Electrical Impedance Tomography: Image Algorithms and Applications

Andy Adler

Assistant Professor,
SITE, U.Ottawa
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 $\Omega$ there is $E$ and $J$.

\[ J_c = \sigma E \]

\[ J_d = \varepsilon \varepsilon_0 \frac{dE}{dt} \]

\[ J = (\sigma - j \omega \varepsilon \varepsilon_0)E \]
EIT: Physics

In the absence of magnetic fields

\[ E = -\nabla V \]

No charge build up in conductive medium

\[ \nabla \cdot J = -\frac{\partial \rho}{\partial t} = 0 \]

We have

\[ \nabla \cdot (\sigma - j \omega \varepsilon \varepsilon_0) \nabla V = 0 \quad \text{in} \; \Omega \]
Image Reconstruction: Static Imaging

*Static imaging* reconstructs the absolute conductivity from measurements.

**Algorithms:**
- Iterative (Newton-Raphson)
- Layer Stripping
Block Diagram of Iterative Algorithm

Patient

Current Injection and EIT data measurement

Real Data

Does simulation approximate real data

Simulation Data

Update conductivity distribution

Finite Element Model

EIT data simulation

A. Adler, Oct 28, 2002
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.

Current Injection $I^+$

$I^-$

$M^-$ $M^+$

Equipotential Region
Inverse Techniques

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

\[
\begin{align*}
  z_j &= \frac{z(\sigma_h) - z(\sigma_h + \delta_j)}{\delta_j} \\
  z &= H\Delta\sigma
\end{align*}
\]
Inverse Techniques

• Classic least-squares inverse

\[
\hat{x} = \left( H^t H \right)^{-1} H^t z
\]
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:

\[ z = Hx + n \]

Maximum A Posteriori (MAP) estimate is:

\[
\hat{x} = \left( H^t R_n^{-1} H + \mu R_x^{-1} \right)^{-1} \left( H^t R_n^{-1} z + \mu R_x^{-1} x_\infty \right)
\]
Regularized Imaging

- Parameters $W, Q, x_\infty$, represent \textit{a priori} statistical knowledge of problem

$$x_\infty = E[x]$$

$$R_x = E[(x - x_\infty)^t(x - x_\infty)] = E[x^tx] - x_\infty^tx_\infty$$

$$R_n = E[n^tn] = \begin{bmatrix} \sigma_1^2 & 0 & \cdots \\ 0 & \sigma_2^2 & \cdots \\ \vdots & \vdots & \ddots \end{bmatrix}$$
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
• $x_\infty$: represents the background conductivity distribution (heart, lungs, etc)
• $\mu$: “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
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