Budapest, Hungary

# Electrical Impedance Tomography

## *Challenges and What We Are Doing about Them*

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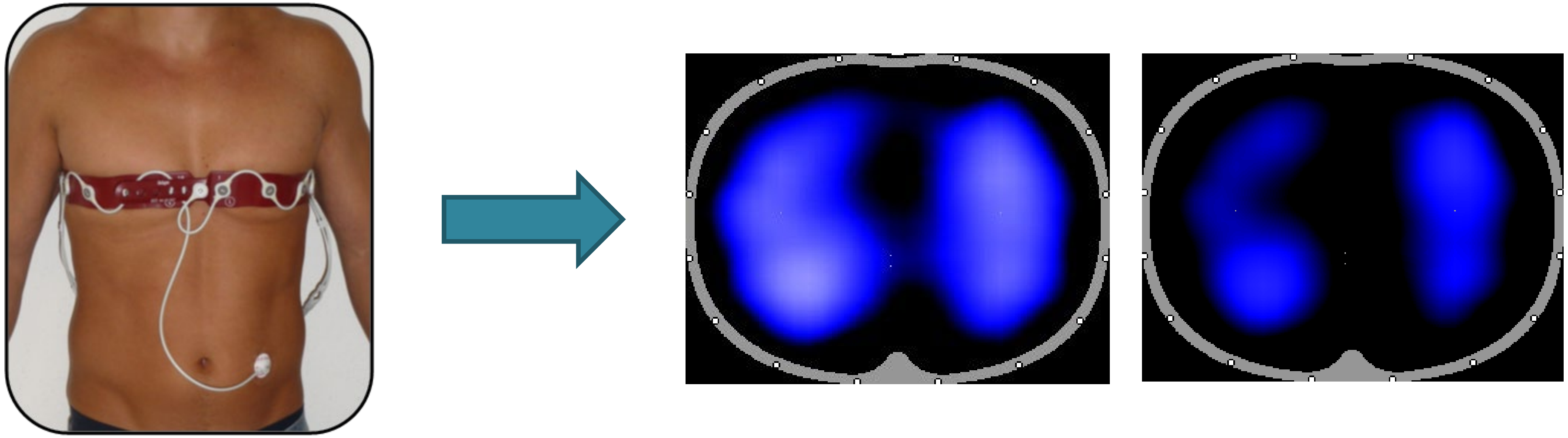
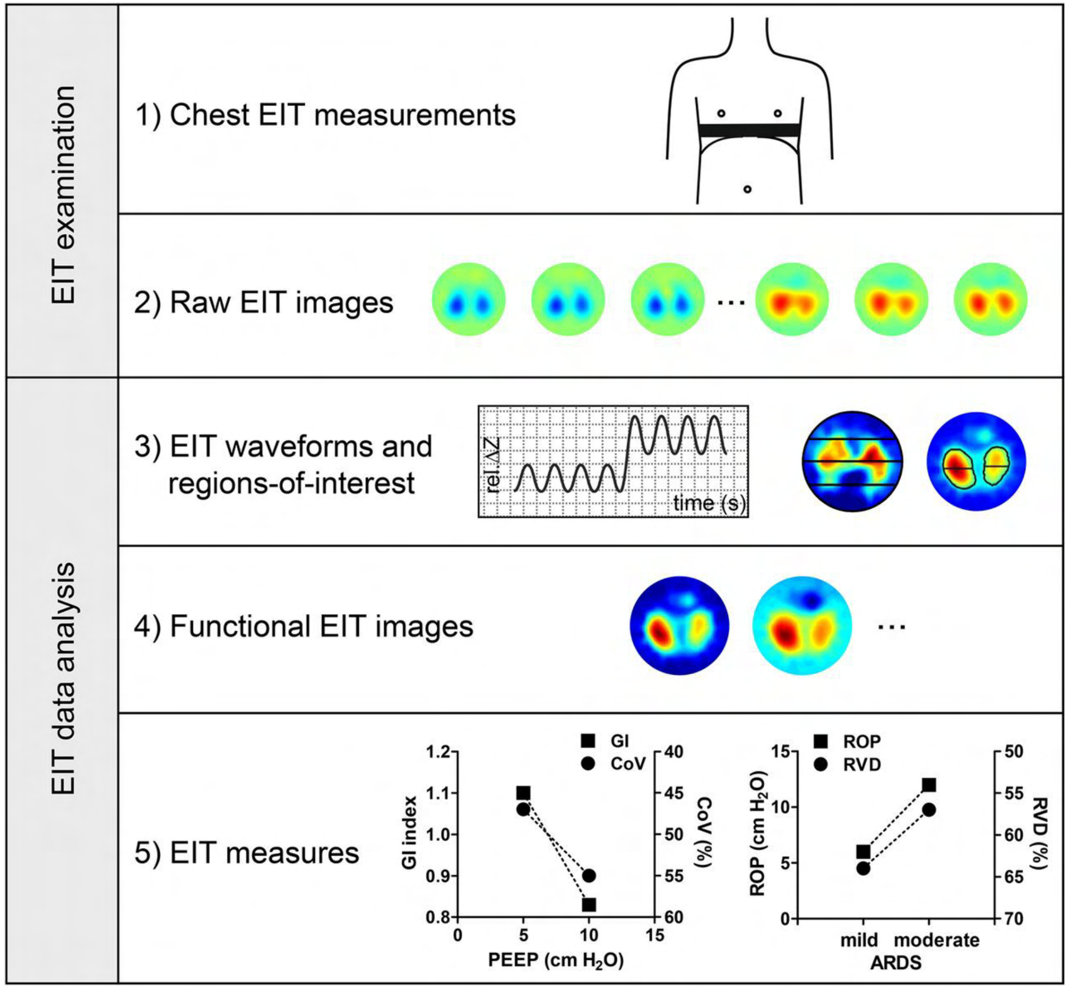
## Electrical Impedance Tomography (EIT)

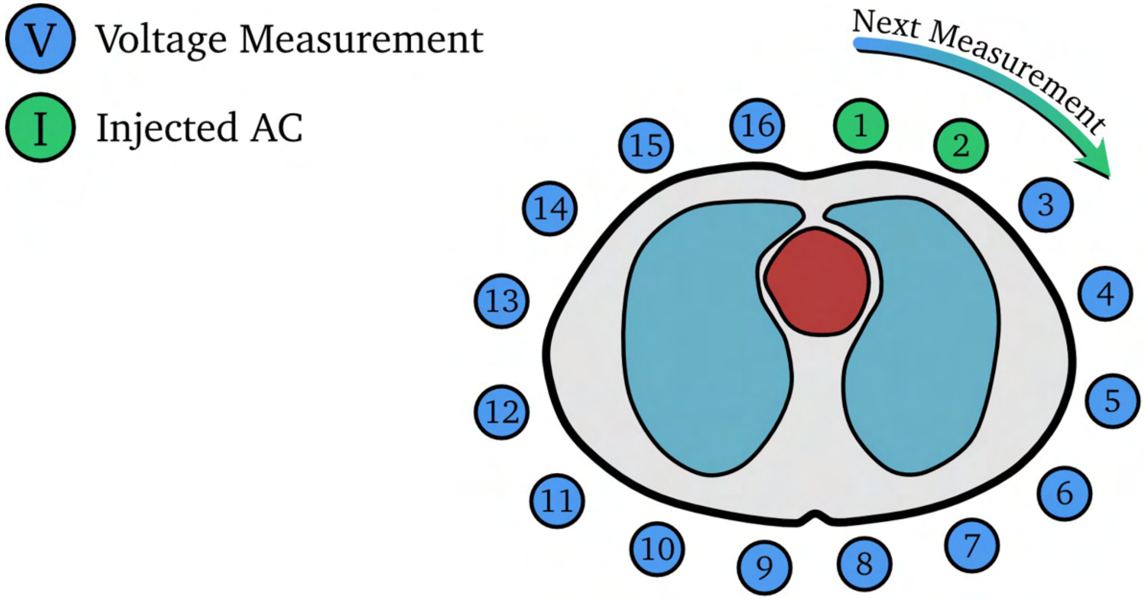


- monitoring of regional changes in ventilation without radiation
- air content and blood flow modify the electrical impedance of the lung tissue
- electrical potentials caused by excitation of a small alternating current are measured between electrodes placed around the thorax
- a typical EIT scan delivers 20-50 images per second

# Introduction




Five core processes during EIT examination and data analysis



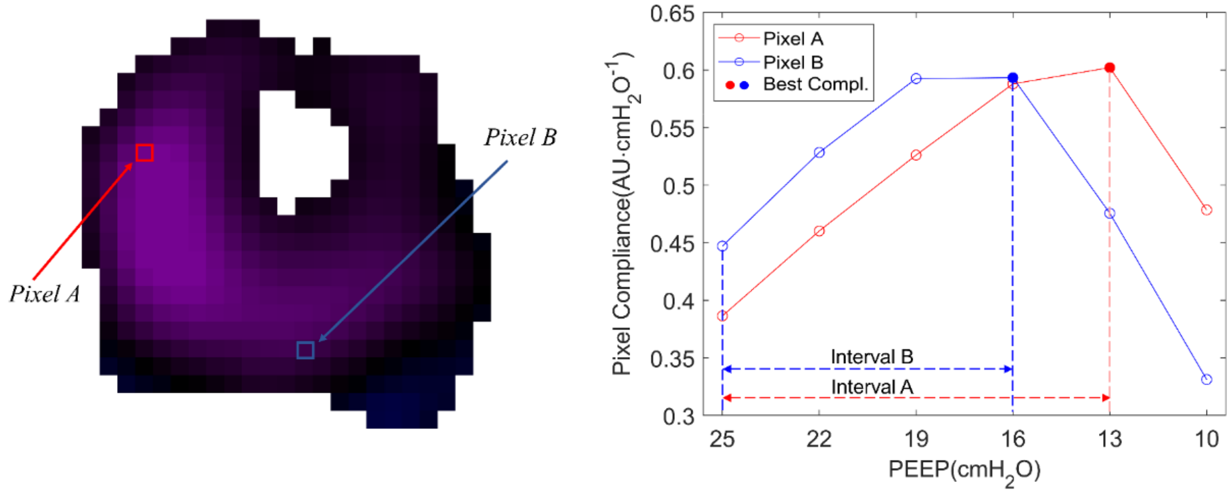



Frerichs I. et al.. Chest electrical impedance tomography examination, data analysis, terminology, clinical use and recommendations: consensus statement of the TRanslational EIT developmeNt stuDy group. Thorax. 2017 Jan;72(1):83-93. doi: 10.1136/thoraxjnl-2016-208357.

## Optimal Positive End-expiratory Pressure (Recruitment & PEEP titration)

- Dynamic respiratory system compliance ($C_{dyn}$) is a measure of the lung expandability;
- $C_{dyn}$ is the ratio between the incoming air (local tidal volume) and the corresponding driving pressure;
- The local tidal volume is highly correlated with the impedance change $\Delta Z$.

EIT-derived pixel compliance $$C_{pixel} = \frac{\Delta Z}{P_{plateau} - PEEP}$$




a b

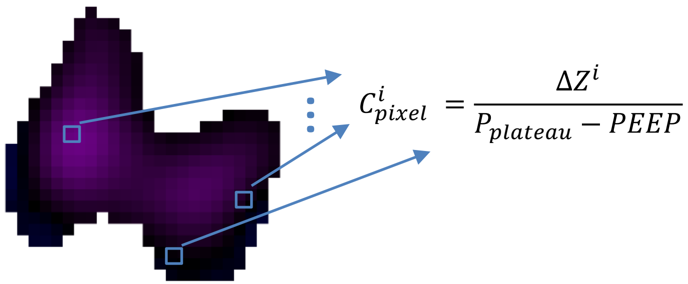
Different pixels are observed with different behaviour during the decremental PEEP trial (PEEP titration).

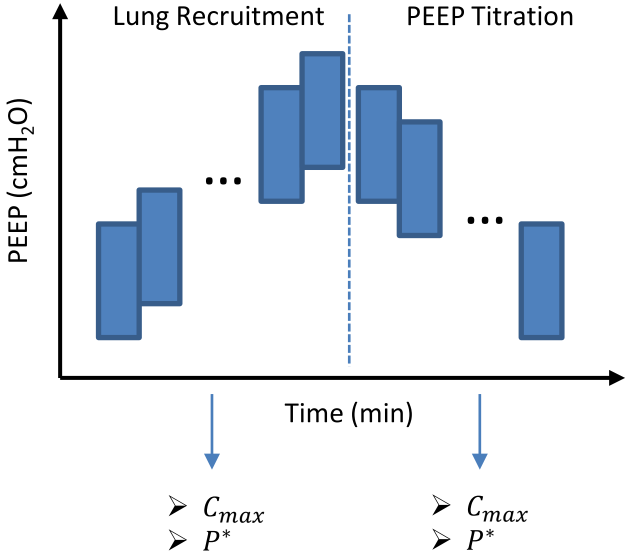
# Application

## Regional Collapse and Overdistention Estimation[*1,*2]

**Input**: EIT monitoring data during the PEEP trial, plateau pressures and PEEP settings ($P$).

1. Calculate the EIT-derived pixel compliance $C_{pixel} = \frac{\Delta Z}{P_{plateau} - PEEP}$ for each pixel;
2. Determine the pixelwise maximum compliance and the PEEP setting when it was achieved:
$$C_{max} = max\{C_{pixel}(P)\}$$
$$P^* = \arg max\{C_{pixel}(P)\}$$
3. The fraction of collapse and overdistention units in a given pixel at a designated PEEP level ($P$) is calculates:
$$F(P) = \begin{cases} \frac{C_{pixel}(P) - C_{max}}{C_{max}}, if\ P < P^* \\ \frac{C_{max} - C_{pixel}(P)}{C_{max}}, if\ P \geq P^* \end{cases}$$



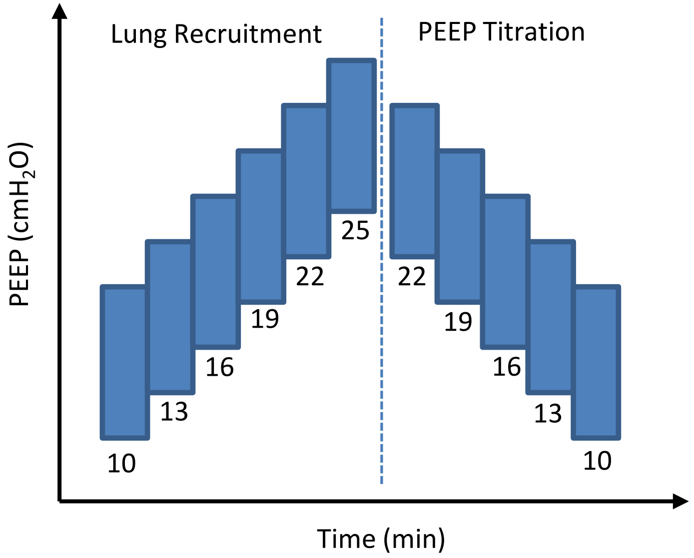




*1E. L. V. Costa et al., Bedside estimation of recruitable alveolar collapse and hyperdistension by electrical impedance tomography, doi: 10.1007/s00134-009-1447-y.
*2C. Gomez-Laberge, J. H. Arnold, and G. K. Wolf, A Unified Approach for EIT Imaging of Regional Overdistension and Atelectasis in Acute Lung Injury, doi: 10.1109/TMI.2012.2183641.

## Patient data analysis

| Patient Ref. | Gender | Age, yr | BMI, $kg/m^2$ | APACHE II | RASS Scale | Days of trial |
|---|---|---|---|---|---|---|
| A | Male | 79 | 27.7 | 16 | -4 | 2 |
| B | Female | 67 | 29.7 | 17 | -4 | 7 |
| C | Male | 83 | 26.0 | 22 | -4 | 4 |
| D | Female | 81 | 31.2 | 18 | -5 | 12 |

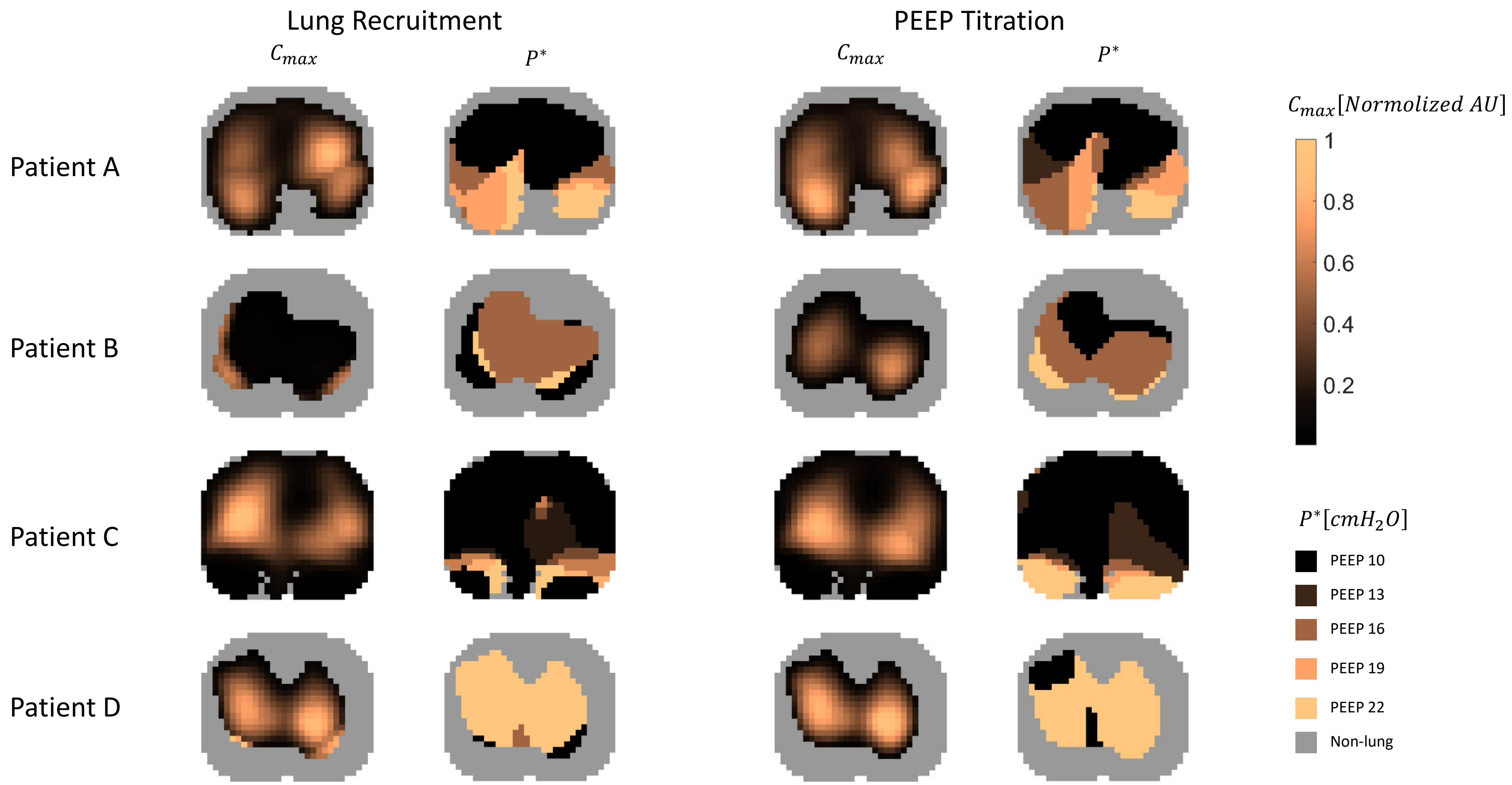
- All patients were sedated and supported by mechanical ventilation (pressure control);
- All patients were applied with the same PEEP trial maneuver: 3 $cmH_2O$ step, 10→25→10 $cmH_2O$, each PEEP step 2 mins;
- EIT data were collected by Dräger PulmoVista 500 (Dräger Medical, Lübeck, Germany) with belt on 5th intercostal space (ICS);
- EIT reconstructed by Newton-Raphson algorithm with Tikhonov prior.




The study was approved by the Human Investigation Review Board of the University of Szeged with approval number 67/2020-SZTE.

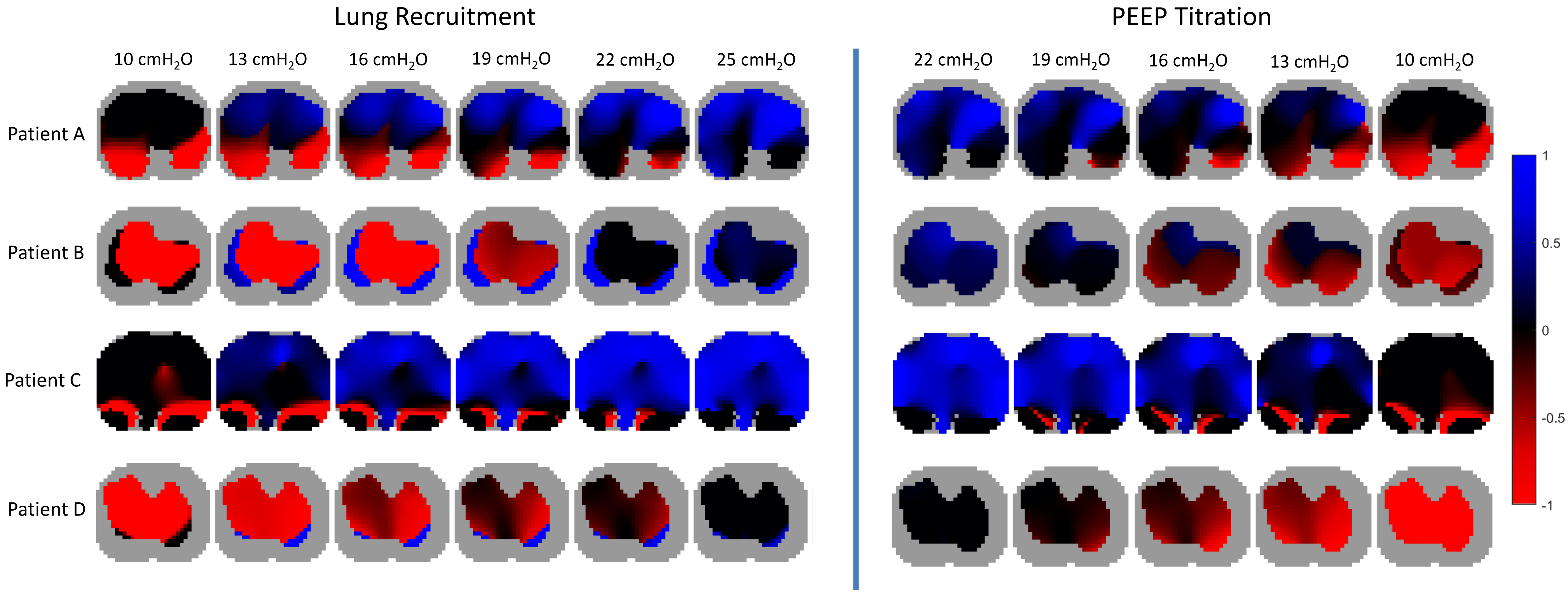
# Application

## $C_{max}$ and $P^*$ maps



# Application

## Regional Collapse (Red) and Overdistention (Blue) Estimation

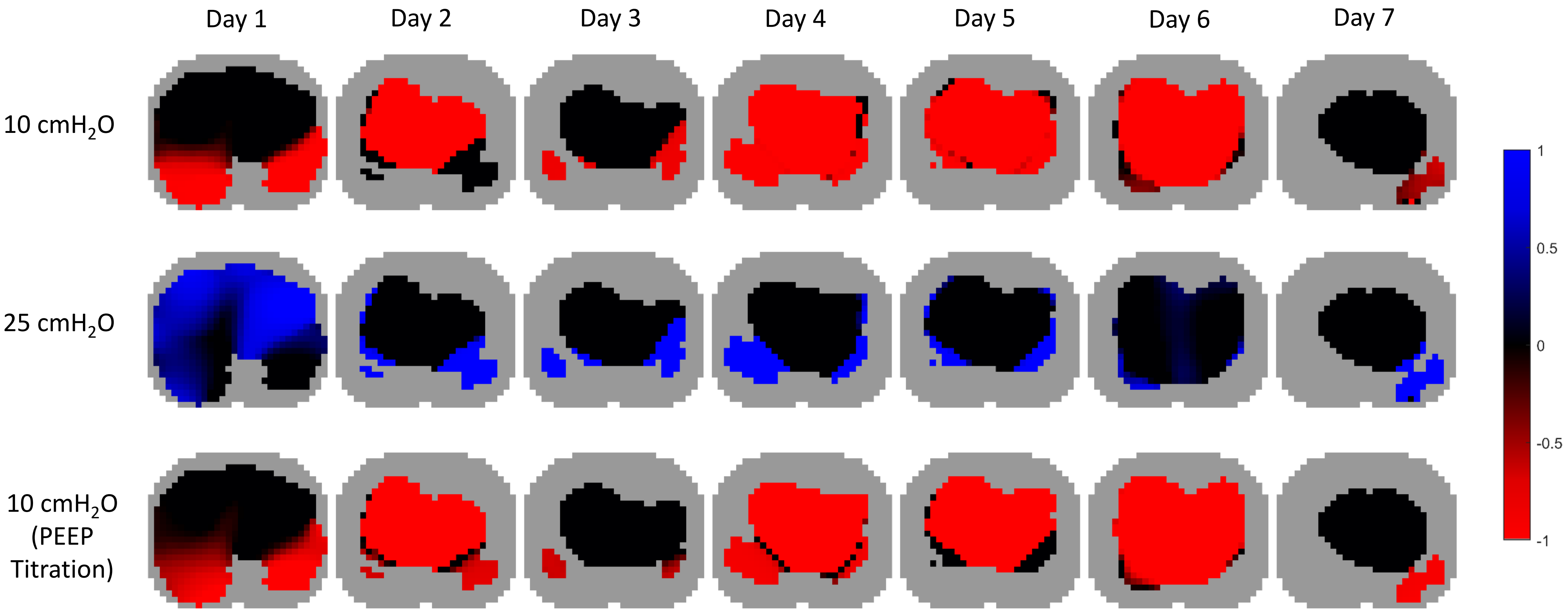



- Collapse is expected at a lower PEEP step, overdistention detected at a higher PEEP step.
- Overdistention ratios for patient A and C are larger than those of patient B and D.
- Patient B and D is observed with larger collapse ratio than other patients.



Lovas A, Chen R, Molnár T, Benyó B, Szlávecz Á, Möller K. Differentiating Phenotypes of Coronavirus Disease-2019 Pneumonia by Electric Impedance Tomography. doi:10.3389/fmed.2022.747570.

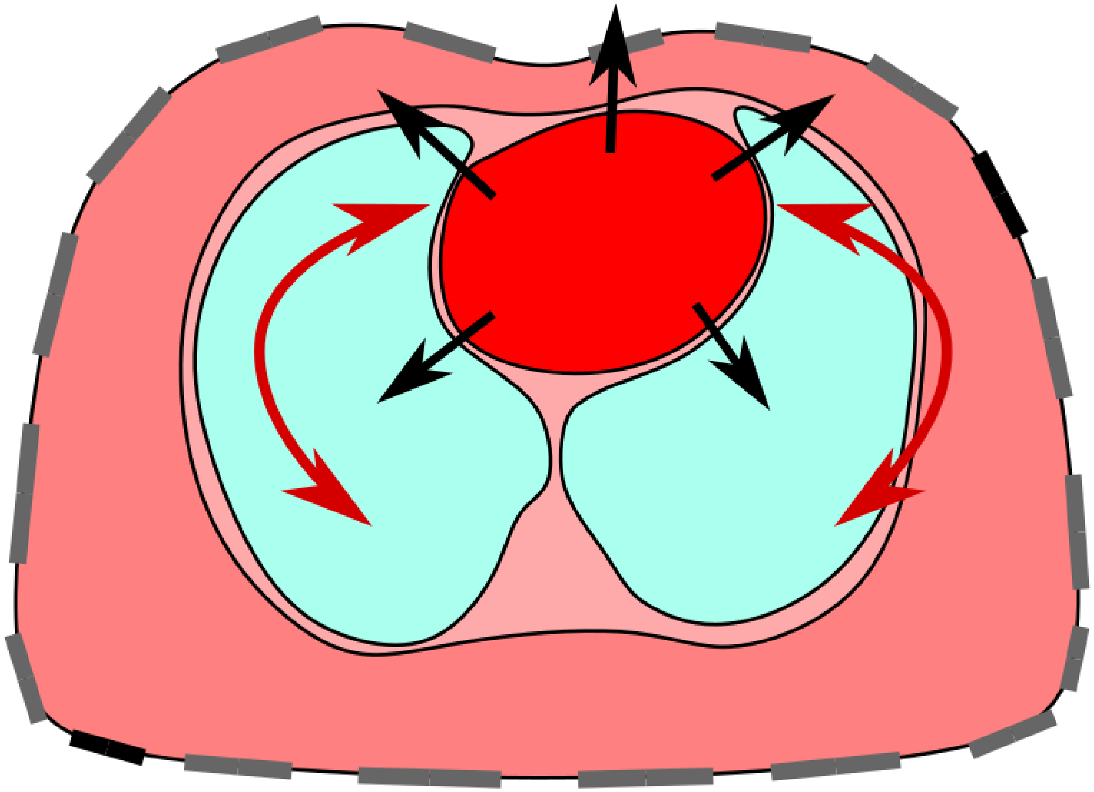
## Long-term monitoring



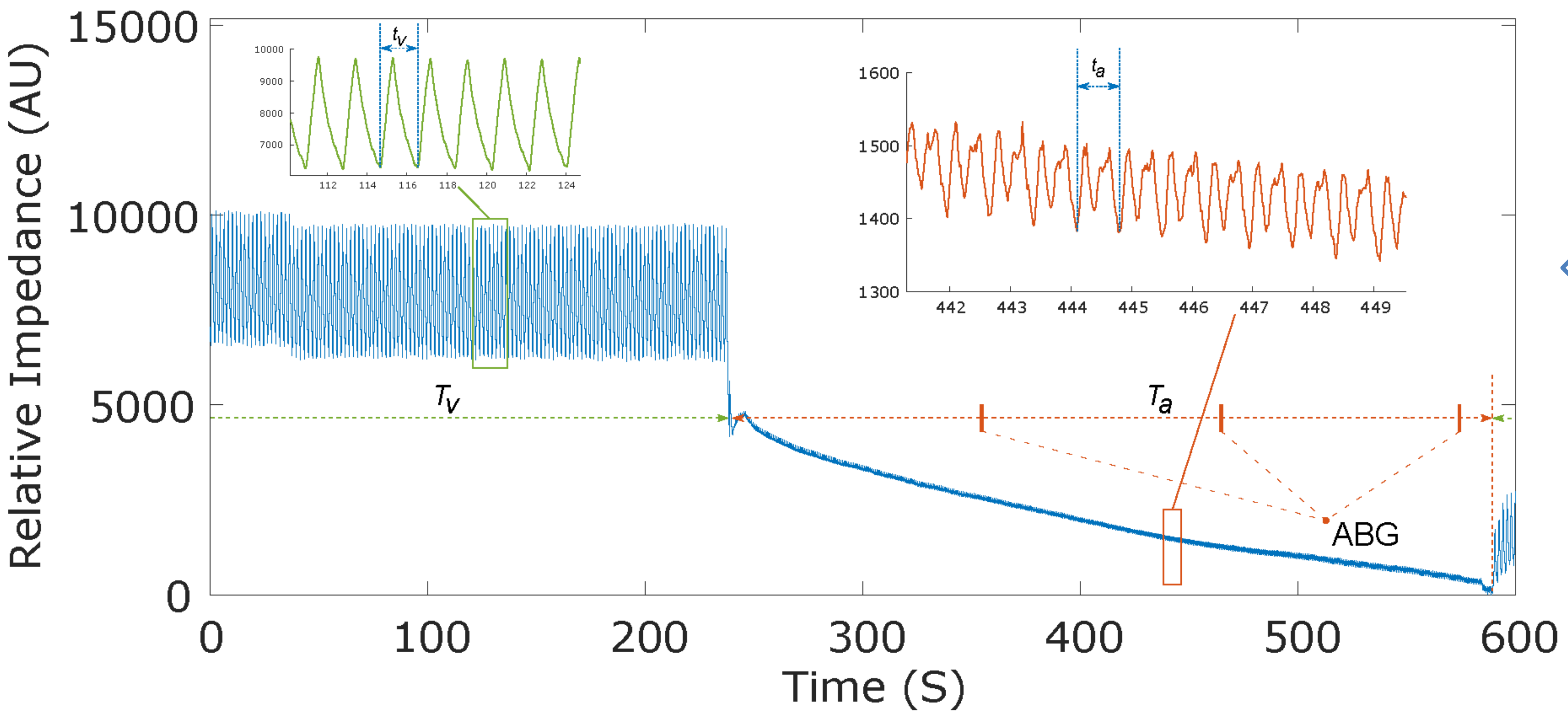

Patient B shows a decreasing trend of overdistention ratio at the PEEP 25 $cmH_2O$ during the seven-day monitoring; the collapse ratio at the PEEP 10 $cmH_2O$ after the PEEP titration generally increased on day 4 to day 6.

## Perfusion Monitoring

- EIT has the potential to determine ventilation related and pulsatile impedance changes in the lung
- Electrical impedance amplitudes caused by ventilation are much higher than those associated by cardiac activity (~ 10 times)



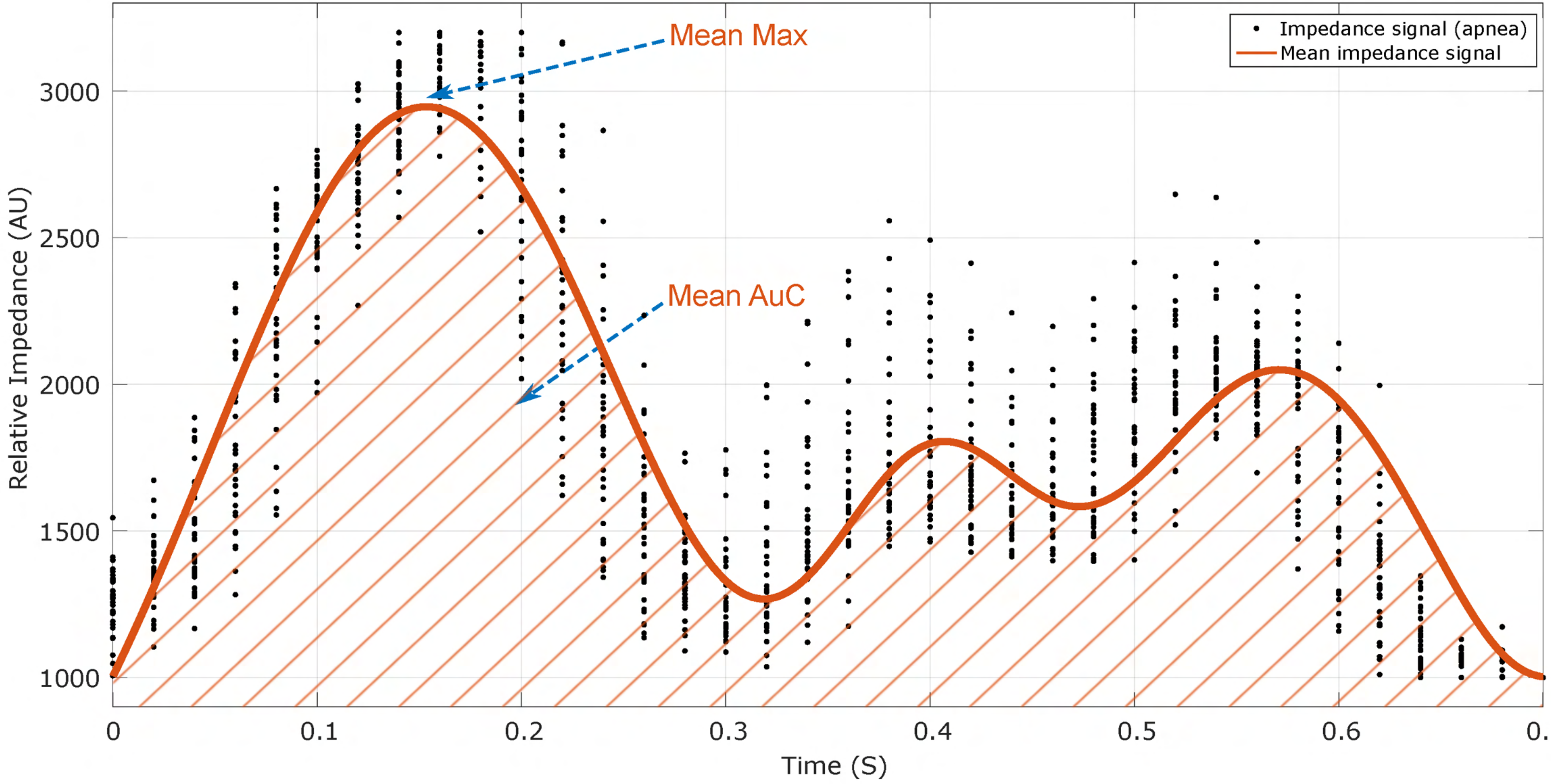
# Application



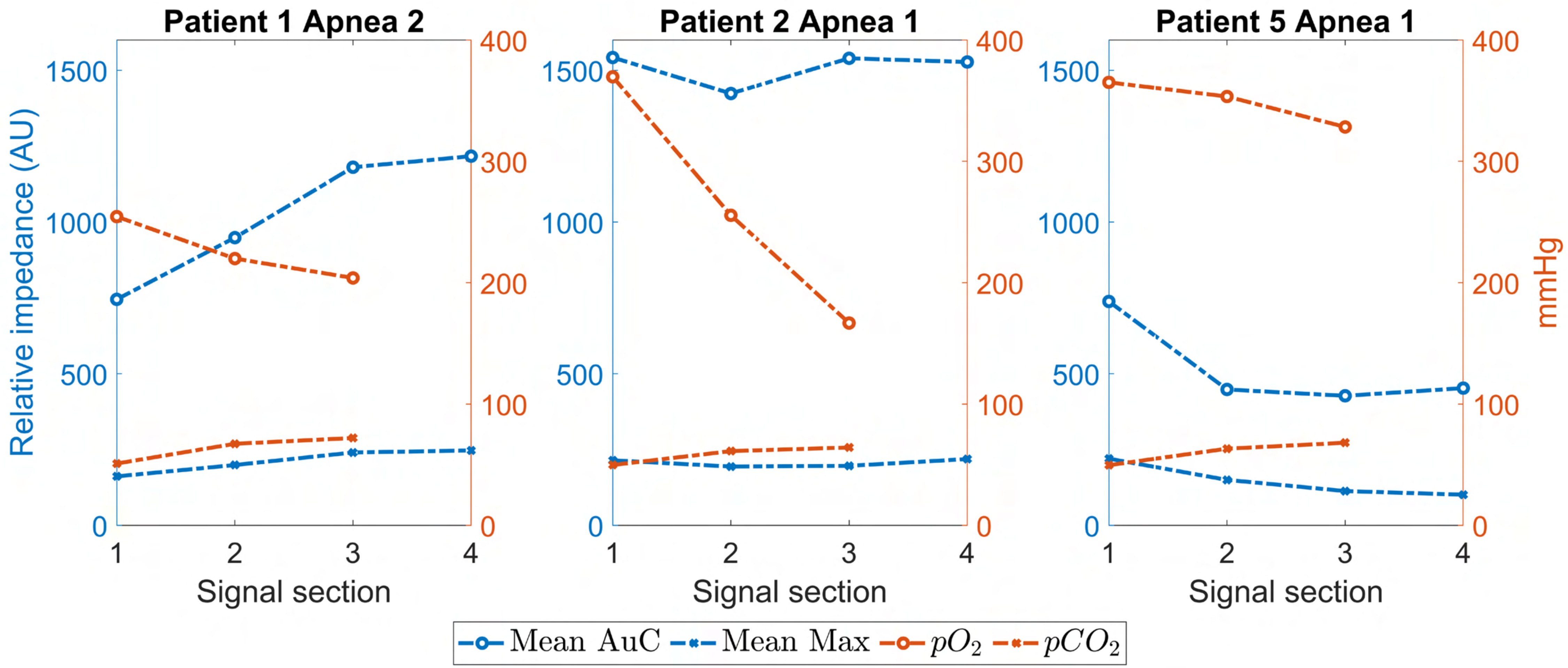

Apnoea Test

- The determination of brain death;
- The patient is disconnected from the ventilator. Oxygen supplementation is at a rate of 6 L/min;
- The duration of an AT is 7 to 10 minutes.

# Application



# Application



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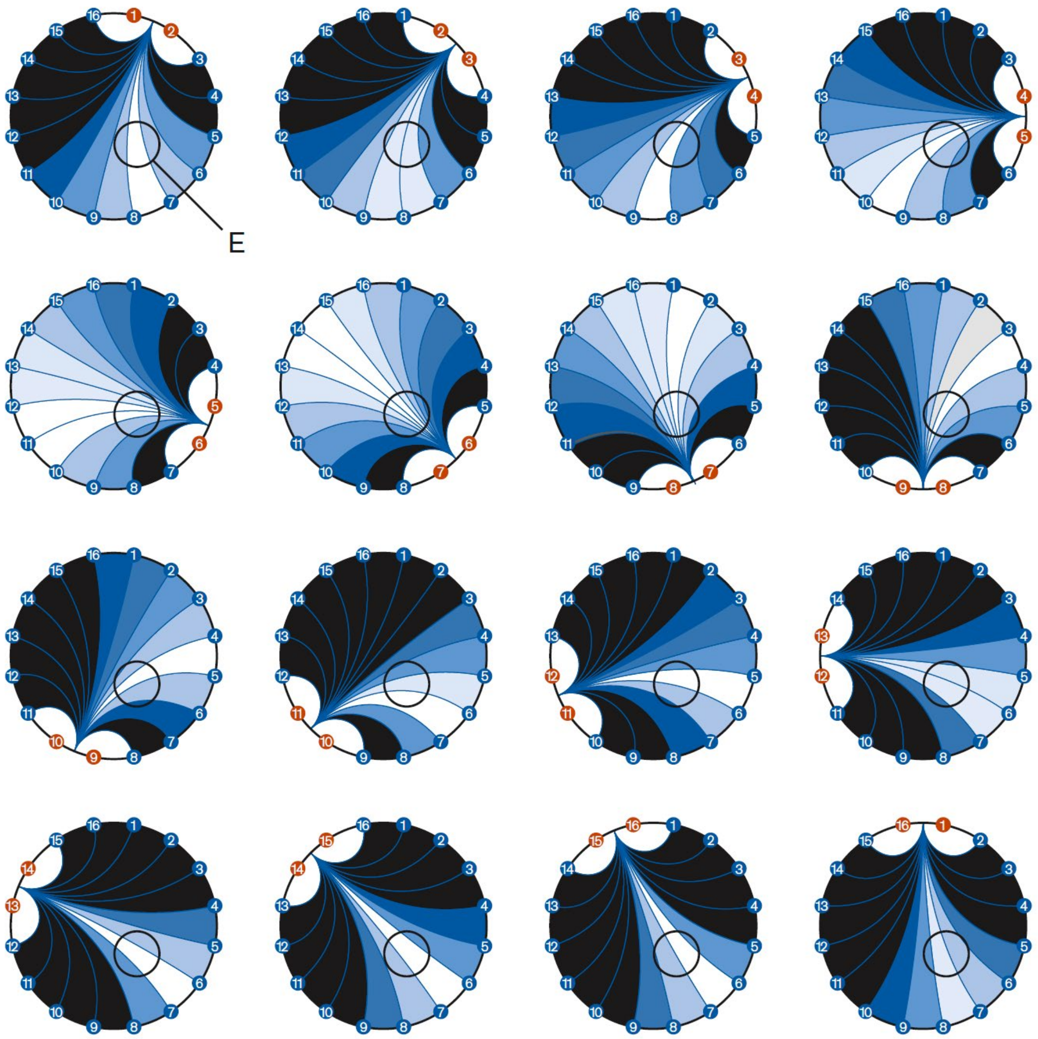
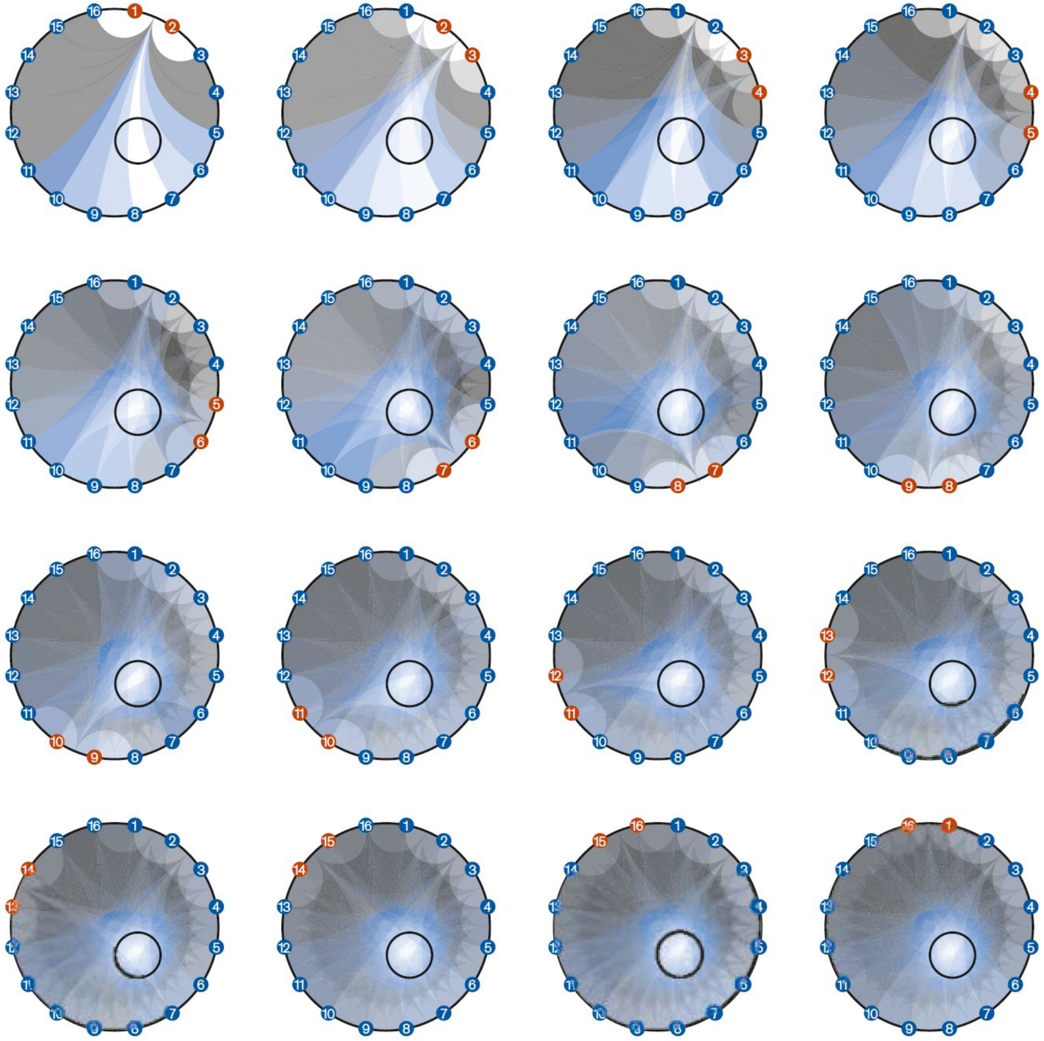
# Algorithms



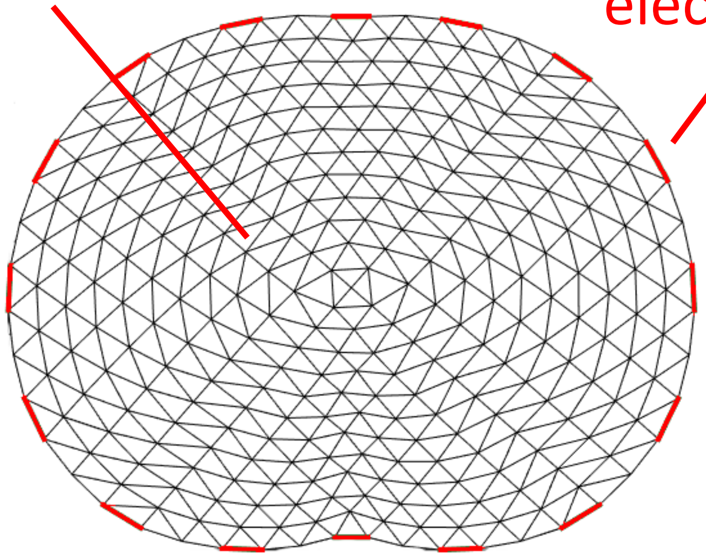

Voltage deviations in the presence of a regional increase of impedance



Successive superposition of the 16 voltage profiles

Photos: Dräger AG, Germany

## EIT Reconstruction




forward model

prior

voltage change (e.g. $\mathbf{y} \in \mathbb{R}^{208}$)

"prior", e.g., Tikhonov, $\mathbf{R} = \mathbf{I}$

$$\hat{\mathbf{x}} = \arg\min_{\mathbf{x}} \left\{ \|\mathbf{J}\mathbf{x} - \mathbf{y}\|_2^2 + \lambda^2 \|\mathbf{R}\mathbf{x}\|_j^j \right\}$$

conductivity change (e.g., $x \in \mathbb{R}^{5000}$)

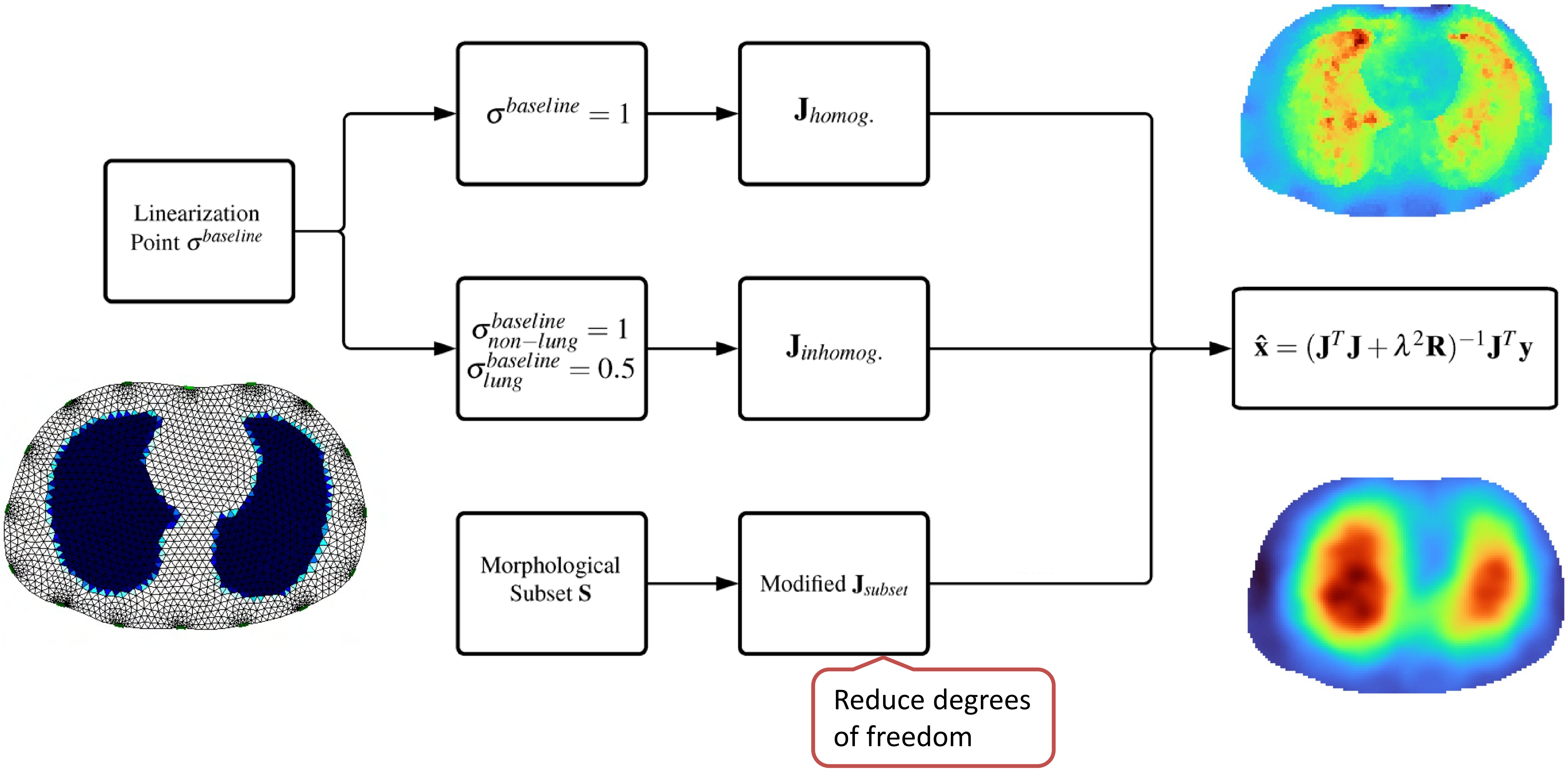
$$\hat{\mathbf{x}} = \left(\mathbf{J}^{\mathbf{T}}\mathbf{J} + \lambda^2 \mathbf{R}\right)^{-1} \mathbf{J}^{\mathbf{T}}\mathbf{y}$$

$\mathbf{x}$: conductivity change
$\mathbf{y}$: boundary voltage measurement
$\mathbf{J}$: Jacobian matrix
$\mathbf{R}$: regularization parameter
$\lambda$: scalar value

$\mathbf{x}$: thousands of unknown conductivities
$\mathbf{y}$: hundreds of measurements

# Algorithms

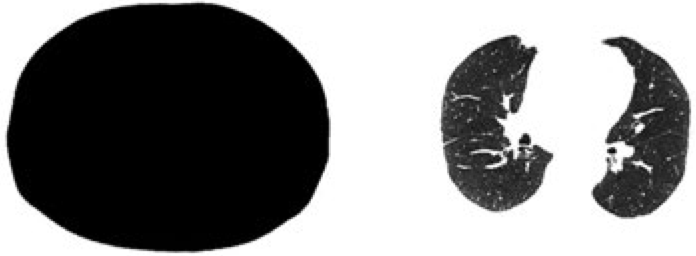
## Structural Priors



# Algorithms

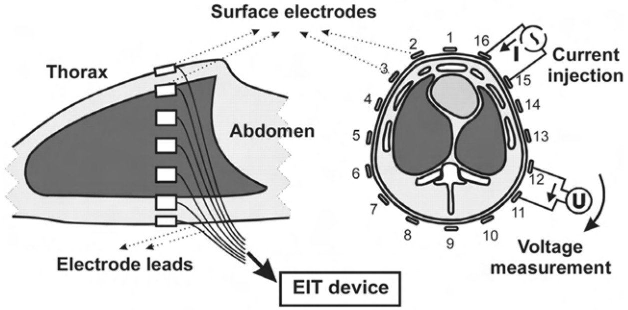
Original CT image

separate thorax contour
and lung contour



generate
patient-specific
forward model

generate
structural prior
mask




- The structural prior mask can be introduced at different stages of the algorithm
- The structural prior mask is used to modify the Jacobian matrix $\mathbf{J}$ in the algorithm
- Structural prior mask is introduced by the discrete cosine transform (DCT)-based EIT algorithm

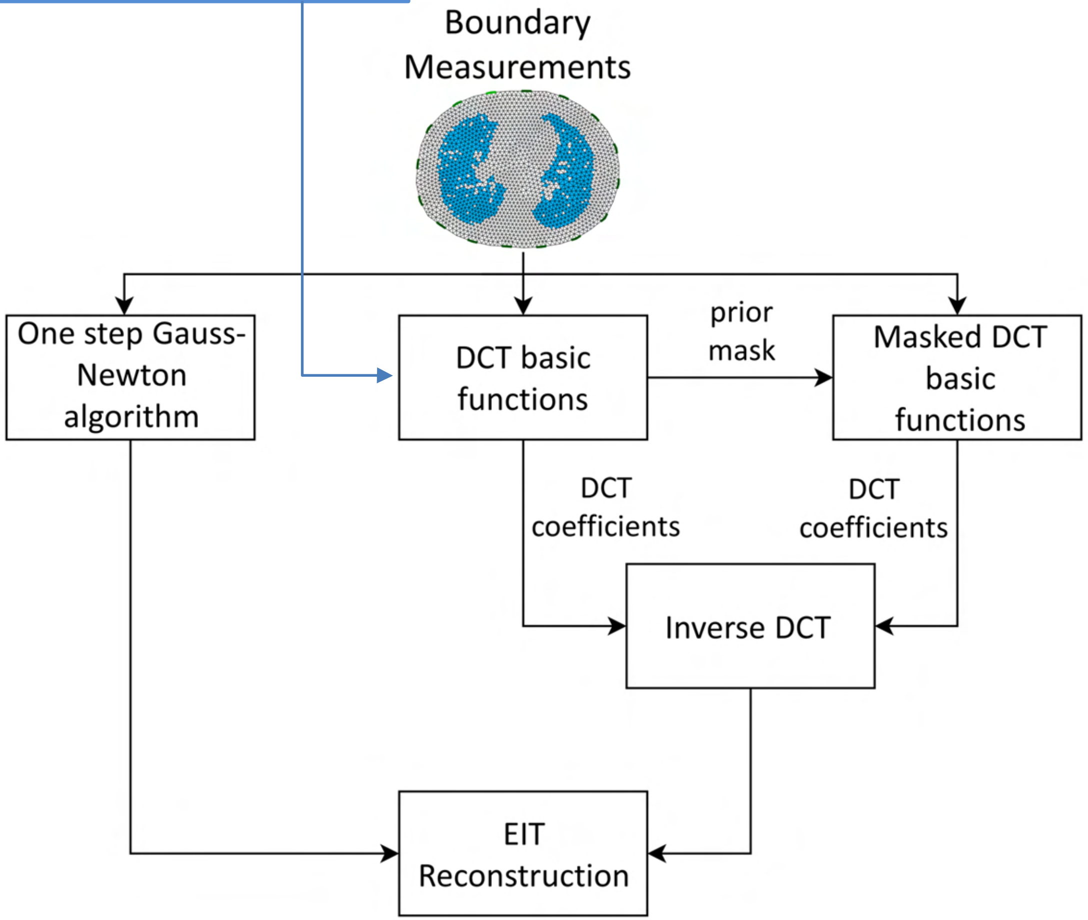


Chen R, Krueger-Ziolek S, Lovas A, Benyó B, Rupitsch SJ, Moeller K. Structural priors represented by discrete cosine transform improve EIT functional imaging. PLoS ONE 18(5): e0285619. doi: 10.1371/journal.pone.0285619

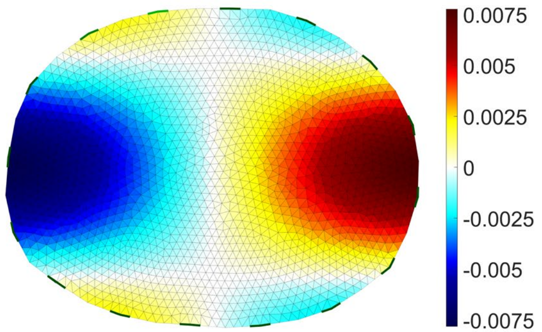
# Algorithms

$\mathbf{K}_j = T(\mathbf{C}(p, q))$

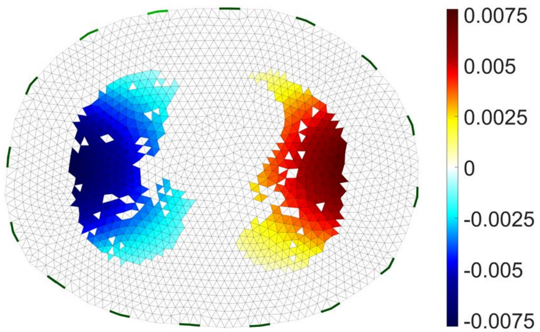
$p, q$: DCT frequencies




For the details of the algorithm, please visit my GitHub: [https://github.com/rongqing-chen/DCT-EIT](https://github.com/rongqing-chen/DCT-EIT)




DCT basic functions
Frequence: p = 1, q = 2

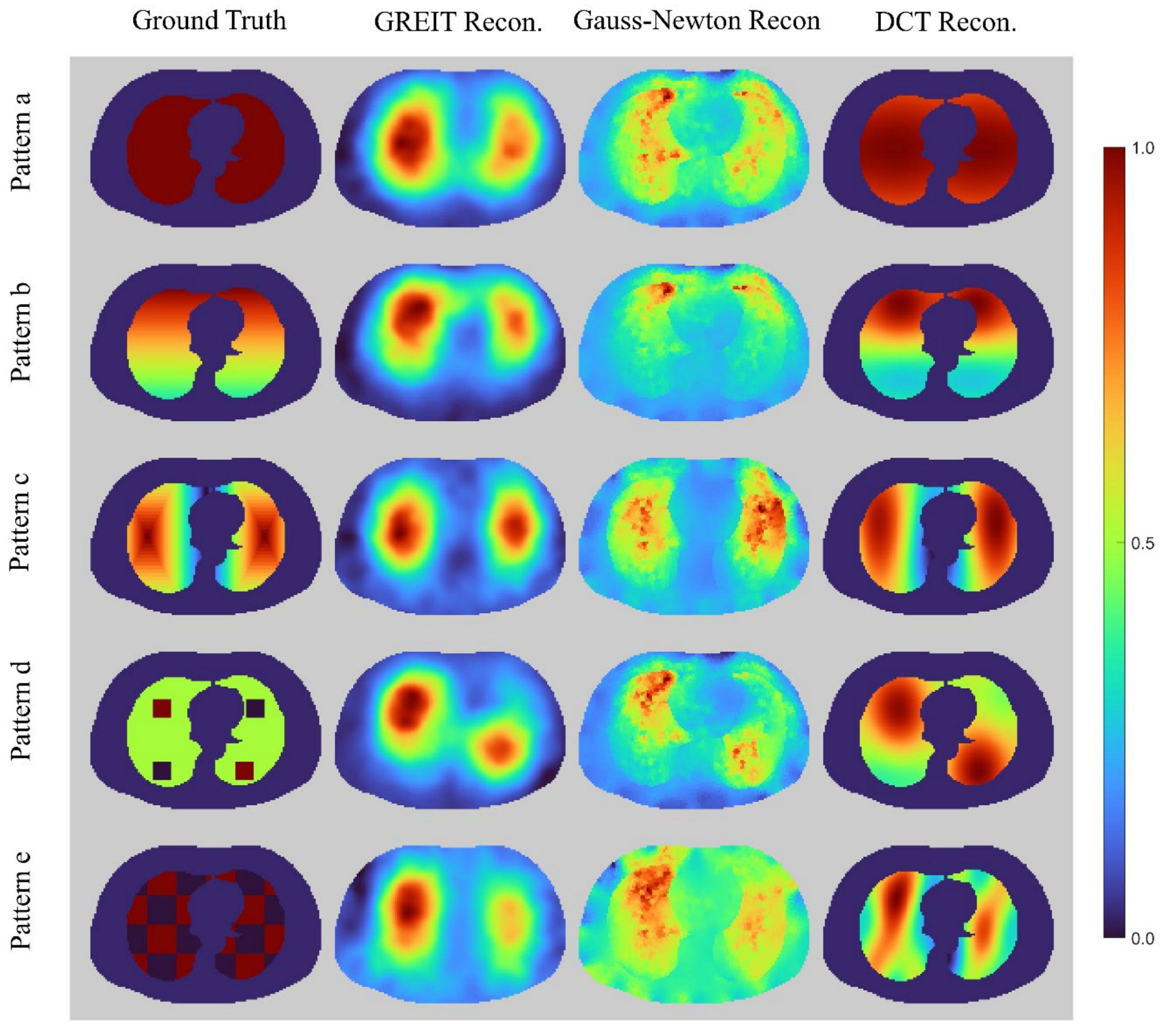


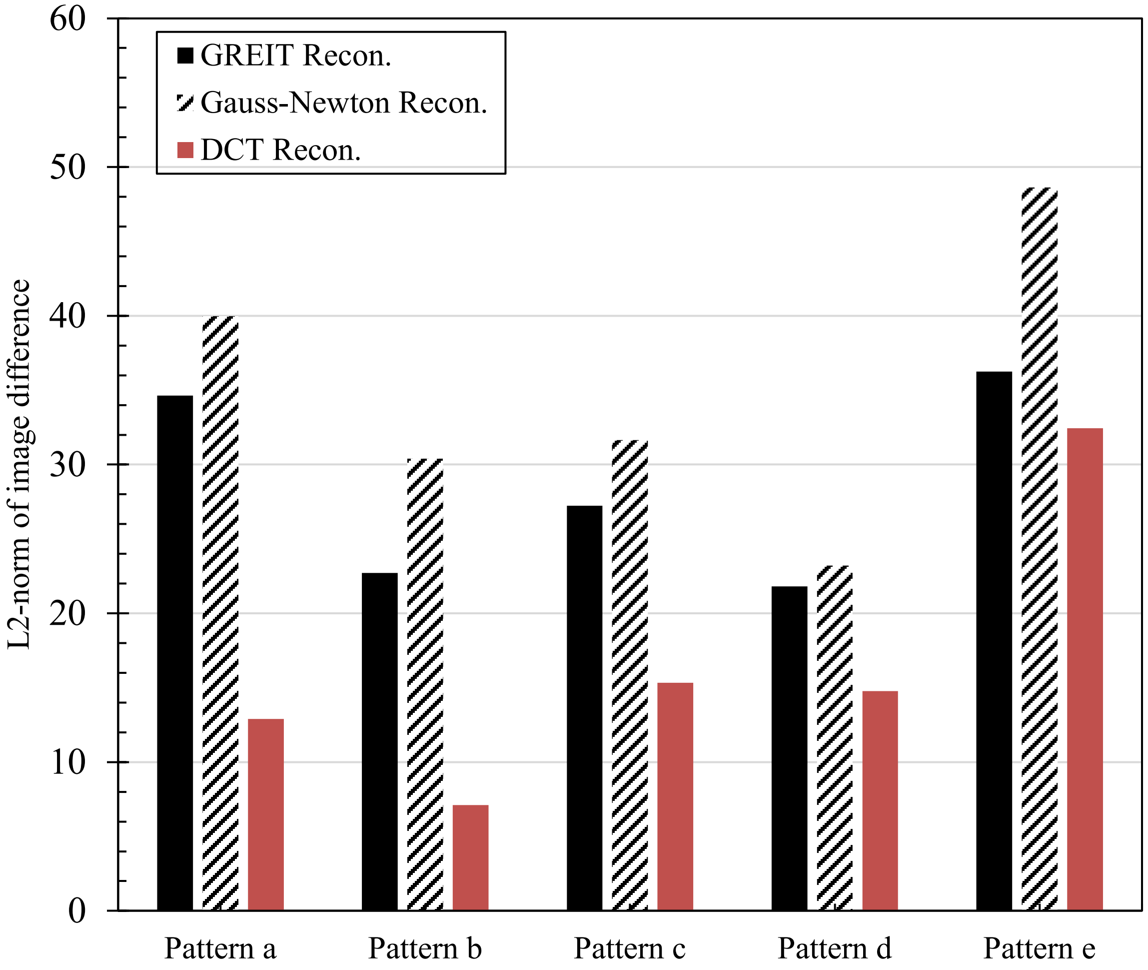

Masked DCT basic functions
Frequence: p = 1, q = 2

- In the conventional EIT algorithm, $\mathbf{J}$ maps the voltage changes to the variation of the conductivity distribution ($\mathbf{J}^{meas \times elems}$)
- In the DCT-based EIT algorithm, $\mathbf{J}_{DCT}$ maps the voltage changes to the variation of the DCT coefficients ($\mathbf{J}_{DCT}^{meas \times subsets}$)
- In this contribution, we have 15 frequencies on x- and y-axis, i.e., 225 combinations in total

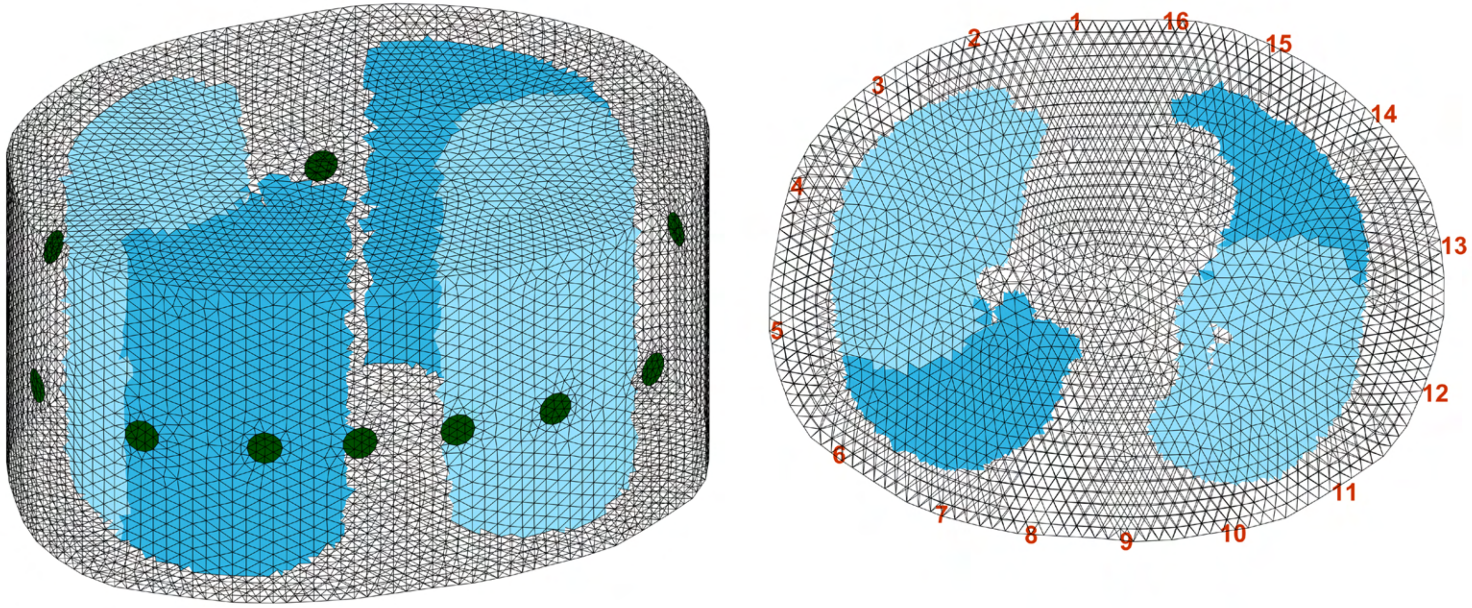
# Algorithms

## Reconstructions – DCT-based



# Algorithms

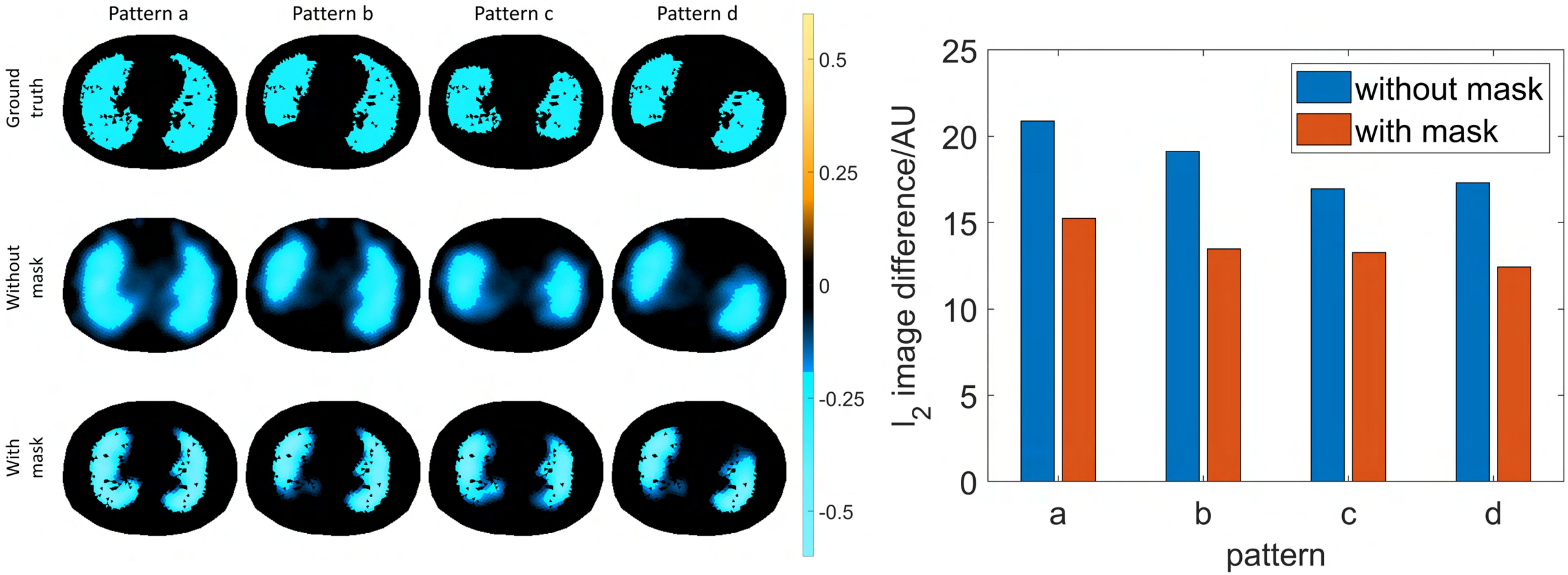



- Four different simulation patterns
    a. complete lung with homogeneous ventilation
    b. dorsal right lung with no ventilation
    c. most ventral and dorsal parts of both lungs with no ventilation
    d. ventral left lung and dorsal right lung with no ventilation
- Simulations were conducted using Eidors Toolbox with Matlab® 2019a
- 1% of the Gaussian noise is added to the voltage measurement



For the details of the Eidors toolbox, please visit: https://eidors3d.sourceforge.net/

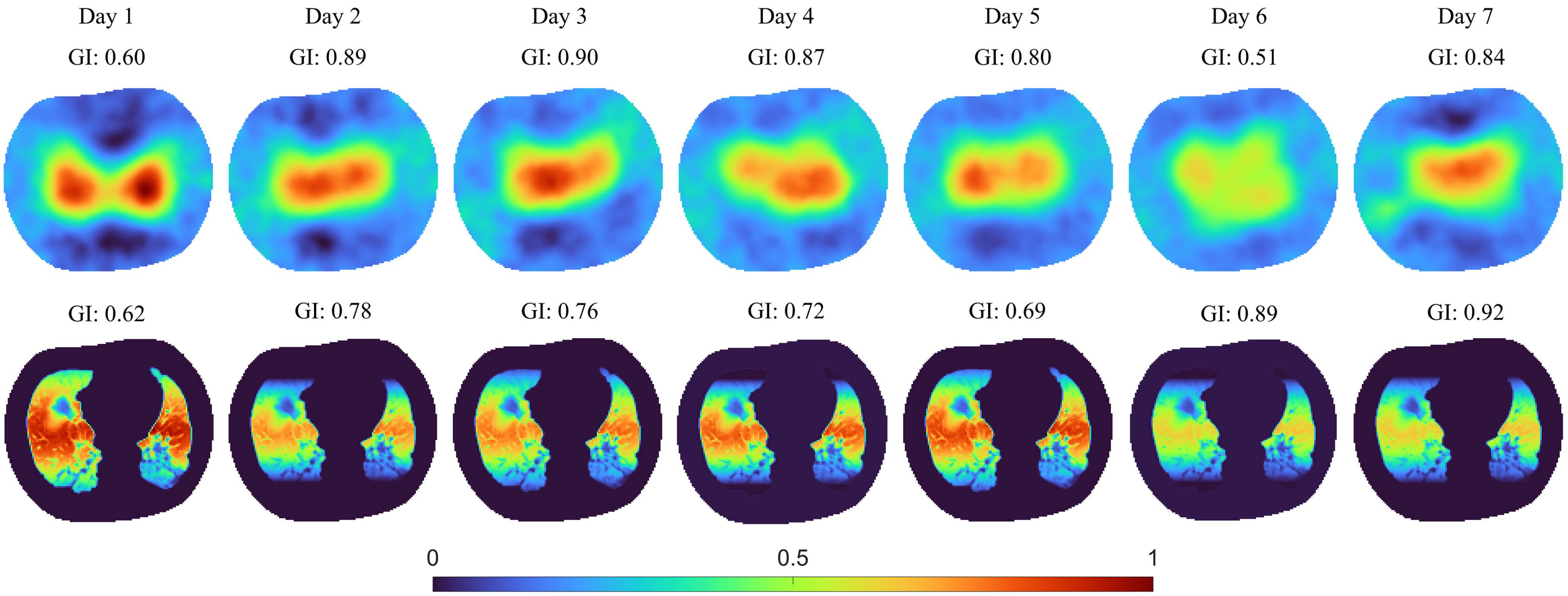
## Reconstructions – DCT & Mask






R. Chen, S. Krueger-Ziolek, A. Battistel, S. J. Rupitsch, and K. Moeller. Effect of a Patient-Specific Structural Prior Mask on Electrical Impedance Tomography Image Reconstructions. Sensors, vol. 23, no. 9, p. 4551, May 2023

## Long-term monitoring – Patient Data




A seven-day monitor procedure of the patient B at the PEEP stage of 25 $cmH_2O$. was reported to undergo an exacerbation on the third day and the sixth day, which is easily recognised as less ventilation is found in the reconstructions.

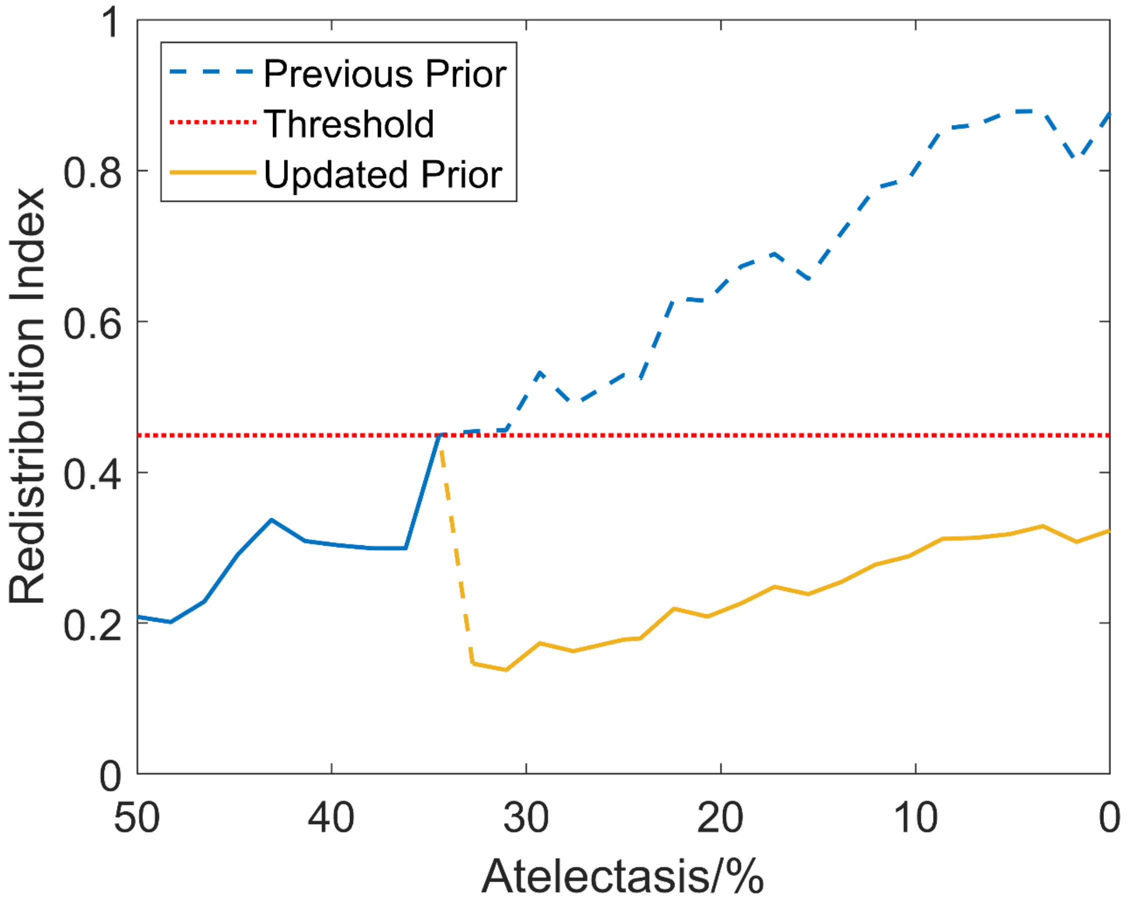
## Outdated Structural Priors

- **Problem**: reconstruction is just as good as the validity of the prior assumption
- During the treatment of patients, or development course of disease, prior might lose its validity
- Outdated prior information might induce a risk in terms of misleading interpretation of the results, and compromise the diagnosis

**PEEP** 15 $cmH_2O$ **VT** 12 ml/kg | **PEEP** 10 $cmH_2O$ **VT** 10 ml/kg | **PEEP** 5 $cmH_2O$ **VT** 8 ml/kg

The reconstruction error induced by structural prior should be quantified.

## Redistribution Index (RI)




- Previous prior (fixed prior) lost validity and produced misleading when the atelectasis scales get reduced. Thus, the RI from AT50 prior increased as the atelectasis scale decreases;
- When RI exceeded the threshold, the difference between the real patient status and fixed prior became intolerant;
- After the prior update, the RI dropped by 62%, which indicates the prior has less difference than the current patient status;
- When the difference between the real patient status and updated prior became larger because of the decreasing atelectasis scale, RI was rising again.

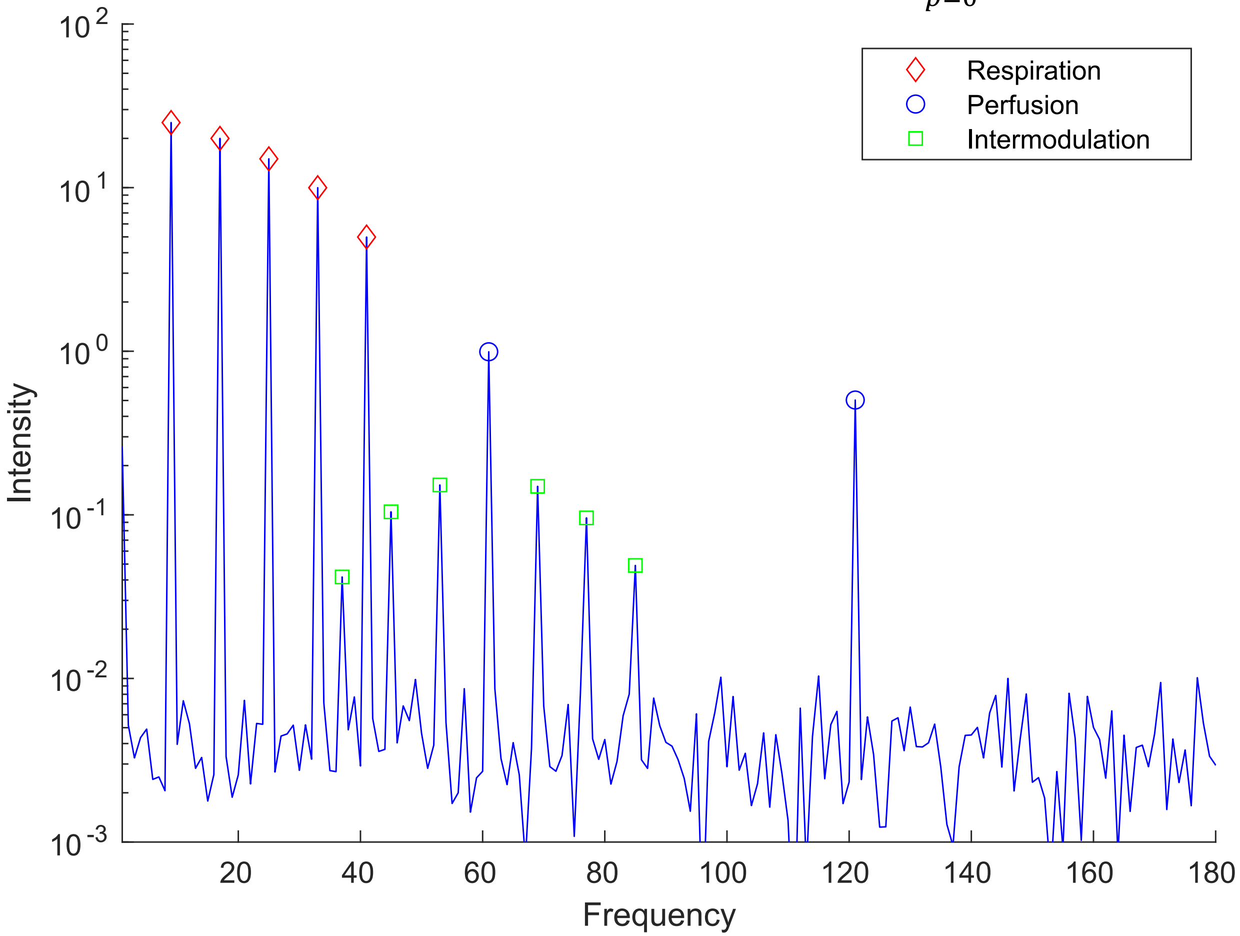
# Separation of respiration and perfusion

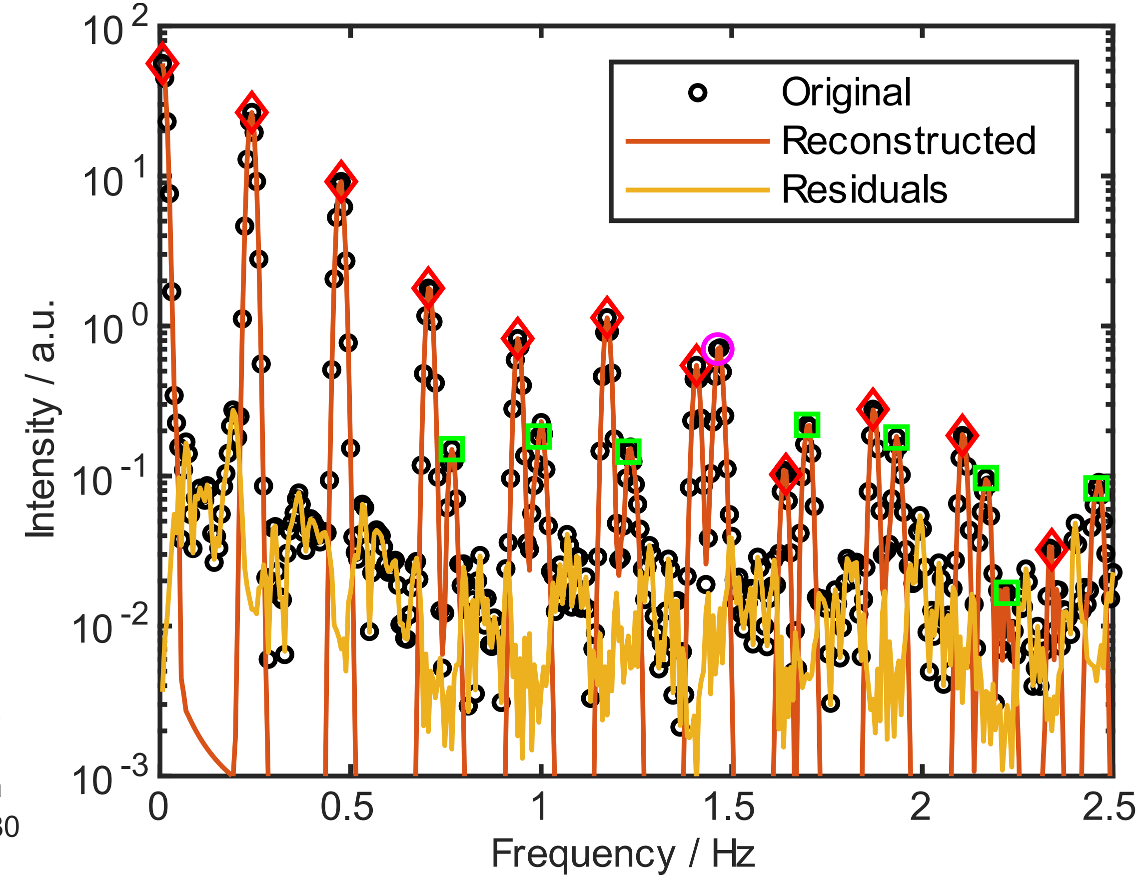
- Pulsatile impedance changes can be obtained by different methods:
  - breath holding (apnoea)
  - use of contrast agents (saline)
  - ECG gating
  - **Harmonic Analysis**

$$y(t) = \sum_{f \in H} g_f(t)\cos(2\pi f t) - h_f(t)\sin(2\pi f t)$$

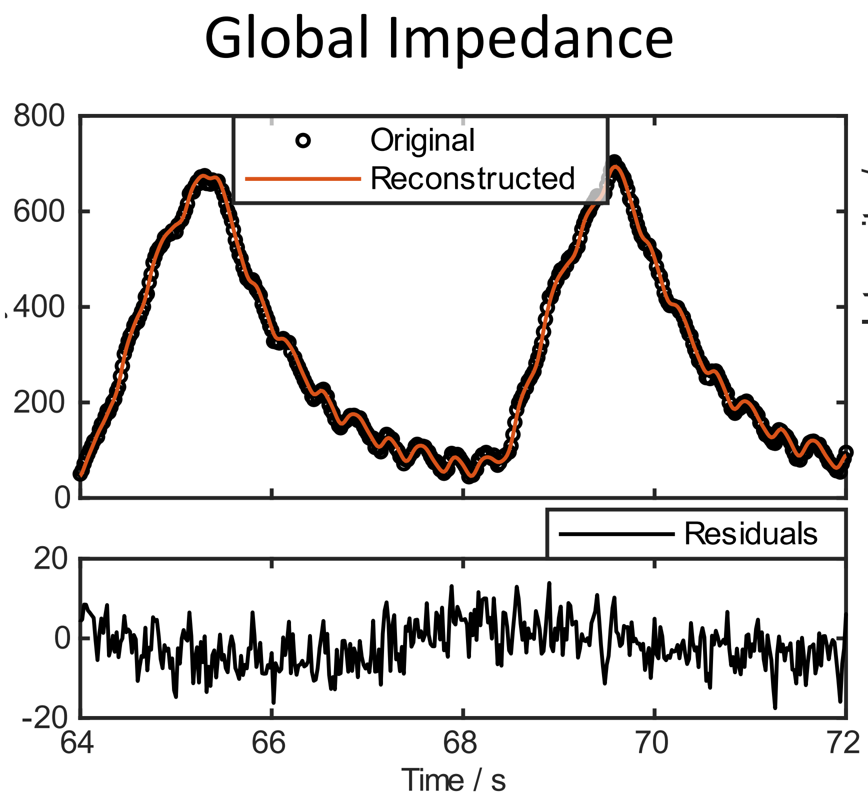
$$g_f(t) = \sum_{p=0}^{N_p} \theta^{g}_{f,p} b_p(t)$$

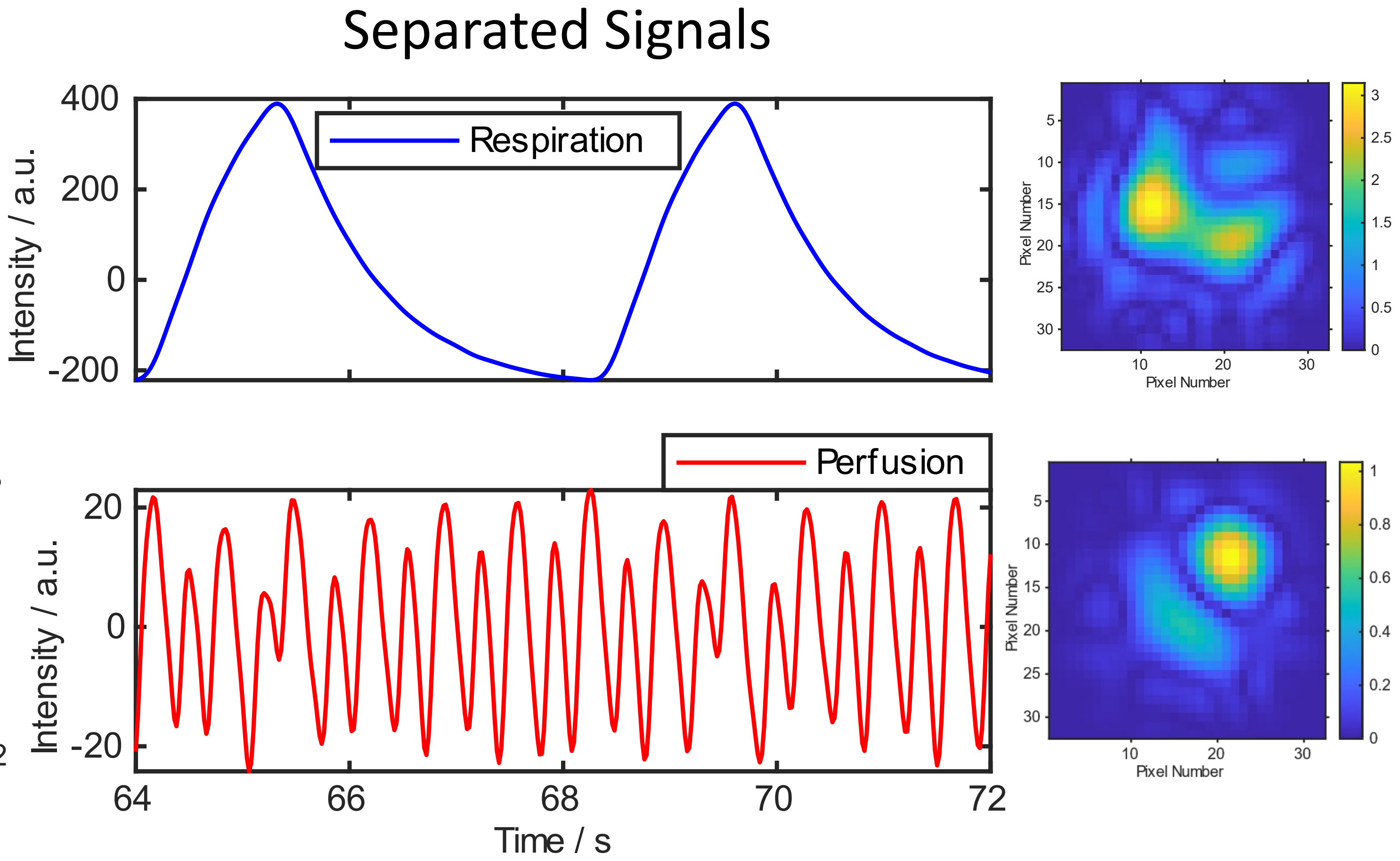
$$h_f(t) = \sum_{p=0}^{N_p} \theta^{h}_{f,p} b_p(t)$$



# Separation of respiration and perfusion





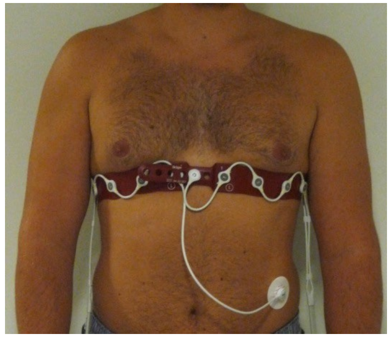

Stein, E., Chen, R., Battistel, A., Krueger-Ziolek, S., & Moeller, K.. Voltage-based separation of respiration and cardiac activity by harmonic analysis in electrical impedance tomography. IFAC Journal of Systems and Control, 100248. doi: 10.1016/j.ifacsc.2024.100248

# Combination of Measurements

Electrical Impedance Tomography

Body Plethysmography (Pulmonary Function Test)

Motion Tracking System (VICON)




- Laufer B, Hoeflinger F, Docherty PD, Jalal NA, Krueger-Ziolek S, Rupitsch SJ, Reindl L, Moeller K. Characterisation and Quantification of Upper Body Surface Motions for Tidal Volume Determination in Lung-Healthy Individuals. Sensors. 2023; 23(3):1278. doi: 10.3390/s23031278
- Laufer B, et al.. Optimal Positioning of Inertial Measurement Units in a Smart Shirt for Determining Respiratory Volume. 2023 45th Annual International Conference of the IEEE Engineering in Medicine & Biology Society (EMBC), Sydney, Australia, 2023; pp. 1-4. doi: 10.1109/EMBC40787.2023.10340473

# Summary

- EIT validity and reproducibility was confirmed in several experimental and clinical studies with reference techniques like CT, Single-photon emission CT, PET, inert-gas washout and spirometry;
- General uses of thoracic EIT have been proposed in adult patients:
  - Monitoring of mechanical ventilation;
  - Monitoring of heart activity and lung prefusion;
- EIT examinations over time often provide unique clinical information difficult to obtain by other methods at the bedside. Almost without side effects, EIT allows the sensitive and prompt assessment of lung characteristics over the course of disease and treatment.

# Limitations

- Ill-posed problem and low spatial resolution, that requires prior knowledge;
- Different forms of priors can be incorporated:
  - General constraints;
  - Patient specific e.g. anatomical priors (static) or dynamic prior;
- Priors can be misleading if it lose its validity.

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