# Real-Time Linearized EIT Reconstructions Using a Database of Simulated EIT Images

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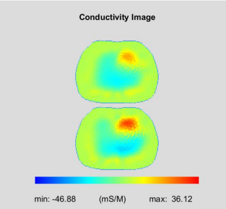
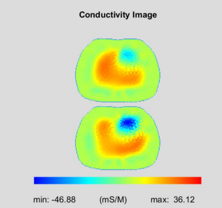
# Electrical Impedance Tomography (EIT)

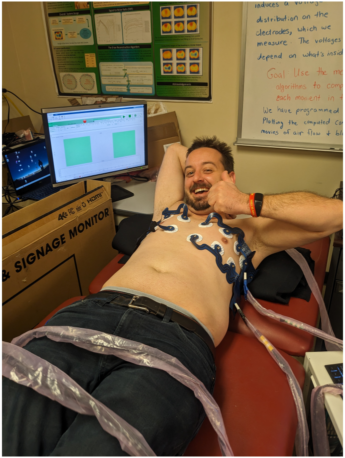
- Real-time imaging method of internal body structures and functions using electrical properties
- Administer low-amplitude current to body surface and measure resulting voltages
- Solve inverse problem for conductivity distribution of internal body




Diastole

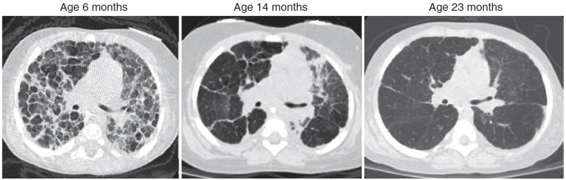



Systole



# BRONCHOPULMONARY DYSPLASIA (BPD) AND EIT

- BPD is the most common cause of lung disease in infants and affects 10,000–15,000 premature infants in the US every year
- Alveolar simplification and abnormal pulmonary vascularization are characteristics of most infants with BPD
- EIT can be used to provide non-ionizing bedside, real-time imaging of lung function during mechanical ventilation, helping prevent ventilator induced lung injury




High resolution CT scans in a severe BPD patient during breath-holding at three different ages

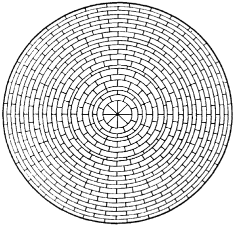
# NOSER Reconstruction Algorithm

- The Newton One-Step Error Reconstructor — or NOSER — is one of the most commonly used algorithms in solving our inverse problem of determining conductivity distribution $\sigma(\boldsymbol{p})$ from the following PDE relation

$$\begin{cases} \nabla \cdot \sigma(\boldsymbol{p}) \nabla u(\boldsymbol{p}) = 0 & \text{for } \boldsymbol{p} \text{ in } B \\ \sigma(\boldsymbol{p}) \frac{\partial u(\boldsymbol{p})}{\partial \nu} = j(\boldsymbol{p}) & \text{for } \boldsymbol{p} \text{ on } S \end{cases}$$

- NOSER aims to find resistivity, $\rho = \frac{1}{\sigma}$, on 496 elements of Joshua tree mesh to minimize square error of voltage estimate $\boldsymbol{U}^k(\boldsymbol{\rho})$

$$E(\boldsymbol{\rho}) = \sum_{k=1}^{L-1} \sum_{l=1}^{L} (V_l^k - U_l^k(\boldsymbol{\rho}))^2$$



- $V_l^k$ and $U_l^k(\boldsymbol{\rho})$ are the measured and estimated voltages, respectively, at the $l$th electrode while applying the $k$th current pattern

# Finding a Minimizer

- The problem reduces to finding $\boldsymbol{\rho}$ to satisfy the necessary conditions for a minimizer

$$0 = \frac{\partial E(\boldsymbol{\rho})}{\partial \rho_n} = -2 \sum_{k=1}^{L-1} \sum_{l=1}^{L} (V_l^k - U_l^k(\boldsymbol{\rho})) \frac{\partial U_l^k(\boldsymbol{\rho})}{\partial \rho_n}$$

- An approximate solution $\hat{\boldsymbol{\rho}}$ is found using one step of Gauss-Newton method with initial guess $\tilde{\boldsymbol{\rho}}$

$$\hat{\boldsymbol{\rho}} = \tilde{\boldsymbol{\rho}} - [\boldsymbol{F}'(\tilde{\boldsymbol{\rho}})]^{-1} \boldsymbol{F}(\tilde{\boldsymbol{\rho}})$$

$$F_n(\tilde{\boldsymbol{\rho}}) = -2 \sum_{k=1}^{L-1} \sum_{l=1}^{L} (V_l^k - U_l^k(\tilde{\boldsymbol{\rho}})) \frac{\partial U_l^k(\tilde{\boldsymbol{\rho}})}{\partial \rho_n}$$

$$F'_{n,m}(\tilde{\boldsymbol{\rho}}) \approx 2 \sum_{k=1}^{L-1} \sum_{l=1}^{L} \frac{\partial U_l^k(\tilde{\boldsymbol{\rho}})}{\partial \rho_n} \frac{\partial U_l^k(\tilde{\boldsymbol{\rho}})}{\partial \rho_m}$$

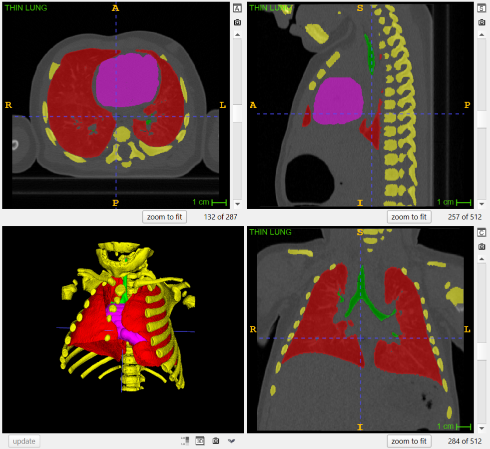
- Constant initial guess $\tilde{\boldsymbol{\rho}} = \rho_b \mathbf{1}$ used to simplify estimates for initial guess, voltage, and gradients

# Anatomically-Informed Initial Guess

- We want to update NOSER with an anatomically-informed initial guess of conductivity distribution
- To do so, we must generate the following
  - Initial guess distribution, $\tilde{\boldsymbol{\sigma}}$
  - Estimated voltage distribution, $\boldsymbol{U}^k(\tilde{\boldsymbol{\sigma}})$
  - Voltage gradients, $\frac{\partial \boldsymbol{U}^k(\tilde{\boldsymbol{\sigma}})}{\partial \sigma_n}$
- An Anatomical Atlas was developed and used in numerical generation of these components, allowing for an improvement to NOSER's initial conditions

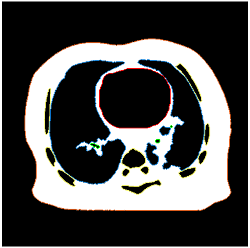
# Segmentation of CT Scans

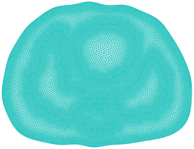
- Anatomical Atlas generated from a set of 89 chest CT scans of infants aged 0 to 3 months from New Mexico Decedent Database
- CT scans were segmented into lung, trachea, bone, and soft tissue
- "Average" hearts were manually added



# Conductivity and Voltage Modeling

- Segmented scans divided into 8,171 2-D cross-sectional images
- Organ boundaries are then imported into MATLAB, with conductivity and susceptivity values assigned to each type of tissue
- Values randomized for each image 10 times, resulting in 81,710 total slices
- Finite Element Method modeling used to numerically compute EIT output voltage distributions

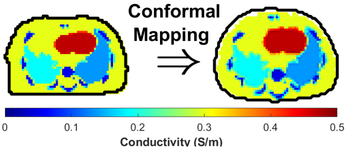


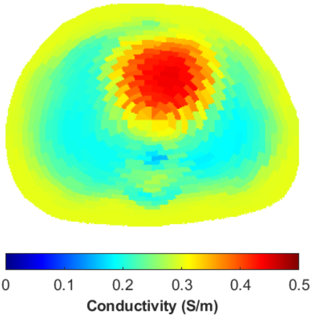


| Tissue (S/m) | Heart | Soft Tissue | Lung | Trachea | Bone |
|---|---|---|---|---|---|
| **Mean Conductivity** | 0.5 | 0.3 | 0.15 | 0.15 | 0.05 |
| **Mean Susceptivity** | 0.4 | 0.2 | 0.4 | 0.05 | 0.05 |

# Mean Baby

- We computed the mean conductivity distribution $\bar{\sigma}$ to be our anatomically informed initial condition
- Prior to averaging, slices from anatomical atlas were conformally mapped to a common body shape to normalize body structure



# Mean Baby Reconstructions

- We compute reconstructions using the Gauss-Newton method

$$\hat{\boldsymbol{\sigma}} = \bar{\boldsymbol{\sigma}} - [\boldsymbol{F}'(\bar{\boldsymbol{\sigma}})]^{-1}\boldsymbol{F}(\bar{\boldsymbol{\sigma}})$$

$$F_n(\bar{\boldsymbol{\sigma}}) = -2\sum_{k=1}^{L-1}\sum_{l=1}^{L}(V_l^k - U_l^k(\bar{\boldsymbol{\sigma}}))\frac{\partial U_l^k(\bar{\boldsymbol{\sigma}})}{\partial \sigma_n}$$

$$F'_{n,m}(\bar{\boldsymbol{\sigma}}) \approx 2\sum_{k=1}^{L-1}\sum_{l=1}^{L}\frac{\partial U_l^k(\bar{\boldsymbol{\sigma}})}{\partial \sigma_n}\frac{\partial U_l^k(\bar{\boldsymbol{\sigma}})}{\partial \sigma_m}$$

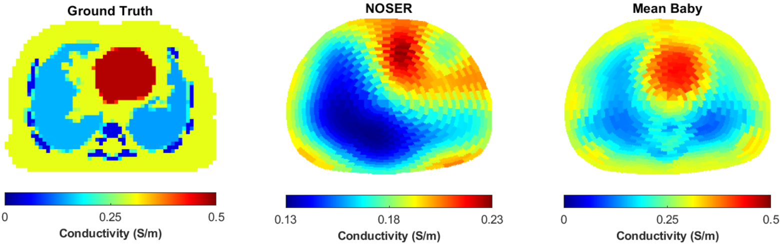
- Voltage estimate, $\boldsymbol{U}^k(\bar{\boldsymbol{\sigma}})$, computed using finite element method, and gradients $\frac{\partial \boldsymbol{U}^k(\bar{\boldsymbol{\sigma}})}{\partial \sigma_n}$ estimated using central difference method
- $\boldsymbol{F}'$ matrix is ill-conditioned, so we regularize

$$F'_{n,m} \leftarrow F'_{n,m} + \gamma F'_{n,m}\delta_{n,m}$$

$$\boldsymbol{F}' \leftarrow \boldsymbol{F}' + \alpha \max_n(F'_{n,n})I$$

# Simulated Model Reconstructions

- NOSER appears to create more "blobby" reconstructions
- Mean Baby captures spinal column and division between lungs
  - Note conductivity scaling, Mean Baby provides conductivity estimates on the same scale as ground truth



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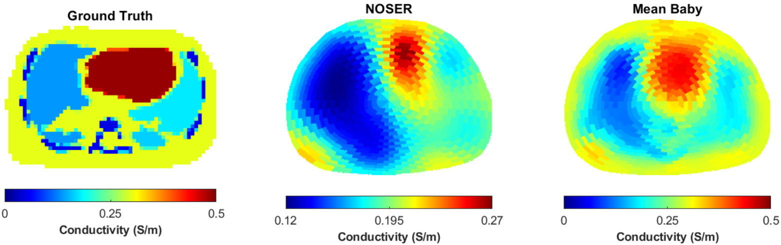

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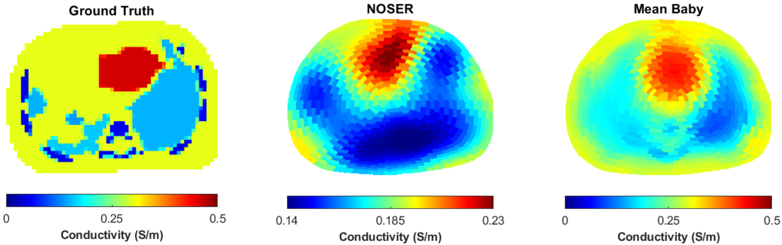

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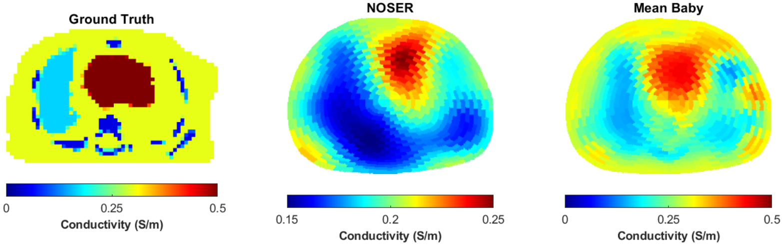
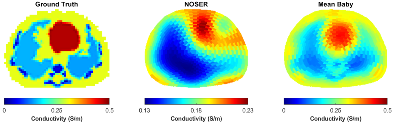
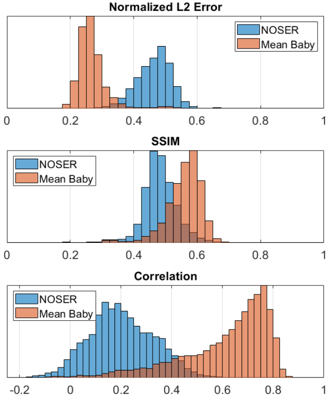


# Quantitative Comparison

- Statistics computed for each of the 16,341 cross-sectional test slices
- Distributions show improved performance from Mean Baby approach

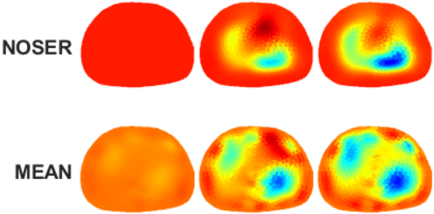



| Reconstruction | $L^2$ Error | SSIM | Correlation |
|---|---|---|---|
| NOSER | 0.4825 | 0.4607 | 0.3259 |
| Mean Baby | 0.2215 | 0.6101 | 0.8118 |



# Clinical Data Analysis

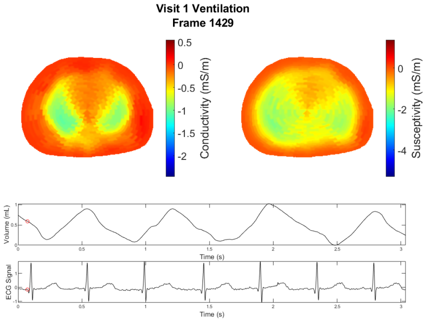
- Clinical data collected on premature infants with BPD using 16 electrode configuration of ACT-5 EIT system at Children's Hospital Colorado
- Since ground truth is unknown we are limited to qualitative inspection
- We visualize difference images $\Delta\hat{\boldsymbol{\sigma}}_i = \hat{\boldsymbol{\sigma}}_i - \boldsymbol{\sigma}_{ref}$ from some reference conductivity $\boldsymbol{\sigma}_{ref}$, typically selected at full expiration


This study was conducted in accordance with the amended Declaration of Helsinki. Data were collected at Children's Hospital Colorado (CHCO) in Aurora, Colorado, under the approval of the institutional review board (IRB) (approval number 18-1843). Informed parental consent was obtained prior to participation.

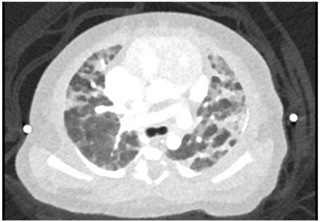
# Healthy Patient

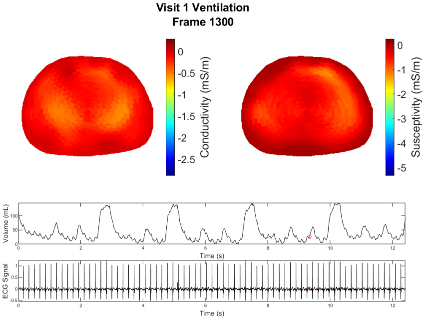
- For reference, we look at an example of a healthy subject aged 15 weeks at imaging
- We note healthy lung structure at full inspiration
- Additionally, we see ventilatory balance in conductivity across both lungs



# Patient with Severe BPD

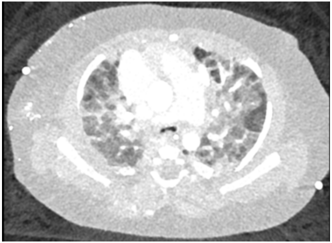
- In comparison, we have images of a patient with severe BPD and accompanying CT scan imaging taken on the same day
- EIT imaging with Mean Baby is able to approximate lung structure
- We see ventilatory balance is disturbed by BPD

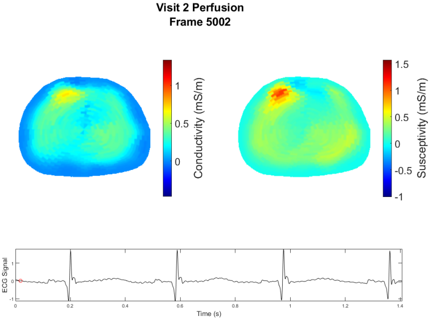




# Perfusion Imaging

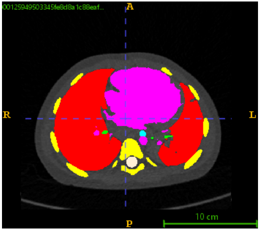
- During a breath pause we can visualize perfusion, or the movement of blood in the circulatory system
- In this case, we are able to visualize the patient's mesocardia, a rare condition where the heart is located in a centered position of the body

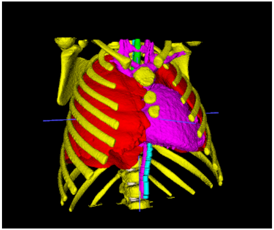




# Next Steps

- Implement Mean Baby algorithm on ACT-5 hardware for clinical use
- Modify Anatomical Atlas for 3-D finite element processing to model and reconstruct volumetric conductivity distributions
- Currently creating Anatomical Atlas from CT scans of subjects aged between 9 months and 19 years old



# Thanks and Acknowledgments

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- Thanks to Kyler Howard, Trevor Overton, Joel Barazza Nava, Mason Faldet, Kristina Moen, Summer Soller, Tyler Stephens, Esther van de Lagemaat, Natalie Wijesinghe, and Kaylee Wong Dolloff for development of Anatomical Atlas
- Thanks everyone for listening!

# References


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