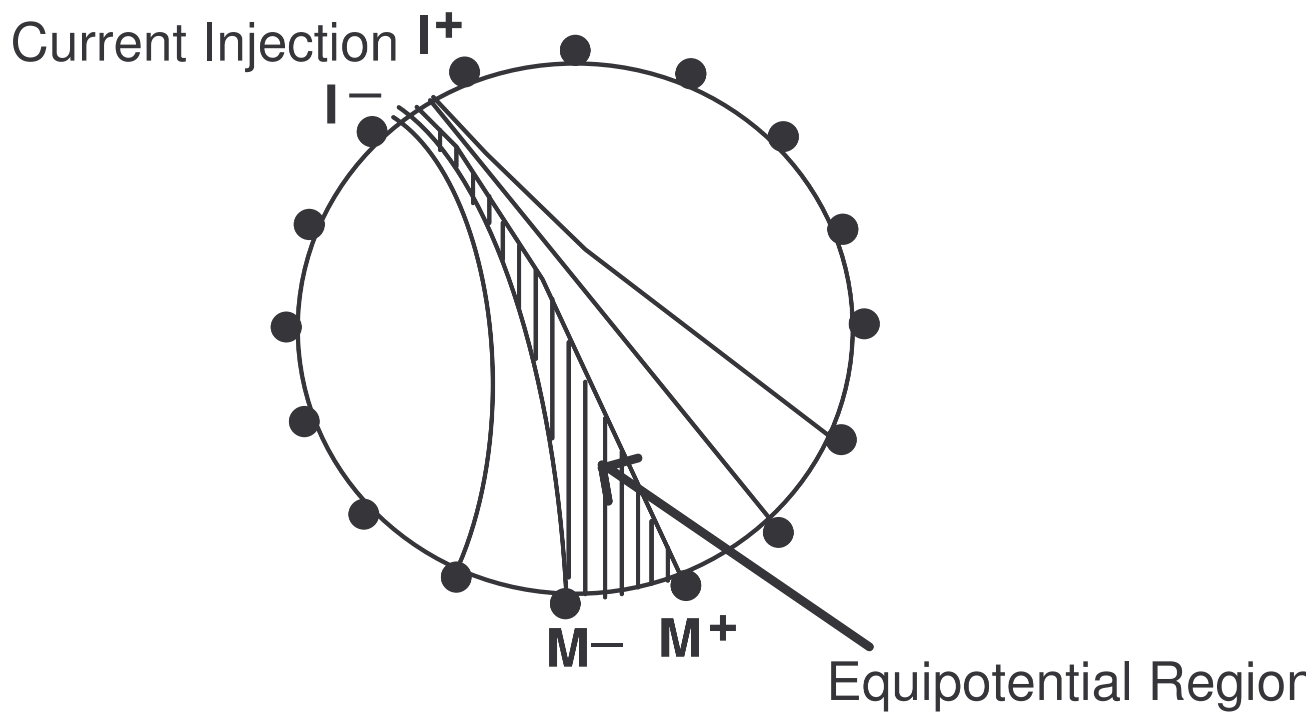
- Extremely sensitive to uncertainties in electrode position
- Ill-conditioned problem
- Numerical instability

# Dynamic Imaging

- Calculate change in conductivity distribution from change in measurements
- Inverse problem *linearized*
- Much reduced sensitivity to electrode and hardware errors.
- Very suitable for physiological imaging: lung, heart, GI

# Dynamic imaging techniques

- *Backprojection:* Voltages are "projected" along the equipotential lines.



# Inverse Techniques

- We can pose dynamic imaging as linear inverse, using a *sensitivity matrix*

$$\mathbf{z}_j = \frac{\mathbf{z}(\sigma_h) - \mathbf{z}(\sigma_h + \delta_j)}{\delta_j}$$

$$\mathbf{z} = \mathbf{H}\Delta\sigma$$

# Inverse Techniques

- Classic least-squares inverse

$$\mathbf{z} = \mathbf{H}\mathbf{x}$$

$$\hat{\mathbf{x}} = \left(\mathbf{H}^t\mathbf{H}\right)^{-1}\mathbf{H}^t\mathbf{z}$$

# Matrix Techniques

However, problem is:

- ill-conditioned: measurements depend much more on data near electrodes than in centre
- ill-formed: more unknowns than measurements

# Regularized Imaging

Given Linear Model:

$$\mathbf{z} = \mathbf{H}\mathbf{x} + \mathbf{n}$$

Maximum A Posteriori (MAP) estimate is:

$$\hat{\mathbf{x}} = \left(\mathbf{H}^t \mathbf{R}_n^{-1} \mathbf{H} + \mu \mathbf{R}_x^{-1}\right)^{-1} \left(\mathbf{H}^t \mathbf{R}_n^{-1} z + \mu \mathbf{R}_x^{-1} \mathbf{x}_\infty\right)$$

# Regularized Imaging

- Parameters **W**, **Q**, $\mathbf{x}_\infty$, represent *a priori* statistical knowledge of problem

$$\mathbf{x}_\infty = E[\mathbf{x}]$$

$$\mathbf{R}_\mathbf{x} = E\left[(\mathbf{x} - \mathbf{x}_\infty)^t (\mathbf{x} - \mathbf{x}_\infty)\right] = E\left[\mathbf{x}^t \mathbf{x}\right] - \mathbf{x}_\infty{}^t \mathbf{x}_\infty$$

$$\mathbf{R}_\mathbf{n} = E\left[\mathbf{n}^t \mathbf{n}\right] = \begin{bmatrix} \sigma_1^2 & 0 & \cdots \\ 0 & \sigma_2^2 & \\ \vdots & & \ddots \end{bmatrix}$$

# Advantages of Regularization

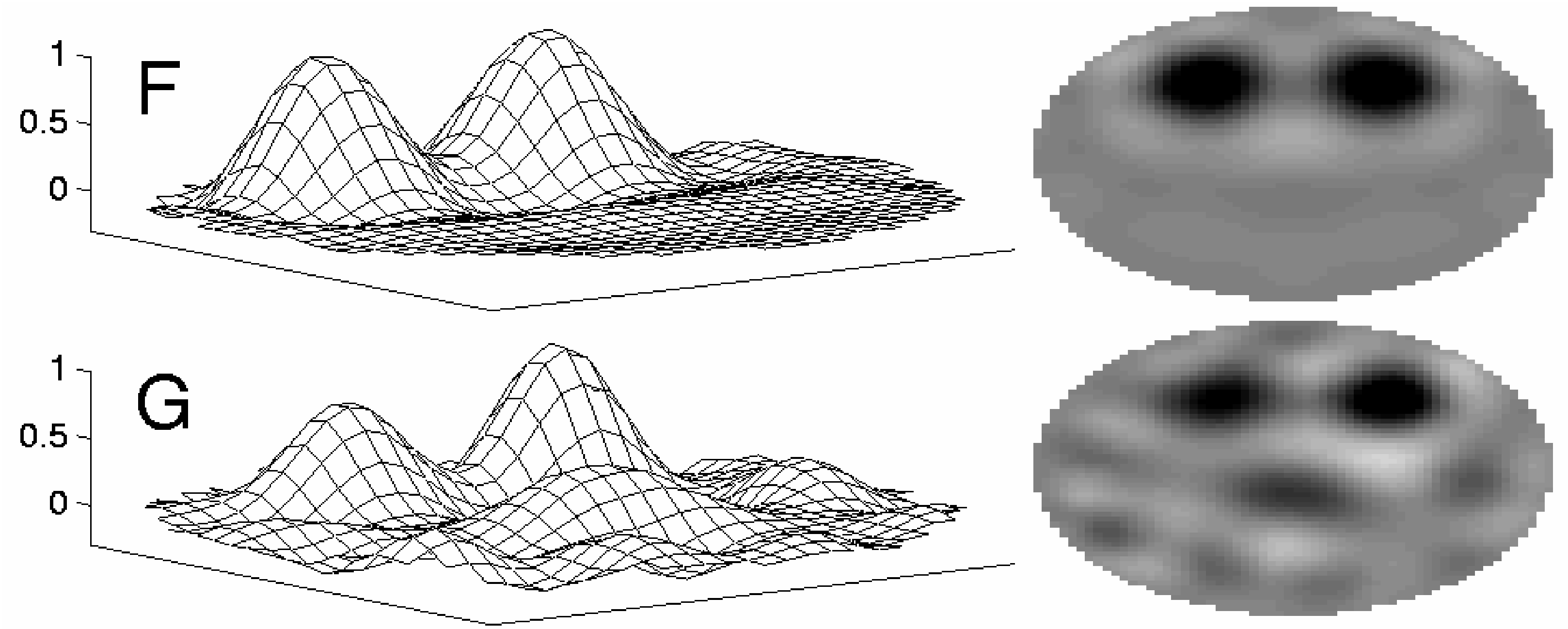
- Stabilizes ill-conditioned inverse
- Introduction of *a priori* information
- Control of *resolution-noise* performance trade-off
- MAP inverse justifies the formulation in terms of Bayesian statistics

# Regularized Inverse

Parameters:

- **W**: models measurement noise
- **Q**: penalizes image features which are greater than data supports
- $\mathbf{x}_\infty$: represents the background conductivity distribution (heart,lungs,etc)
- **μ**: "hyper-parameter" amount of regularization

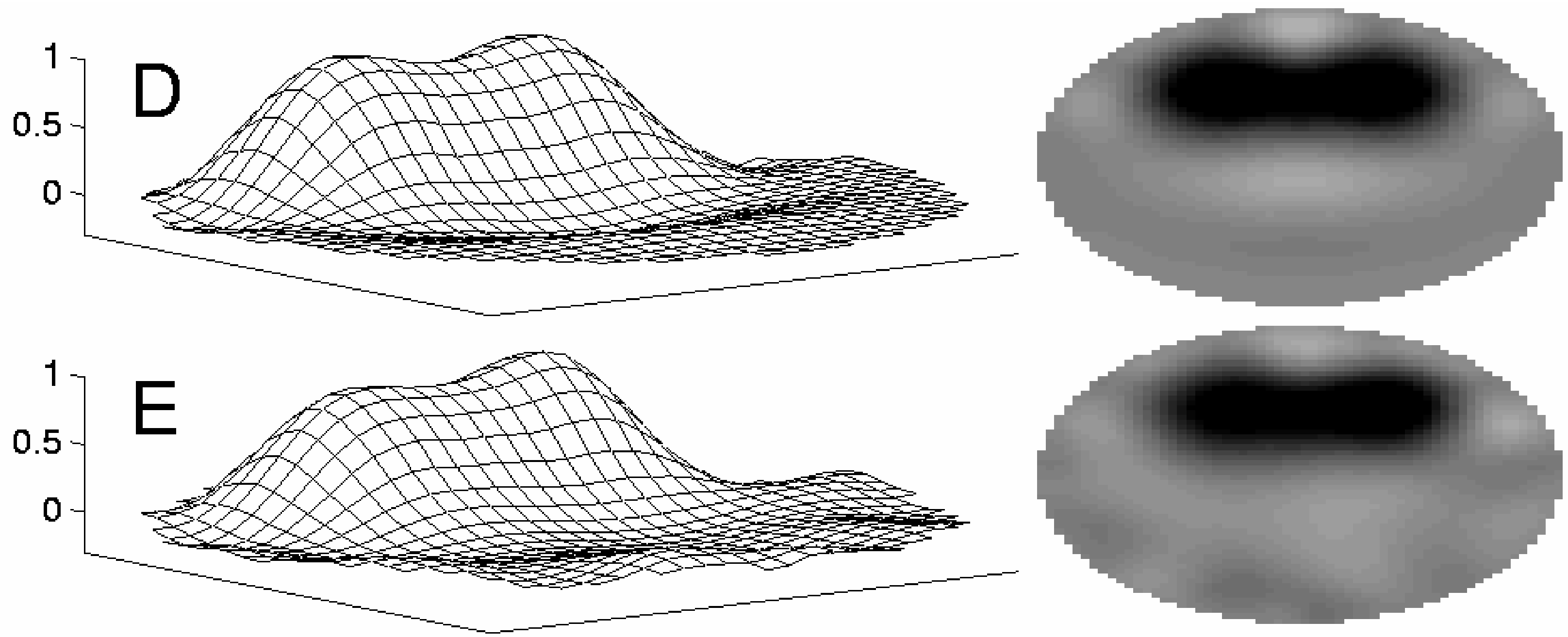
# Noise – Resolution Tradeoff




F: *Meas:* No Noise *Reconst:* NF= 2.0

G: *Meas:* -3dB SNR *Reconst:* NF= 2.0

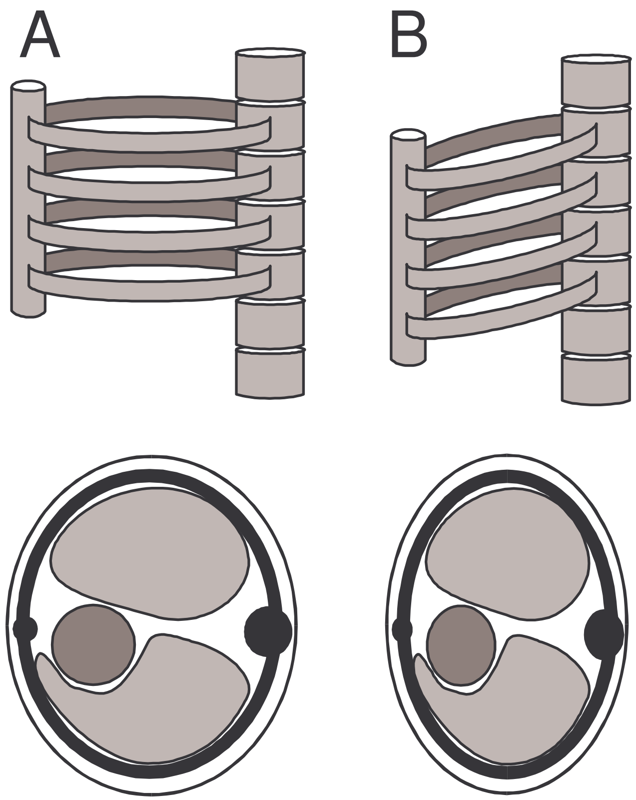
# Noise – Resolution Tradeoff




F: *Meas:* No Noise *Reconst:* NF= 0.4

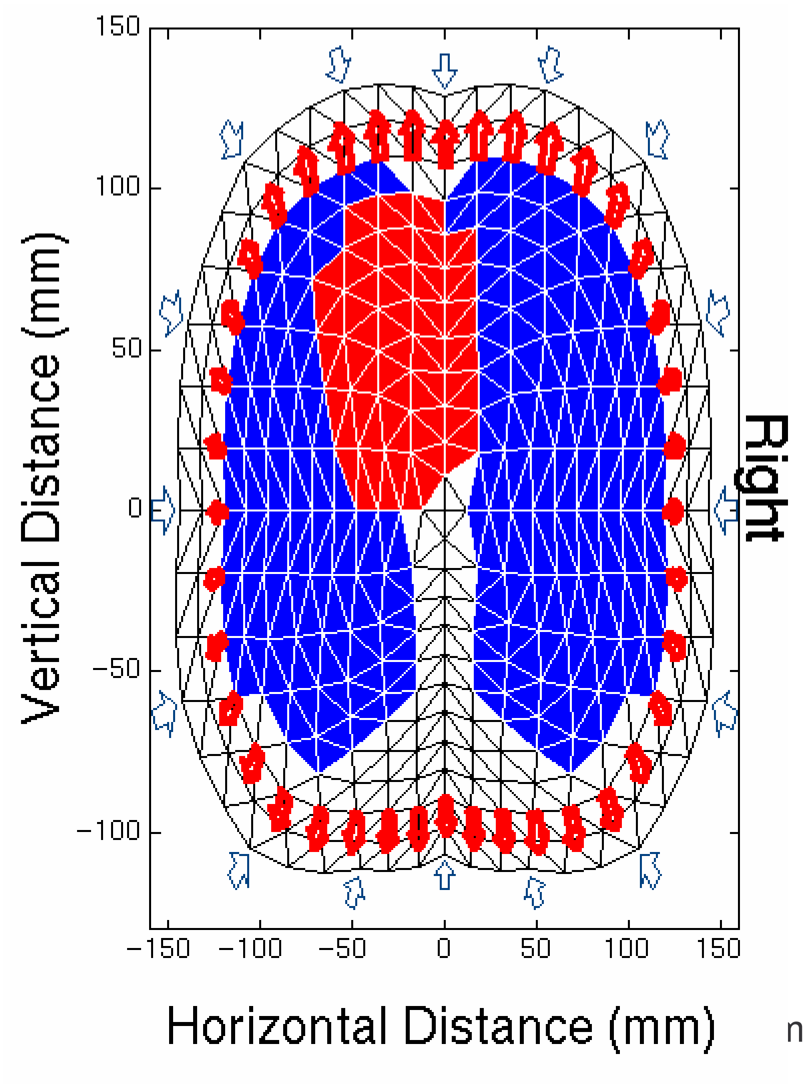
G: *Meas:* -3dB SNR *Reconst:* NF= 0.4

# Electrode Movement




- Electrodes on chest move during breathing
- Figure shows rough movement pattern of rib cage

# Electrode Movement




- FEM of electrical and mechanical properties of thorax to simulate
- Signal from expansion shown to contribute 10-20% of conductivity signal

# Applications: Lung Function and Disease

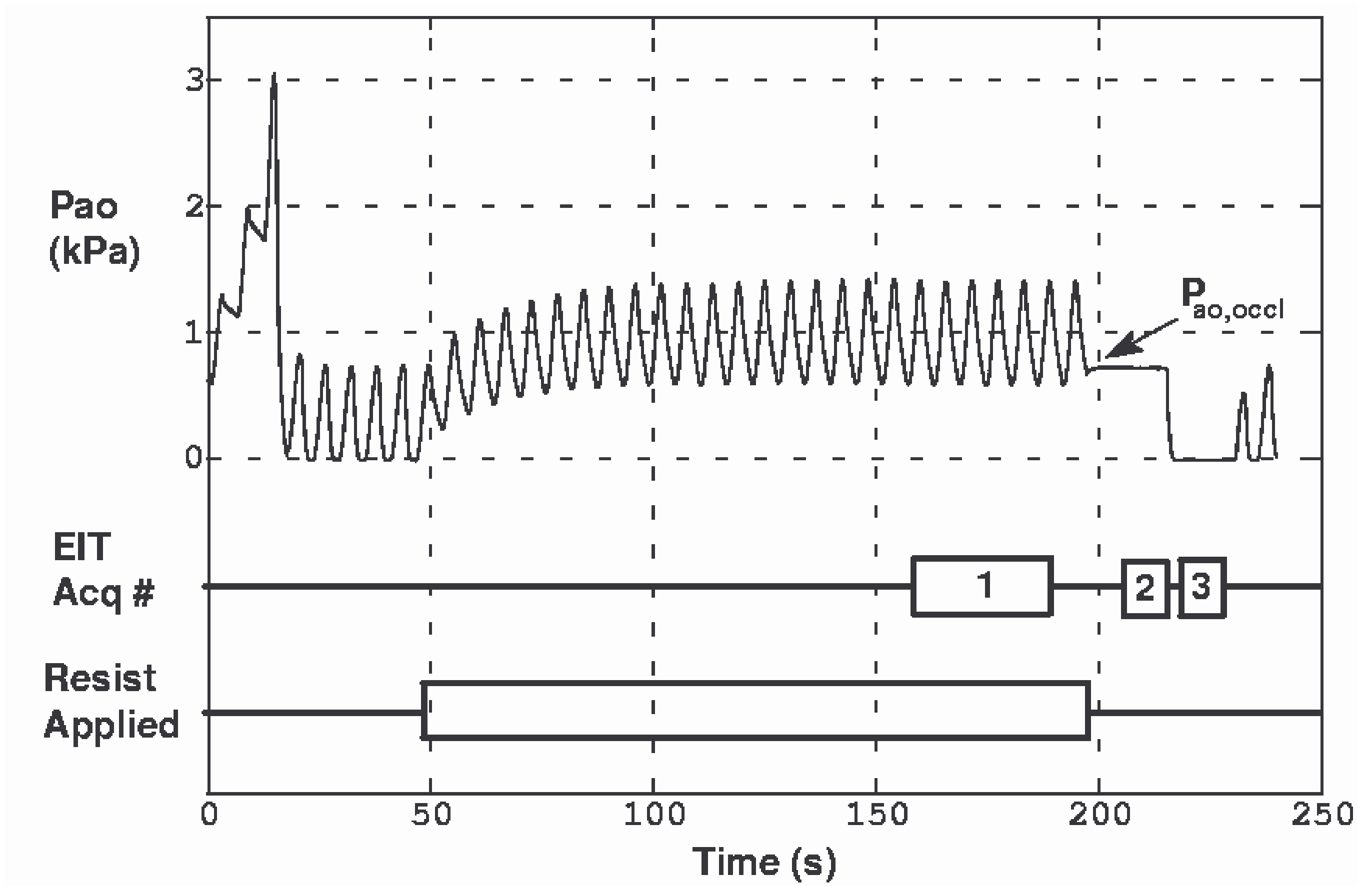
Monitoring of lung function is important in ICU. Issues are:

- Distribution of ventilation
- Ventilation – perfusion match
- Lung Edema
- Flow limitation (obstructive lung disease)

# Lung function tests

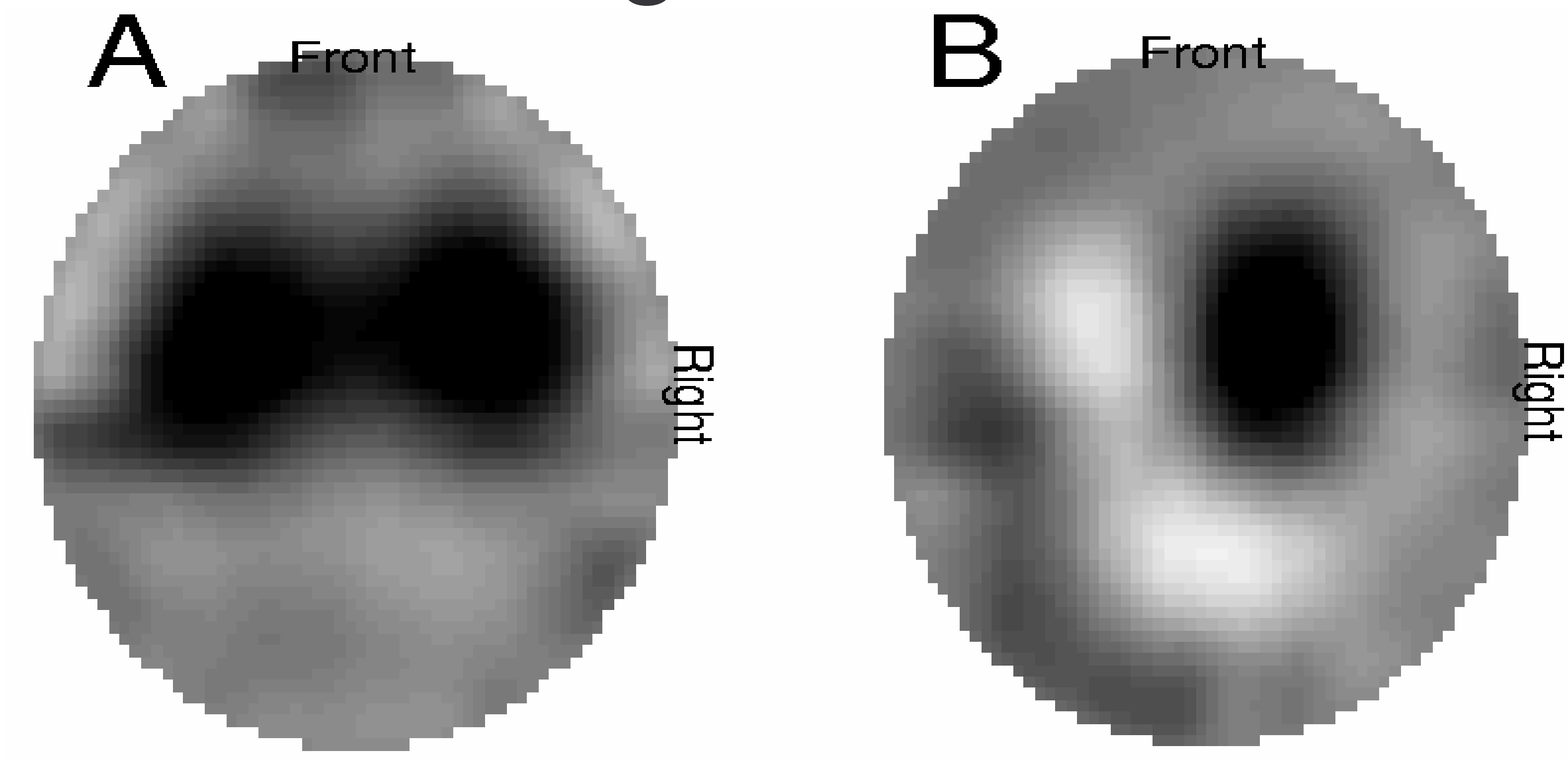
- Patients with obstructive lung disease (emphysema, bronchitis) tend to dynamically hyperinflate: lower inspiration than expiration.
- Simulated with PEEP (positive end expiratory pressure)

# Lung Function: Protocol



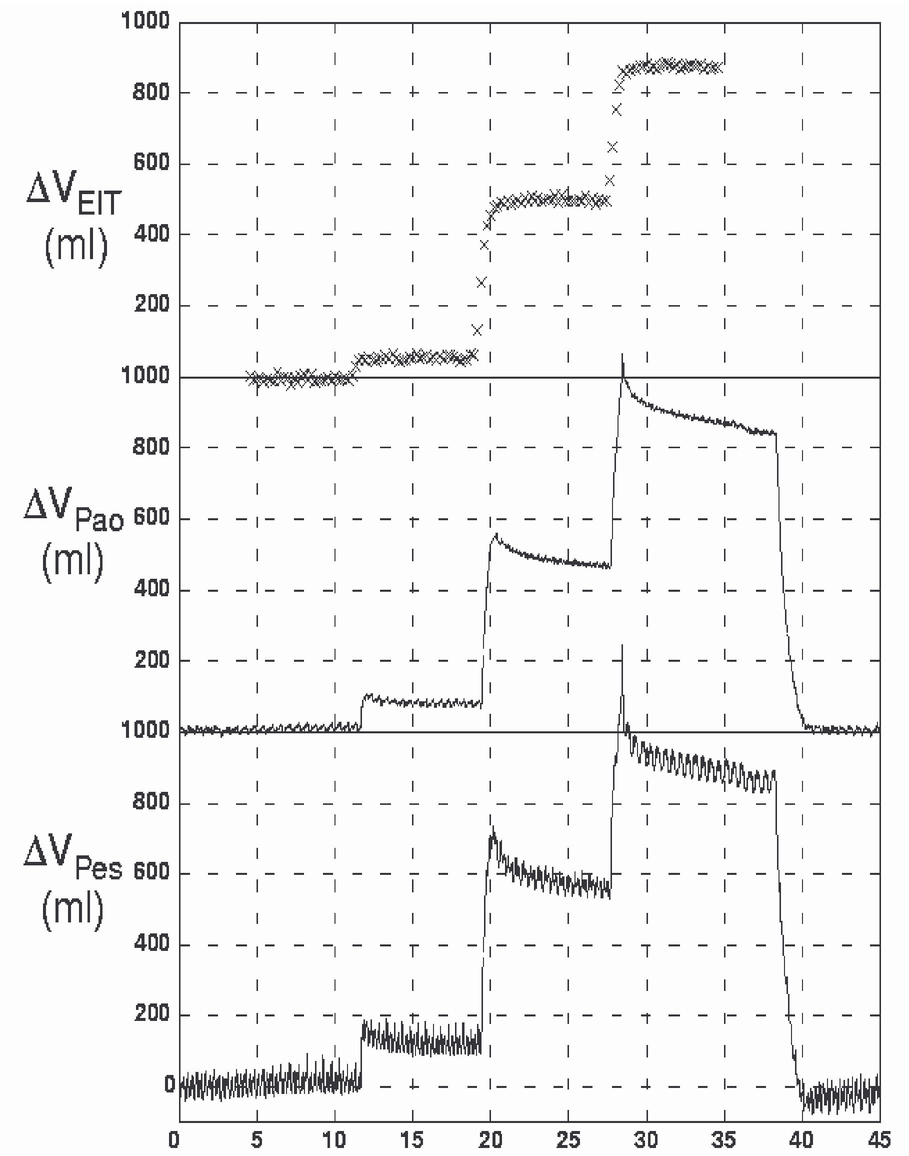

- Initially, inflations to 3 kPa
- dog expires to the applied PEEP
- ventilation stopped, and dog expires against PEEP for 15 s

# Lung Function




*A*: image of section thorax due to ΔVL 800 ml

*B*: image due to a ΔVL 400 where left main stem bronchus was plugged.

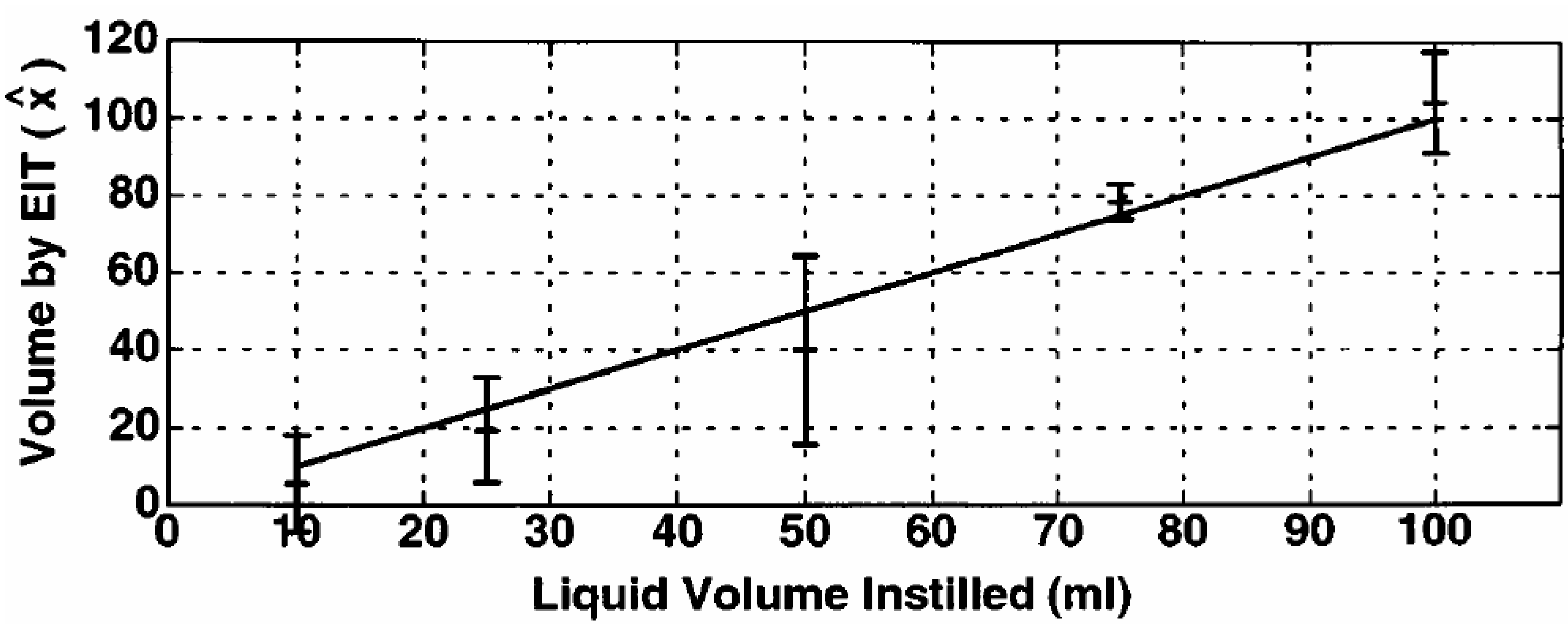



- Volume estimates by EIT, Pao and Pes, after step volume increases of 100ml, 500ml, 900ml.
- Note that EIT signal does not display overshoot

# Pulmonary Edema

- Pulmonary Edema (lungs filled with fluid) plagues ICU patients for heart disease, accident victims
- Typical monitoring techniques are invasive (Swan-Ganz catheter)
- We looked at EIT ability to monitor level of Edema.

# Pulmonary Edema: Results




- Change in lung liquid volume by EIT vs liquid volume instilled

# Imaging

- Algorithms to use data from internal electrodes
- How to manage electrode artefacts
- Arbitrary electrode placements
- Image interpretation and error bounds given artefacts and noise

# Applications of interest

- Longer term monitoring in ICU
- Small animal lung function
- Contrast agents
- Inhomogeneous ventilation on smaller scale