HOCHSCHULE FURTWANGEN UNIVERSITY HFU

ITeM Institute of Technical Medicine

Presentation Univ. of Canterbury 01.02.2024

Electrical Impedance Tomography
Past - Present - Future

State of the art

Current developments

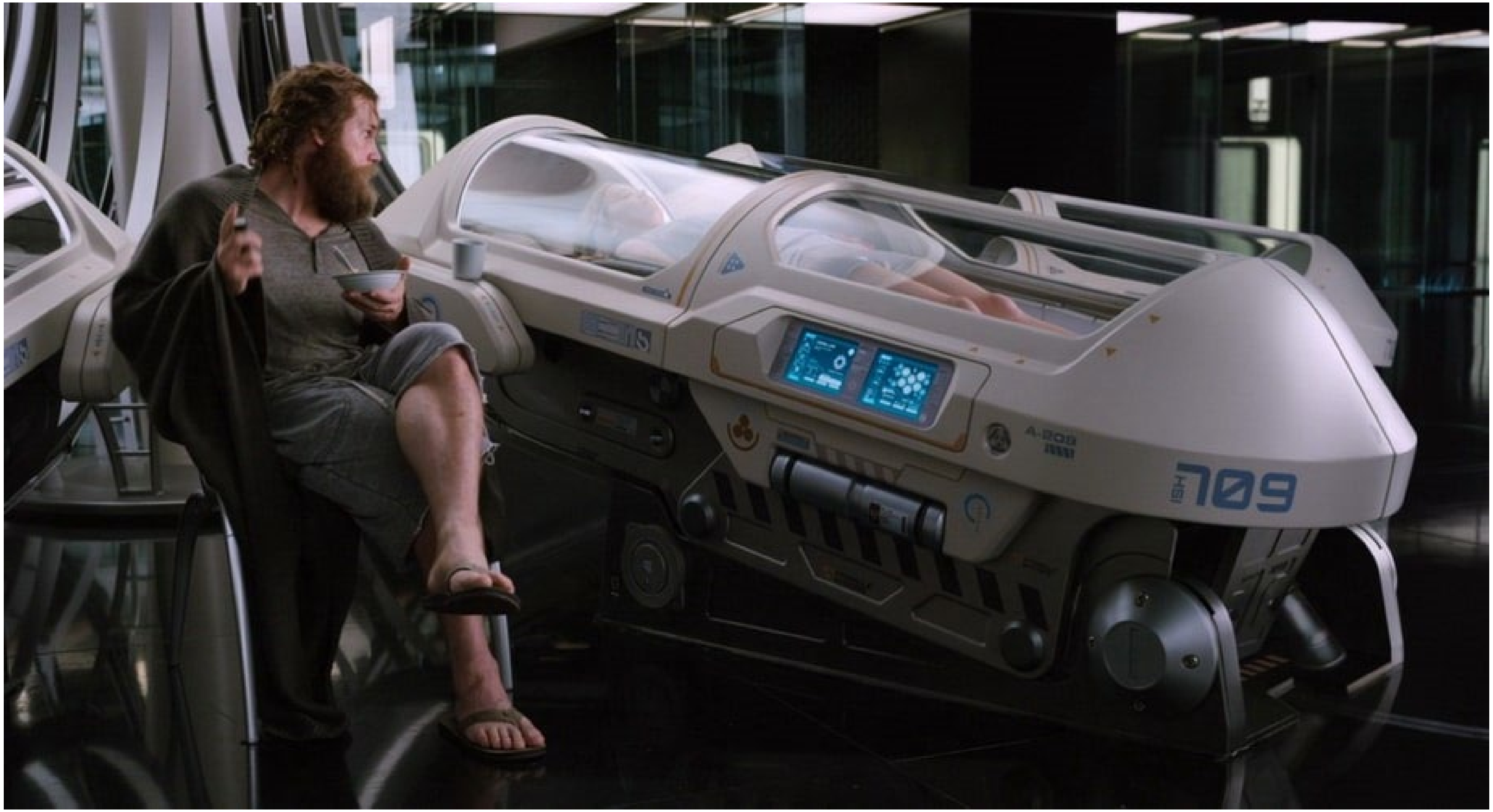
Fancy ideas

Knut Möller

ITeM: Institute of Technical Medicine

Furtwangen University, Germany

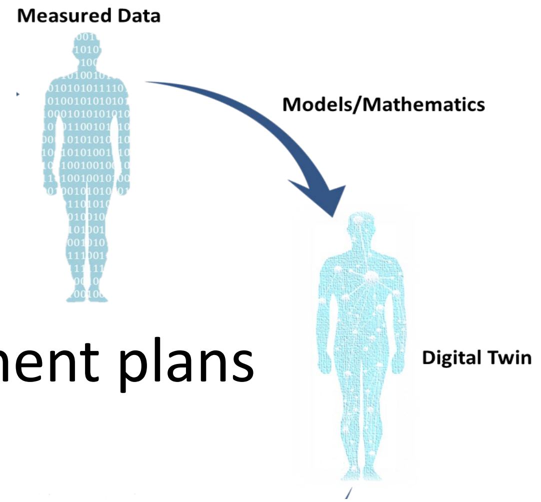
Medicine of the Future:
Diagnosis and Therapy-Unit



Almost there?

- Sensors to capture **structure** and **function** of patient
- Actuators to repair structural damage and disfunction of body systems

- **Understanding** of patho-physiology
- E.g. phys. model
- **Individual** treatment plans



Medical Imaging

- **Individualization** requires information about the patient i.e. sensors that provide signals to be converted into information
- By evolution humans are trained for real-time analysis of images. Thus, it was considered a good idea to present information in form of images or videos to medical staff.
- Medical Imaging for gaining morphological or functional information converts different **properties and characteristics of tissue** into images.

Medical Imaging

Imaging	Principle	Comment
Computer Tomography (CT)	X-ray absorption/ Mass attenuation	Precise, but harming, large equipment
Magnetic Resonance (MRT)	magnetic properties of Hydrogen nucleus	Precise, but expensive, large complex equipment
Ultra Sound (US)	Elastomechanical Properties	Relatively cheap and not harming, but experienced operator required and in many applications not feasible
Microwave Imaging (MI-Radar)	Reflection of electromagnetic waves	Relatively cheap and not harming, but not optimized for most medical applications
Electrical Impedance (EIT)	Complex electrical resistance of tissue	Relatively cheap and not harming, low spatial, but high temporal resolution
Nuclear Medicine (PET/SPECT)	Radionuclide administration	Expensive, harming, low resolution
Optical (e.g. OCT)	Reflection, scattering	No ionizing radiation, high resolution, but just surface (or short penetration depth)

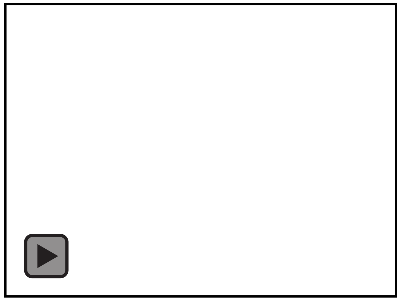
Tissue Resistivity

Tissue	Resistivity (Ω·cm)
Blood	150
Lungs, inspiration	2400
Lungs, expiration	700
Heart muscle, longitudinal	125
Heart muscle, transversal	1800
Skeletal muscle, longitudinal	160–575
Skeletal muscle, transversal	420–5200
Fat	2000–2700
Bone	16,600

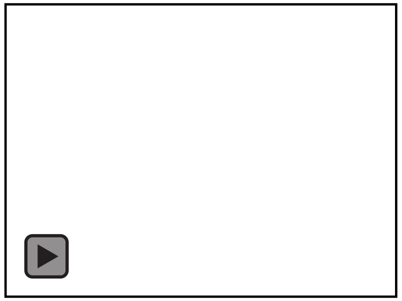
Introduction – Electrical Impedance Tomography (EIT)

- non-invasive radiation-free imaging technique displaying conductivity changes of the lung tissue
- lung tissue conductivity varies significantly between inspiration and expiration → high dynamic contrast
- conductivity changes are mainly based on ventilation and to a smaller amount caused by cardiac activity

→ Functional imaging method visualizing ventilation and 'perfusion' distribution



Ventilation



Perfusion related

Introduction – Why EIT?

- to monitor patients e.g. with obstructive lung diseases (OLD) that show a **heterogenous ventilation** distribution
- **no radiation exposure** compared to other imaging methods, such as x-ray imaging or computed tomography and less expensive equipment
- lung function measures, such as spirometry or multiple-breath inert gas washout, only provide **global** parameters

Further advantages:

- high **temporal** resolution (50 fps)
- small, (relatively) **easy** to handle
- **bedside** monitoring
- **cost**-effective
- no harming side effects

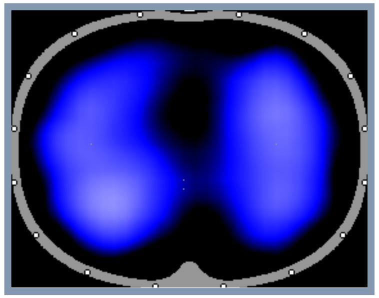
Applications of EIT

Past

Present

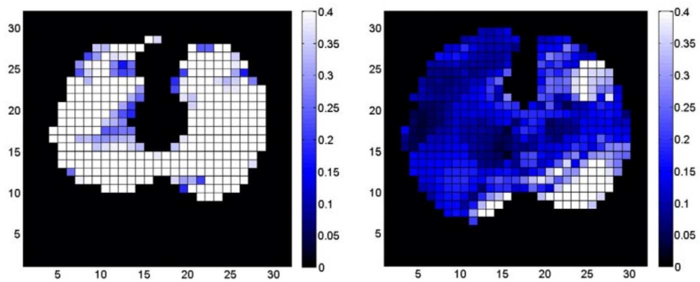
- ventilation distribution monitoring in mechanically ventilated patients

draeger.com



- ventilation distribution monitoring in spontaneously breathing patients with obstructive lung diseases

ganshorn.de



Zhao,Z. J Cyst Fibros 2012;11

EIT- From Measurements to Information

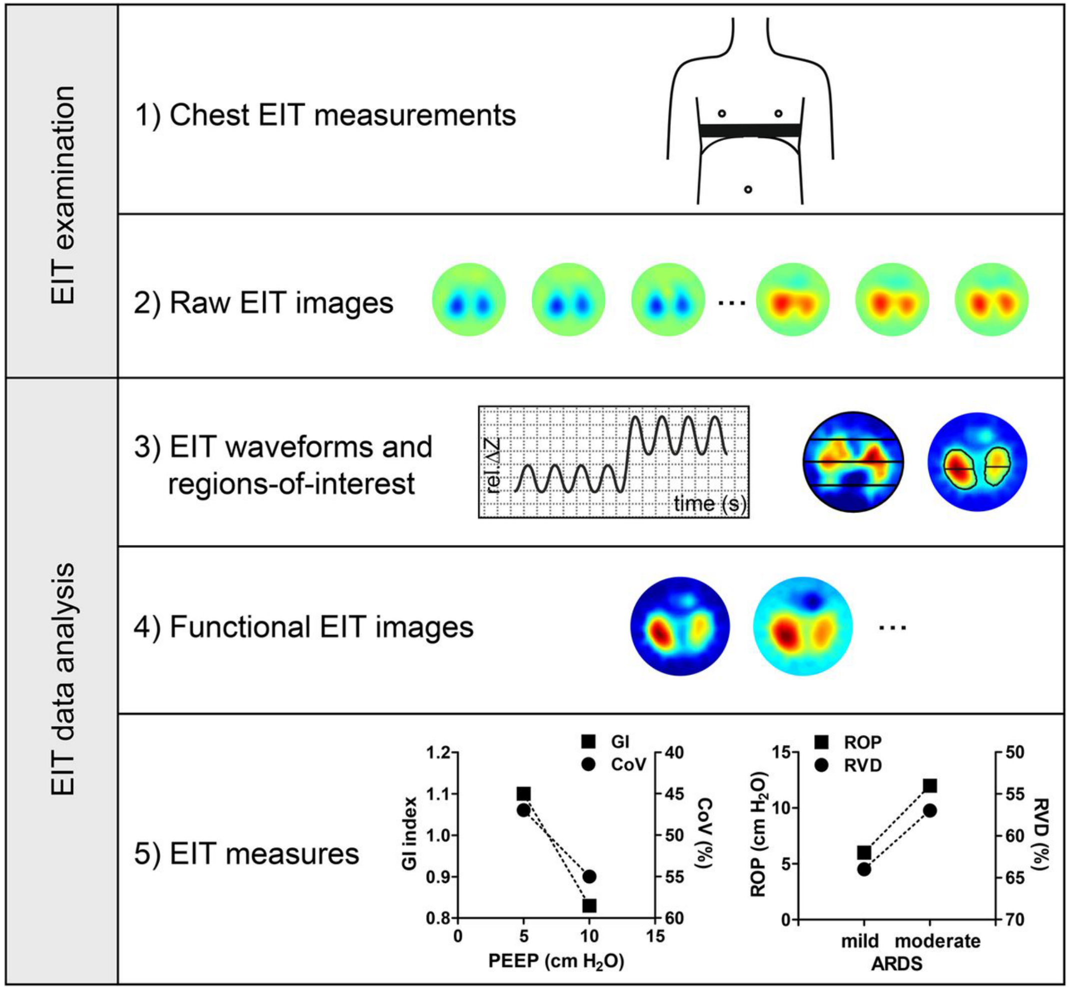
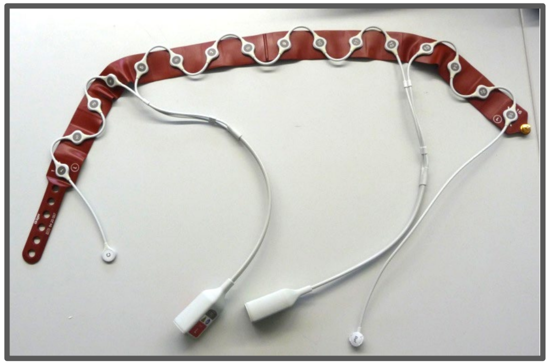


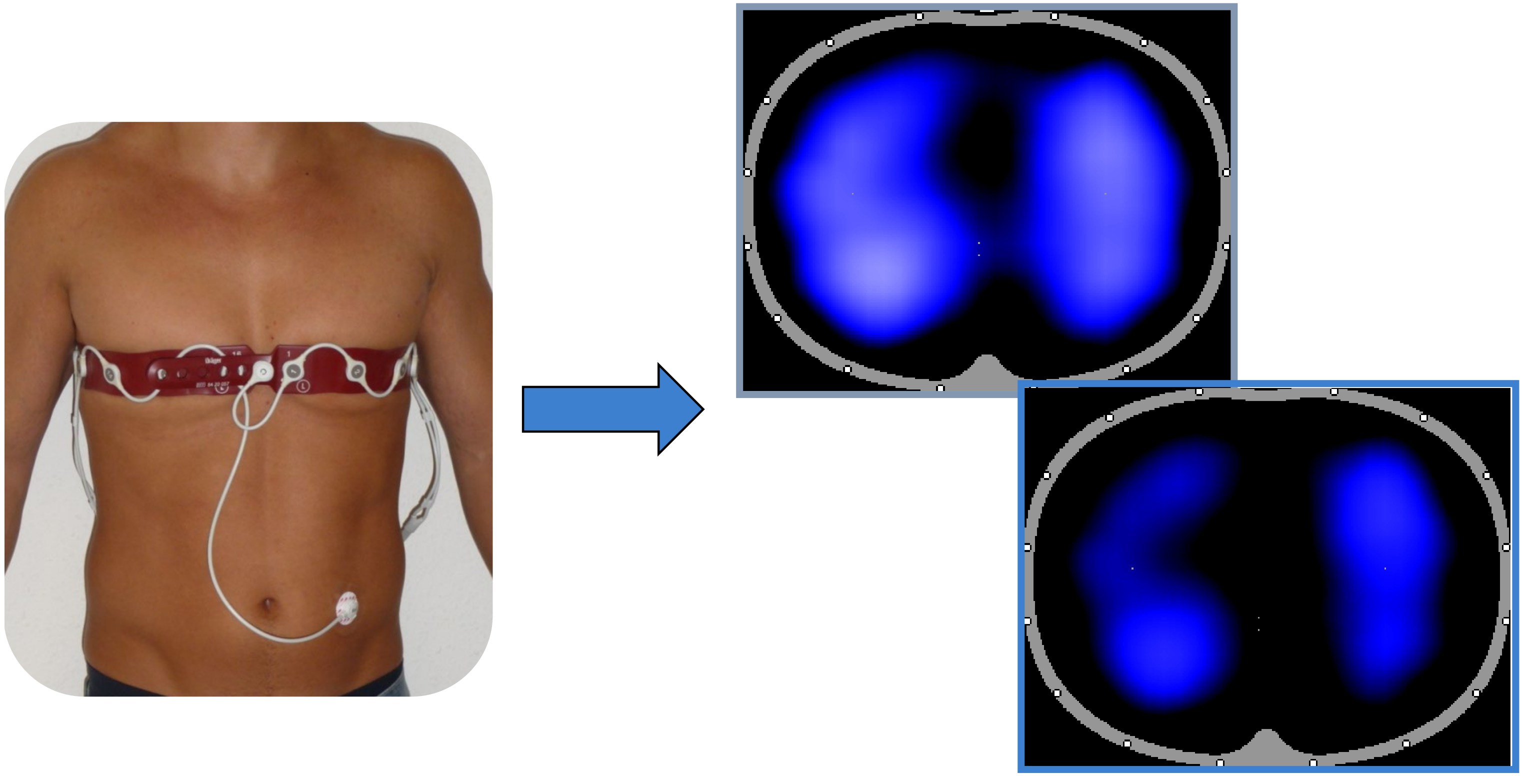
Image reconstruction

Frerichs et al. , Thorax, 2017

1. Introduction: The EIT measurement system

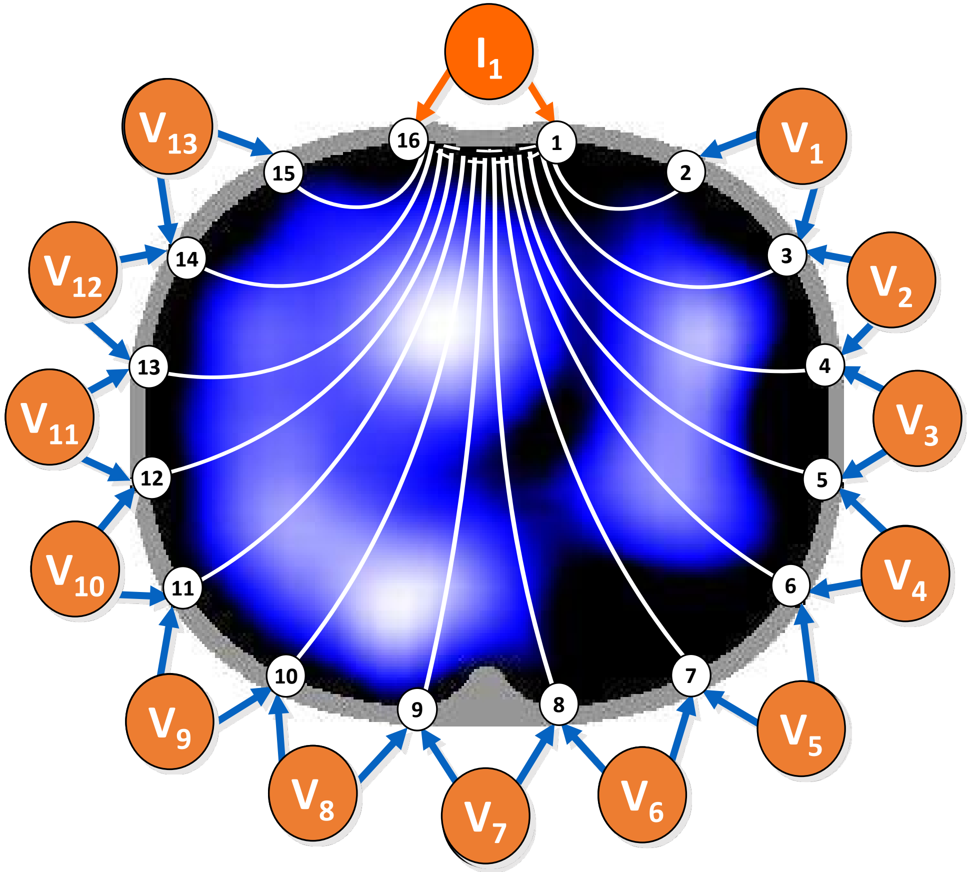


Introduction: The Operating principle



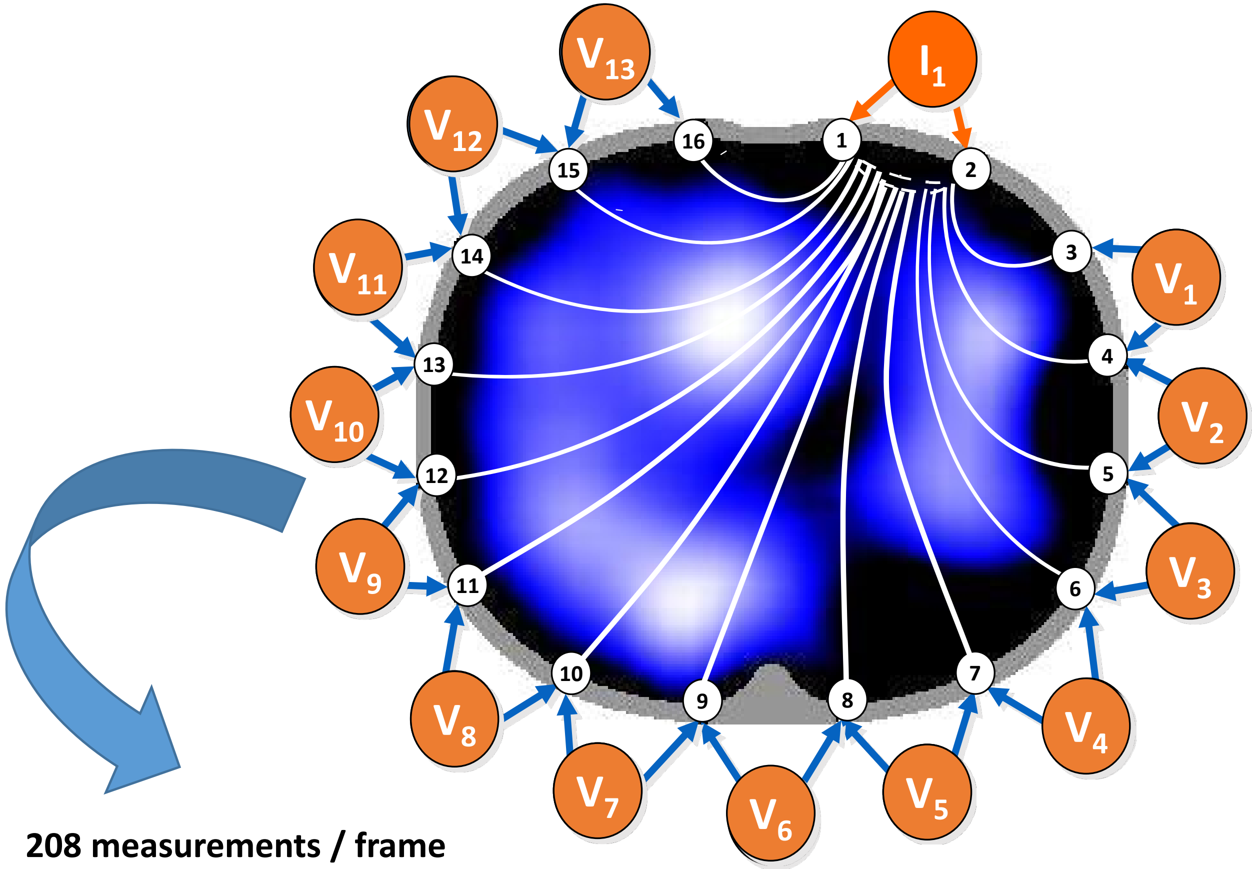
Institute of Technical Medicine

Operating principle



Institute of Technical Medicine

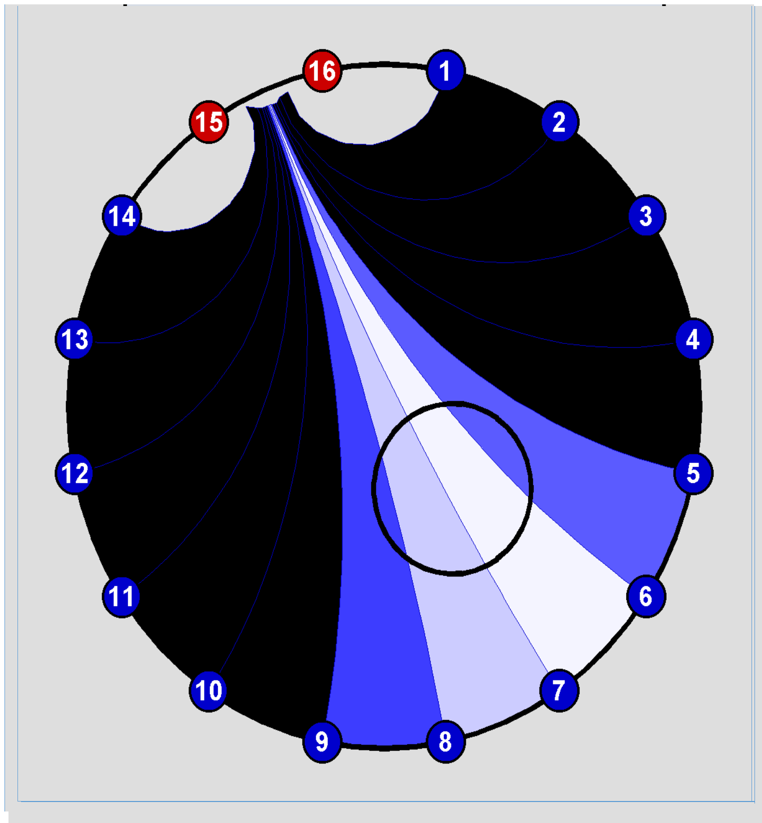
Operating principle



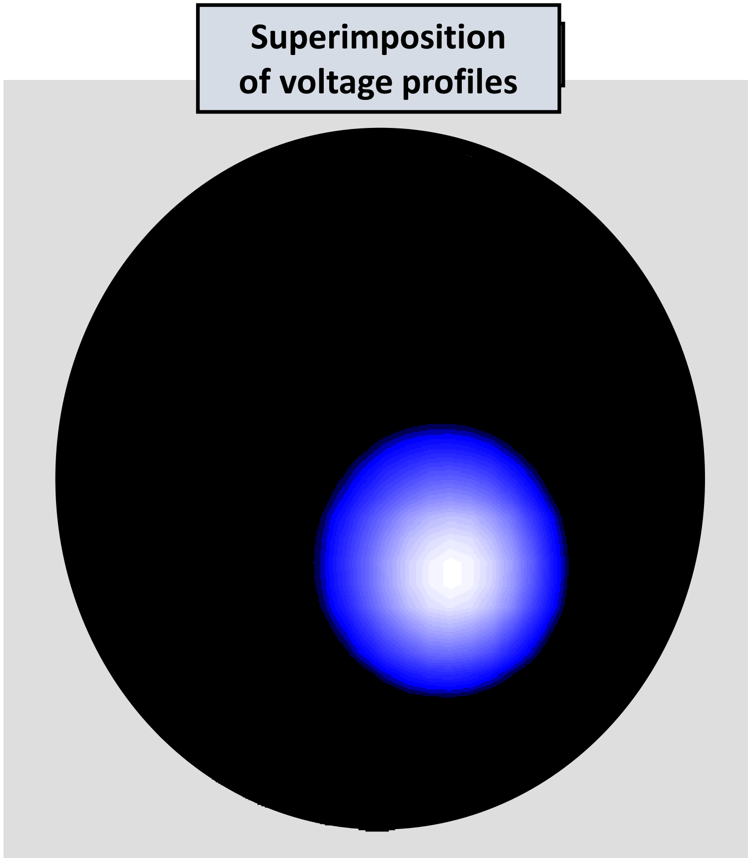
208 measurements / frame

(16 x 13 voltages)

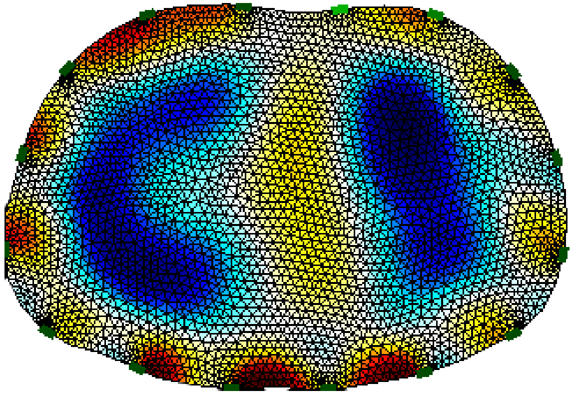
Operating principle

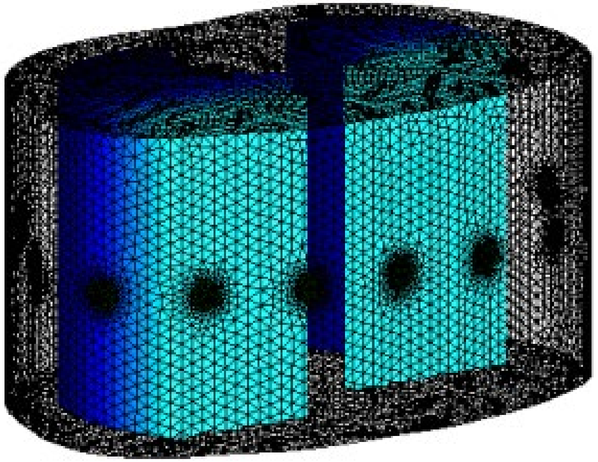


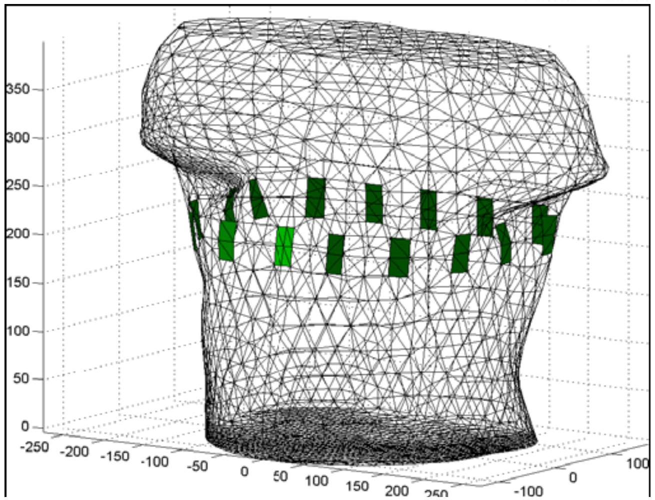
Operating principle



Reconstruction based on FEM - Forward model F(x)





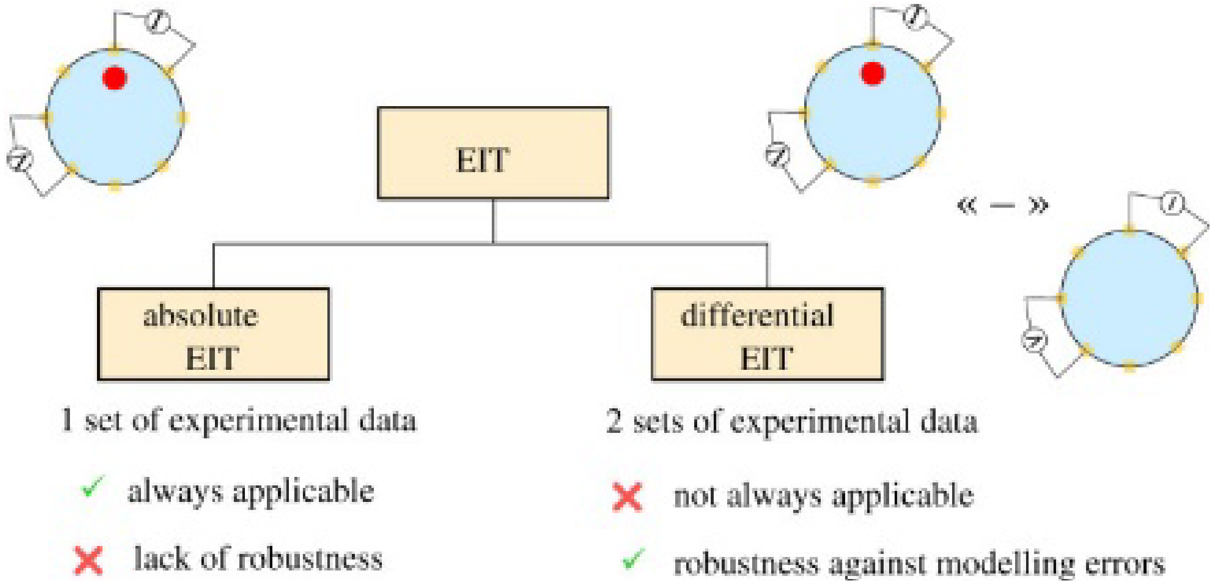


2. Relative Impedance ΔZ (tdEIT)

- **Impedance values** are presented as the relative time-difference with arbitrary units.

  Reference is the impedance of a previous reference time point (Z_{t_ref})

$$\Delta Z = (Z_{t-1} - Z_{t_{ref}})/Z_{t_{ref}}$$



- Global Impedance curves are often used at every point of time

$$\Delta Z_{gl} = \sum \Delta Z_{px}$$

EIT Reconstruction (Time Difference Method)

- The inverse problem: Solve x from

$$\arg\min_x \|F(x) - y\|_2^2 \approx \arg\min_x \|Jx - y\|_2^2$$

  - $F(x)$: nonlin. Forward model
  - J : Jacobian - sensitivity matrix
  - x : conditivity changes
  - y : voltage changes

$$J_{i,j} = \left.\frac{\partial y_i}{\partial x_j}\right|_{\sigma\_baseline}$$

- Reconstruction:
  - Minimize : $\|y - Jx\|_2^2$
  - $x = Ay, \quad A := \left(J^* J\right)^{-1} J^*$
- Reconstruction matrix is ill-conditioned
  - Unstable solution – regularization is needed.
  - For example, Tikhonov or Laplace regularization or Total Variation (TV) regularization

Image reconstruction as an ill-posed optimization problem

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

forward model

$$\hat{\mathbf{x}} = \underset{\mathbf{x}}{\operatorname{argmin}}\{\|\mathbf{J}\mathbf{x} - \mathbf{y}\|_2^2 + \lambda^2\|\mathbf{R}\mathbf{x}\|_2^2\}$$

“prior knowledge”

conductivity change

Image reconstruction

$$\hat{\mathbf{x}} = \underset{\mathbf{x}}{\operatorname{argmin}}\{\|\mathbf{J}\mathbf{x} - \mathbf{y}\|_2^2 + \lambda^2\|\mathbf{R}\mathbf{x}\|_2^2\}$$

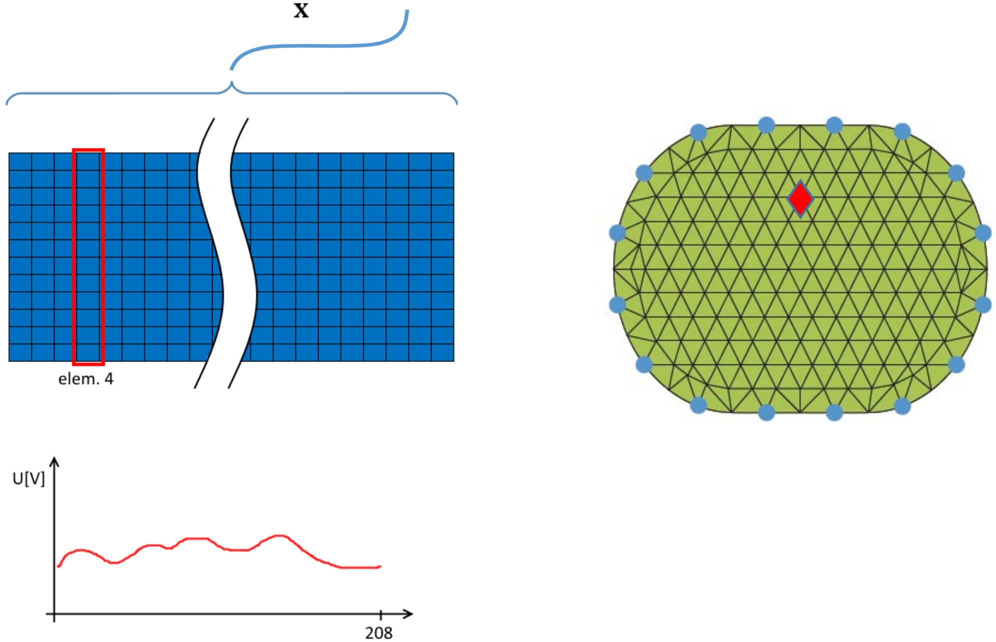
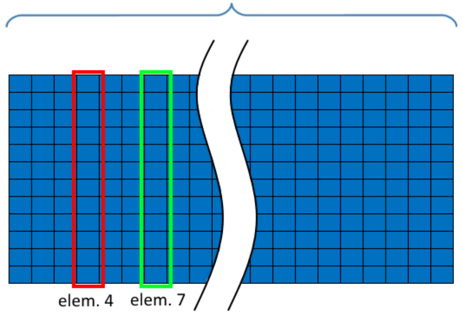
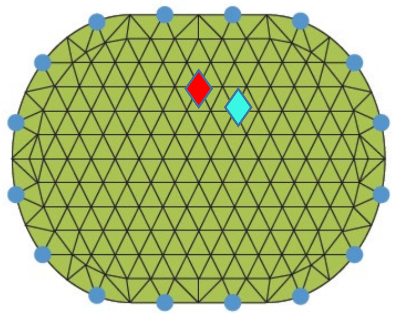


Image reconstruction

$$\hat{\mathbf{x}} = \underset{\mathbf{x}}{\operatorname{argmin}}\{\|\mathbf{J}\mathbf{x} - \mathbf{y}\|_2^2 + \lambda^2\|\mathbf{R}\mathbf{x}\|_2^2\}$$





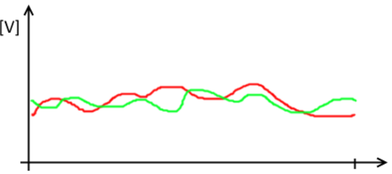
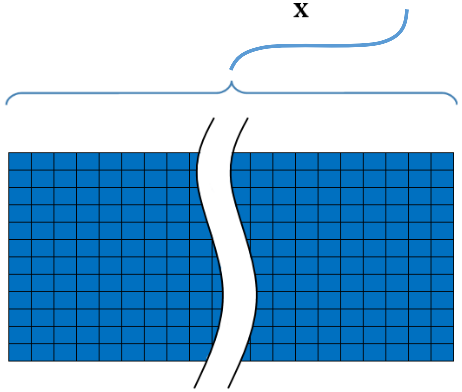
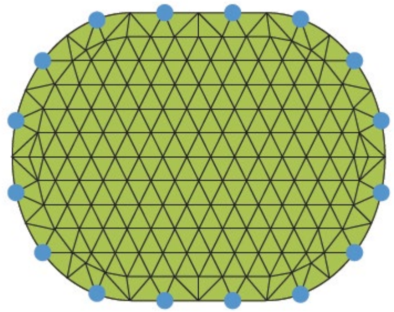


Image reconstruction

$$\hat{\mathbf{x}} = \underset{\mathbf{x}}{\operatorname{argmin}}\{\|\mathbf{J}\mathbf{x} - \mathbf{y}\|_2^2 + \lambda^2\|\mathbf{R}\mathbf{x}\|_2^2\}$$





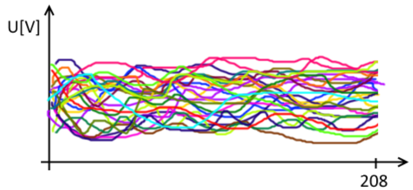


Image reconstruction

$$\hat{\mathbf{x}} = \underset{\mathbf{x}}{\operatorname{argmin}}\{\|\mathbf{J}\mathbf{x} - \mathbf{y}\|_2^2 + \lambda^2\|\mathbf{R}\mathbf{x}\|_2^2\}$$

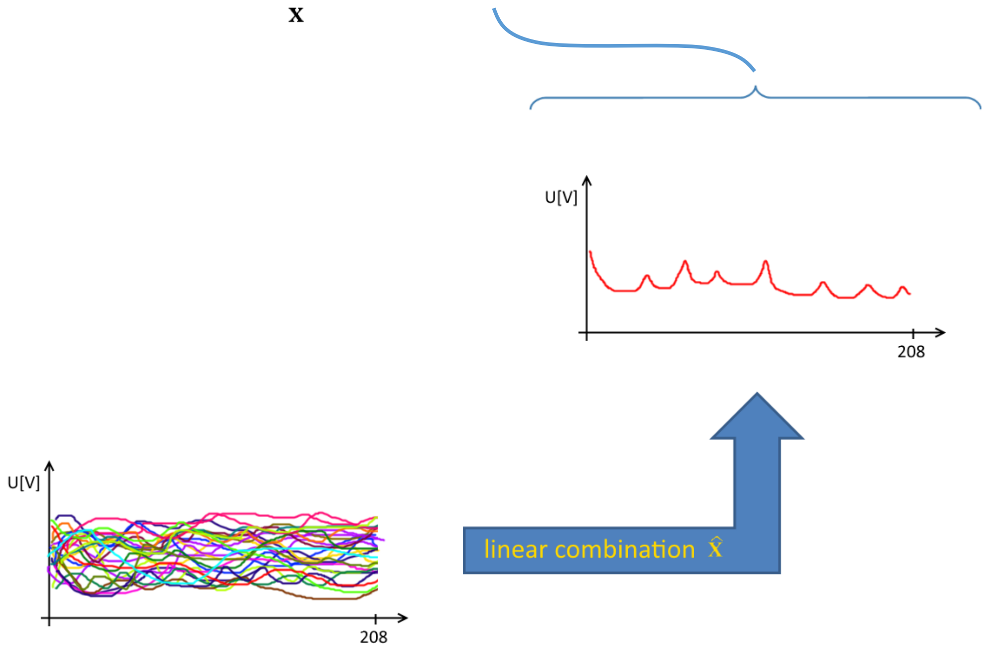


Image reconstruction

$$\hat{\mathbf{x}} = \underset{\mathbf{x}}{\operatorname{argmin}}\{\|\mathbf{J}\mathbf{x} - \mathbf{y}\|_2^2 + \lambda^2 \|\mathbf{R}\mathbf{x}\|_2^2\}$$

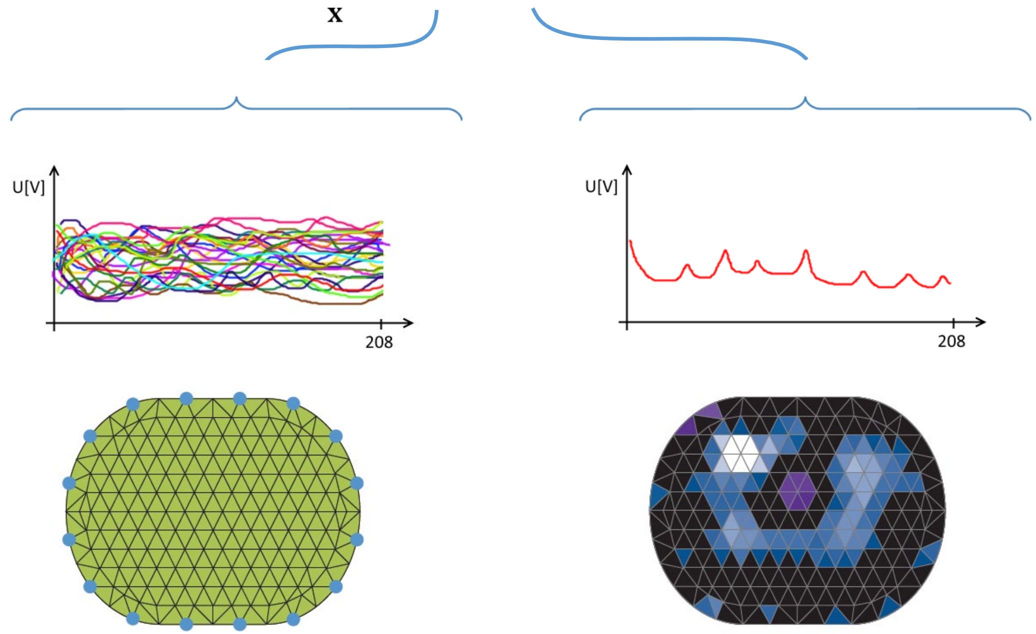
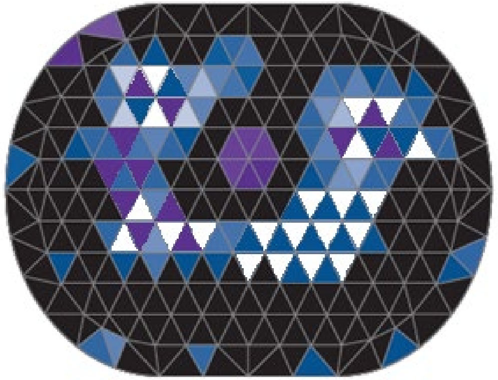
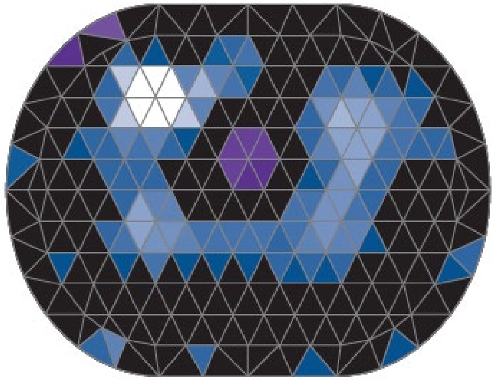


Image reconstruction (What is the truth?)

$$\hat{\mathbf{x}} = \underset{\mathbf{x}}{\operatorname{argmin}}\{\|\mathbf{J}\mathbf{x} - \mathbf{y}\|_2^2 + \lambda^2\|\mathbf{R}\mathbf{x}\|_2^2\}$$



„unrealistic“

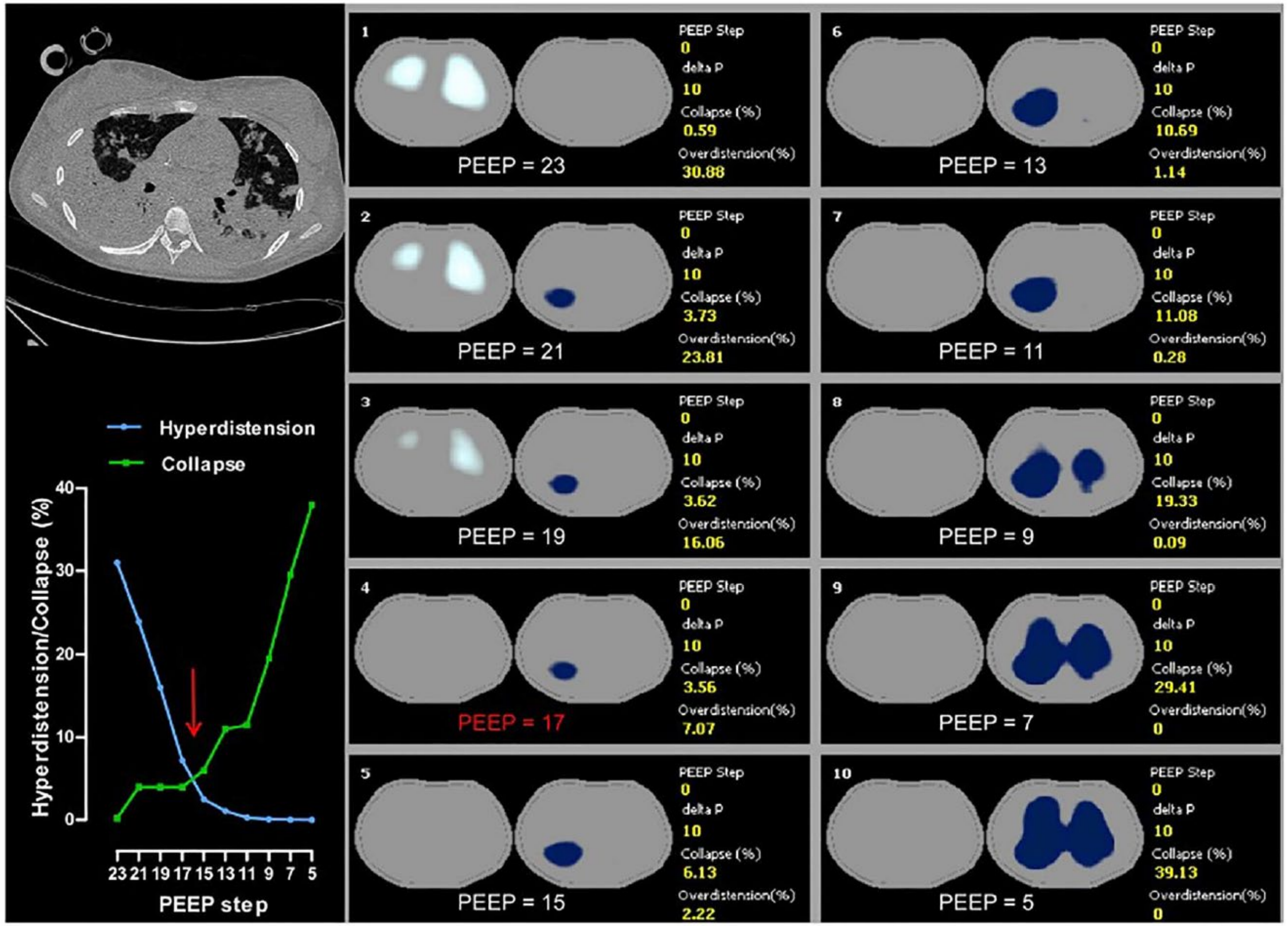


„realistic“

Institute of Technical Medicine

Image reconstruction (Prettified)

„Optimal“ PEEP



Frerichs et al., Thorax 72,2017

Introduction (Present: ongoing work)

EIT algorithms to provide information from impedance measurements to physicians

1. Methods to improve image reconstruction
   I. Faster optimization (Sparse solver, Reduction of degrees of freedom)
   II. Belt Position, Thorax Motion Compensation, 3D reconstruction (Multi-layer measurements)
   III. Incorporation of prior knowledge
2. Methods to analyse and interpret EIT images and video streams
   I. Preprocessing, e.g. Lung contour estimation, heart region detection
   II. EIT measures to reduce complexity, e.g. Center of ventilation, GI scores,
   III. Functional images, e.g. obstruction maps, regional compliance, time delays
   IV. Segmentation and quantification, e.g. Costa-Algorithm
   V. Distribution of „perfusion changes“

e.g. Javaherian A, et al. *Med Biol Eng Comput* 2016

Introduction

EIT algorithms to provide information from impedance measurements to physicians

1. Methods to improve image reconstruction
   I. Faster optimization (Sparse solver, Reduction of degrees of freedom)
   II. Belt Position, Thorax Motion Compensation and 3D reconstruction (Multi-layer measurements)
   III. Incorporation of prior knowledge
2. Methods to analyse and interpret EIT images and video streams
   I. Preprocessing, e.g. Lung contour estimation, heart region detection
   II. EIT measures to reduce complexity, e.g. Center of ventilation, GI scores,
   III. Functional images, e.g. obstruction maps, regional compliance, time delays
   IV. Segmentation and quantification, e.g. Costa-Algorithm
   V. Distribution of „perfusion changes“

Combination of Measurements for Pseudo 3D

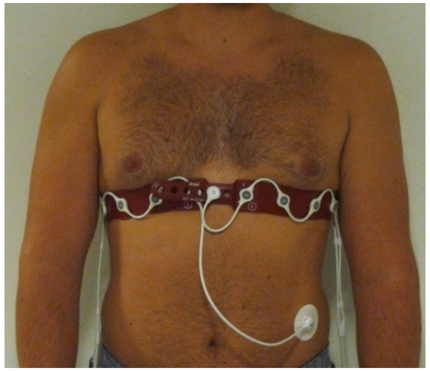
Bodyplethysmograph

Electrical Impedance Tomography

Motion Tracking System

ITeM Institute of Technical Medicine

Combination Bodyplethysmograph / EIT

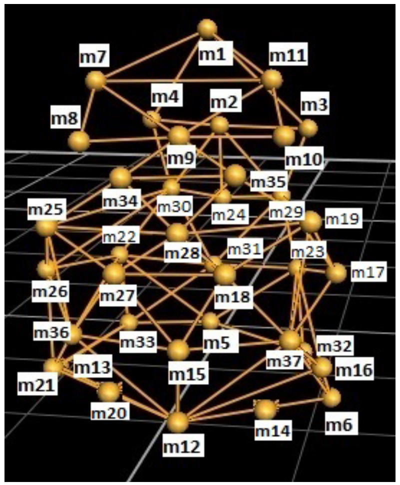


Motion Tracking System:

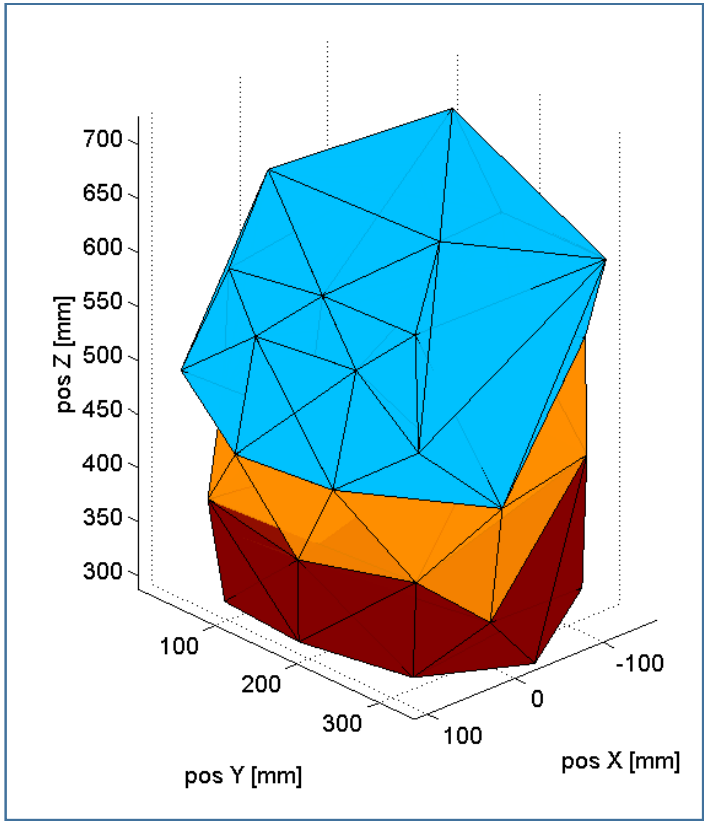
Recording of Chest Motion during Breathing:

- high resolution of surface motion (<0.3 mm)
- reconstruction of 3D-trajectories
- high density of markers possible

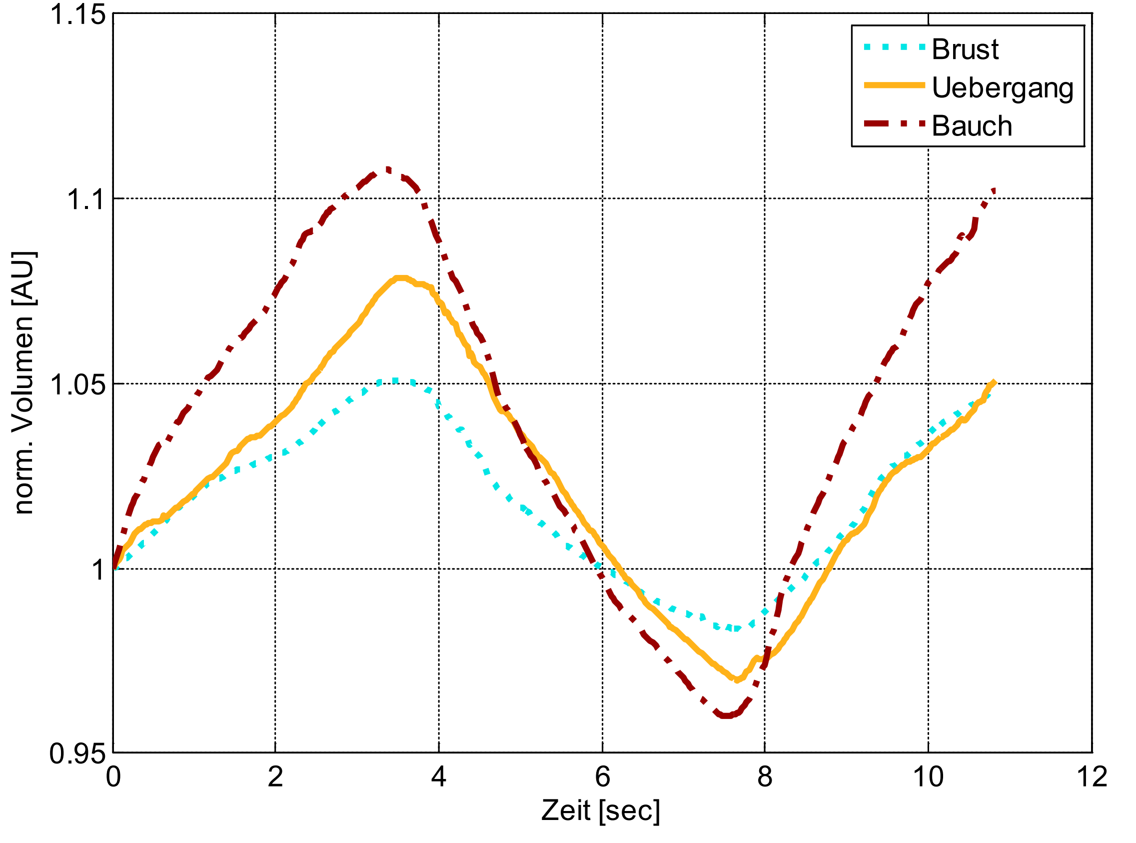
➔ Analysis of motion with respect to the ratio of Chest-/Belly and breathing amplitude



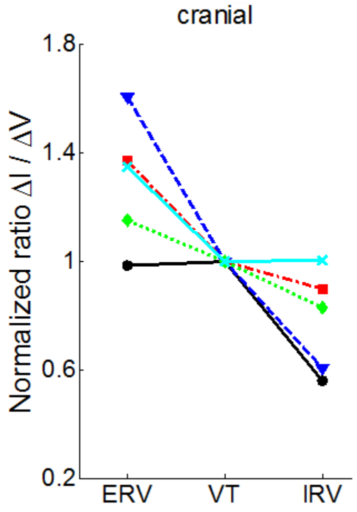
Combination Bodyplethysmograph / Motion Tracking

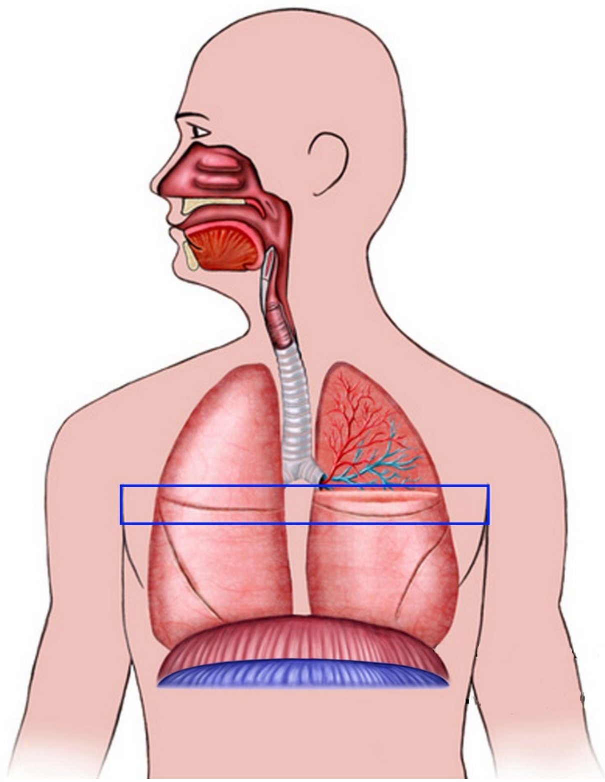


Combination Bodyplethysmograph / Motion Tracking

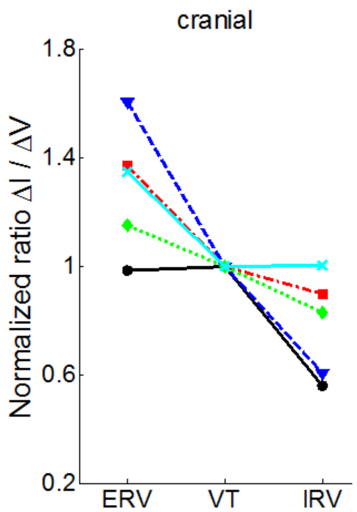


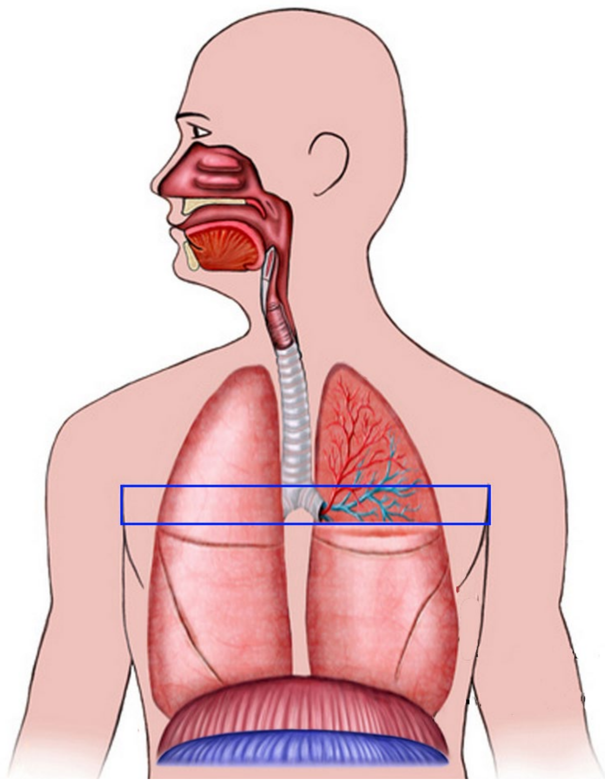
Influence of Lung shift in EIT



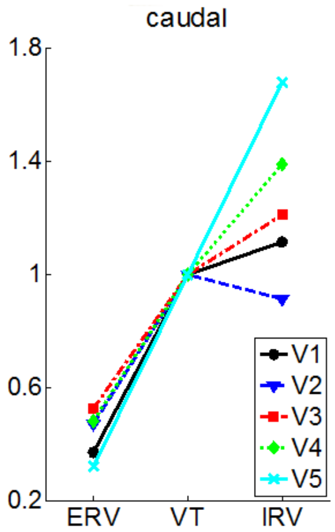


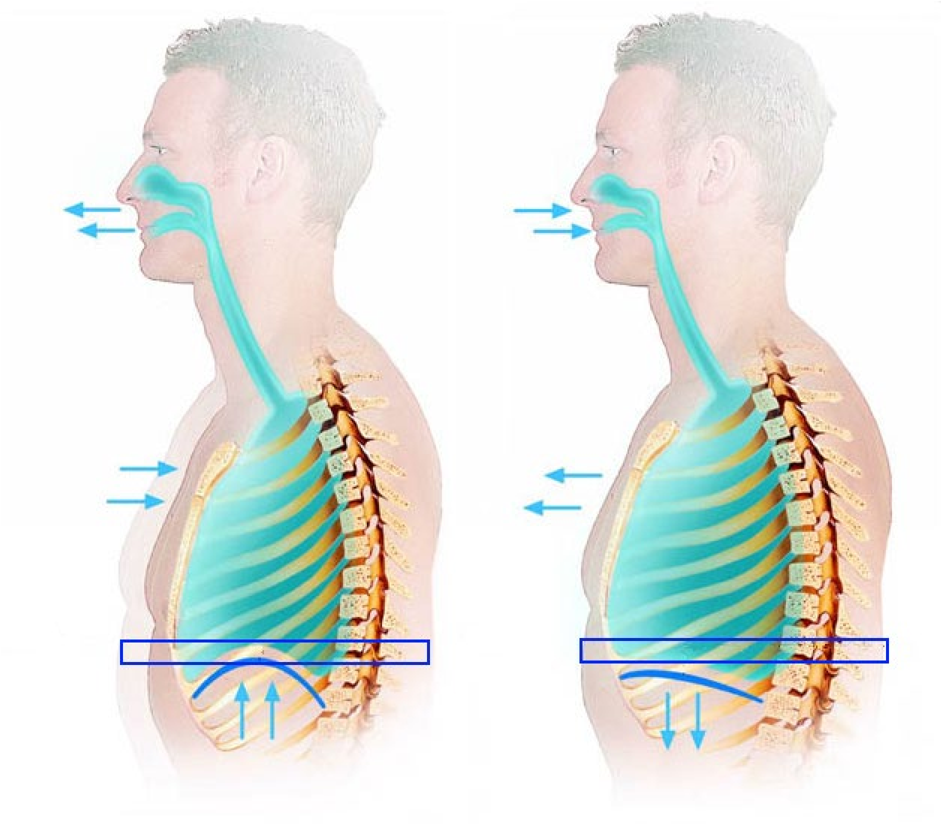
Influence of Lung shift in EIT





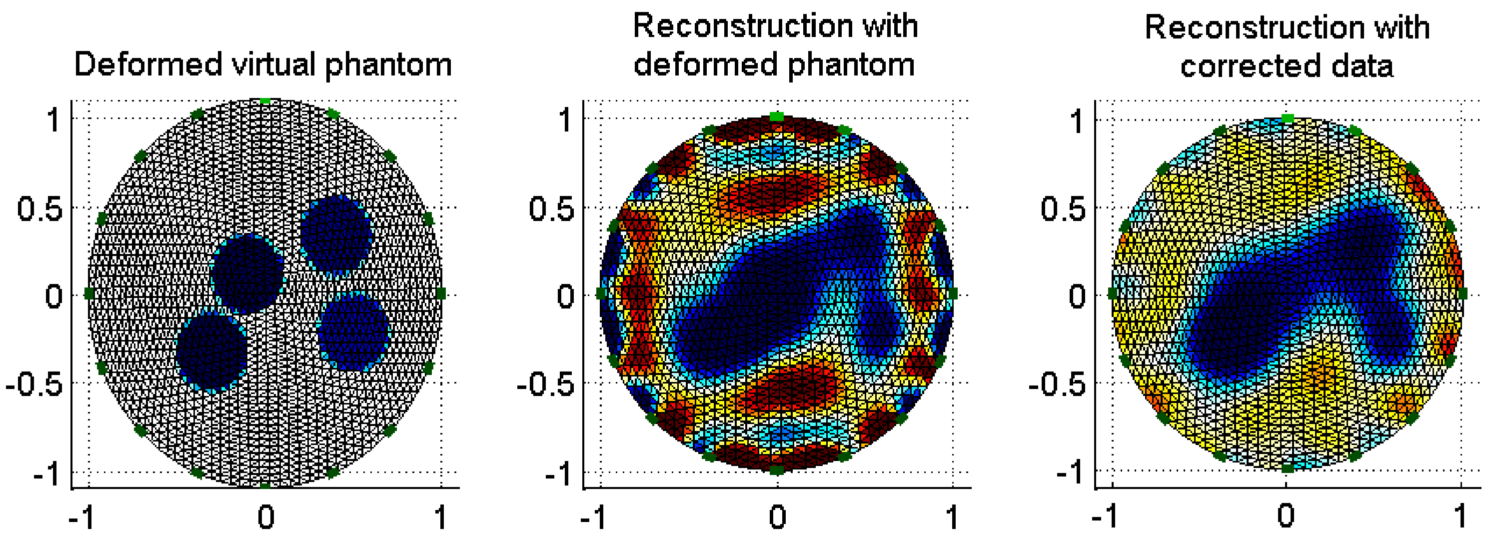
Influence of Lung shift in EIT





Krueger-Ziolek et al. Phys.Meas. 2015 Krueger-Ziolek et al. Resp.Phys & Neurobio. 2016

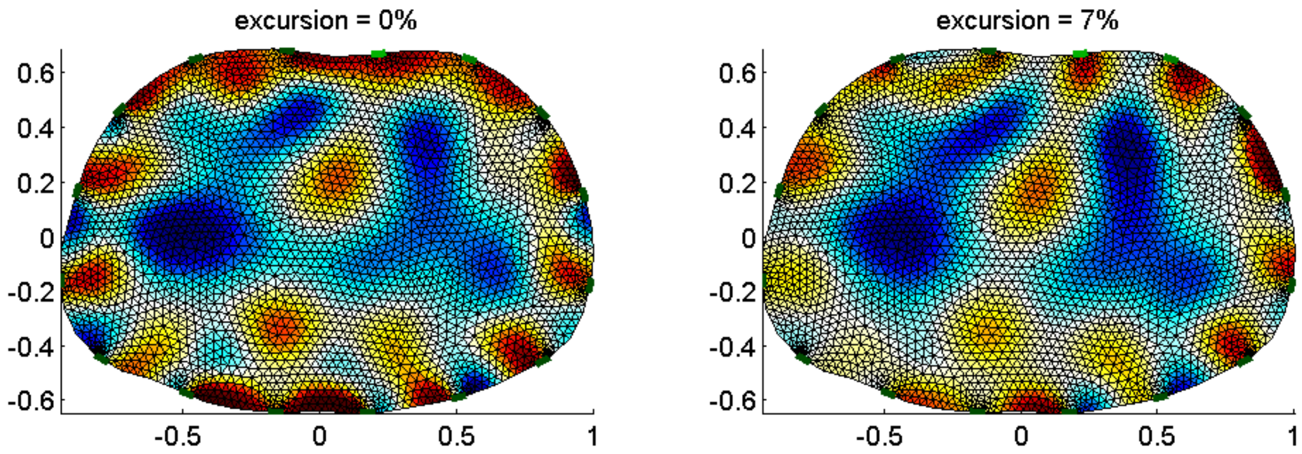
Compensation of Thorax motion in EIT imaging



B Schullcke et al. , Cur.Dir. in Biomed.Eng.g 1 (1), 274-277

B Schullcke, et al. IFAC-PapersOnLine 48 (20), 130-134

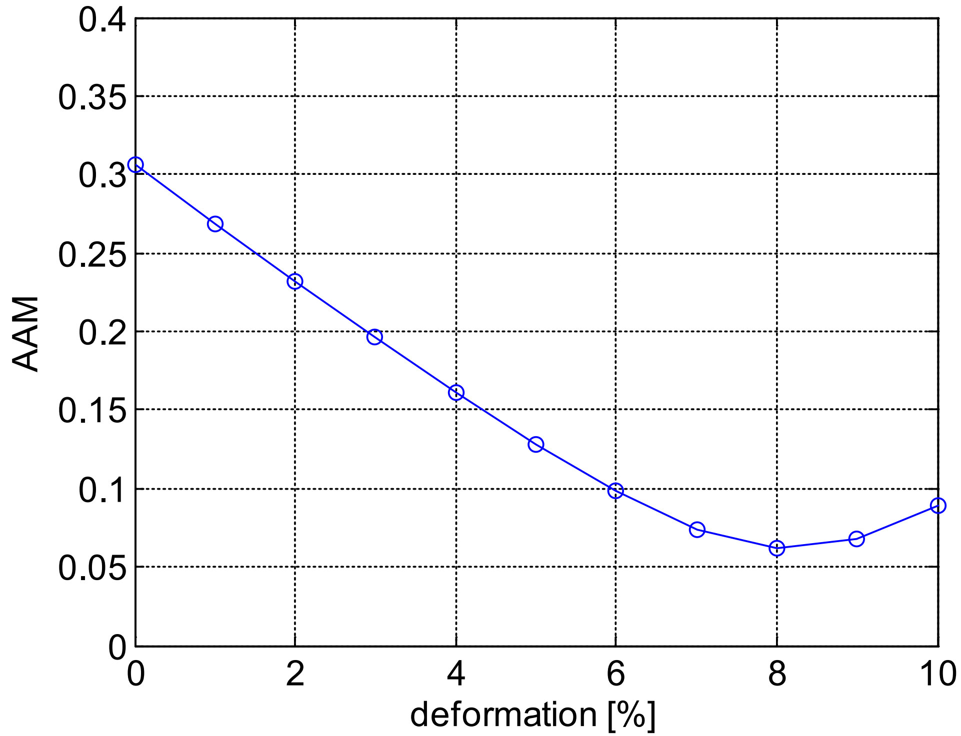
Compensation of Thorax motion in EIT imaging



Artifact Amplitude Measure (AAM):

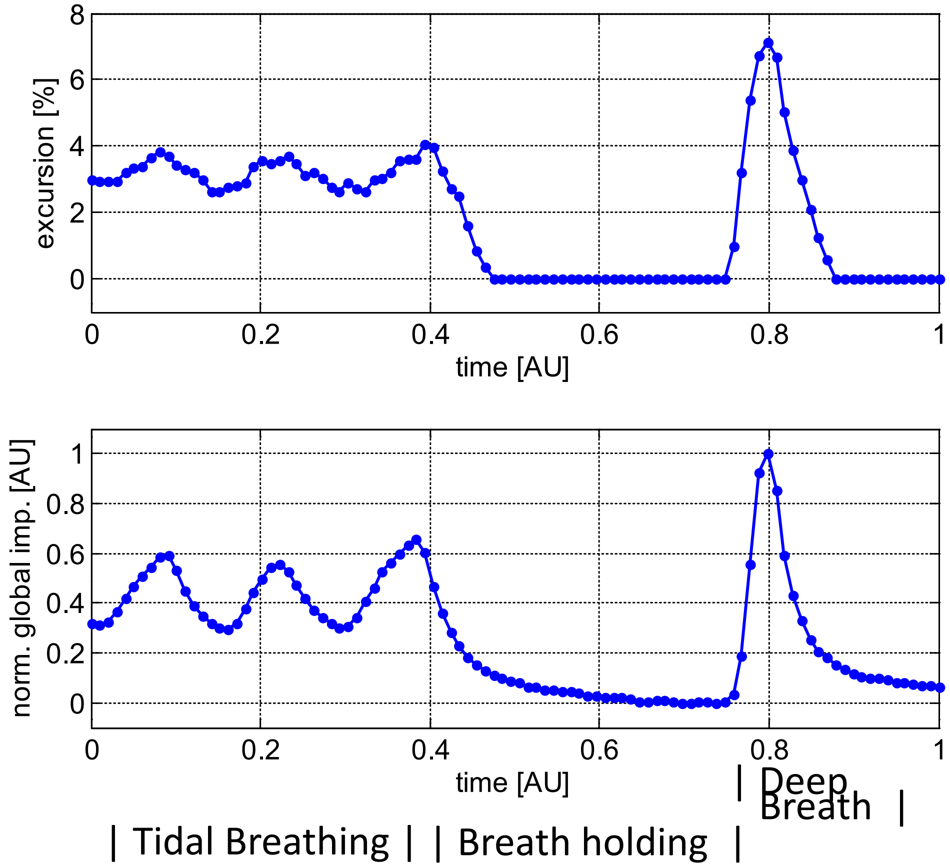
$$\hat{\delta} = \min_{\delta} \sqrt{\frac{\sum_{i \in L} \Omega_i x_i^2}{\sum_{i \in L} \Omega_i}}$$

Relation AAM and Thorax deformation



Compensation of Thorax motion in EIT imaging

Inverse Reasoning



Compensation of Thorax motion in EIT imaging

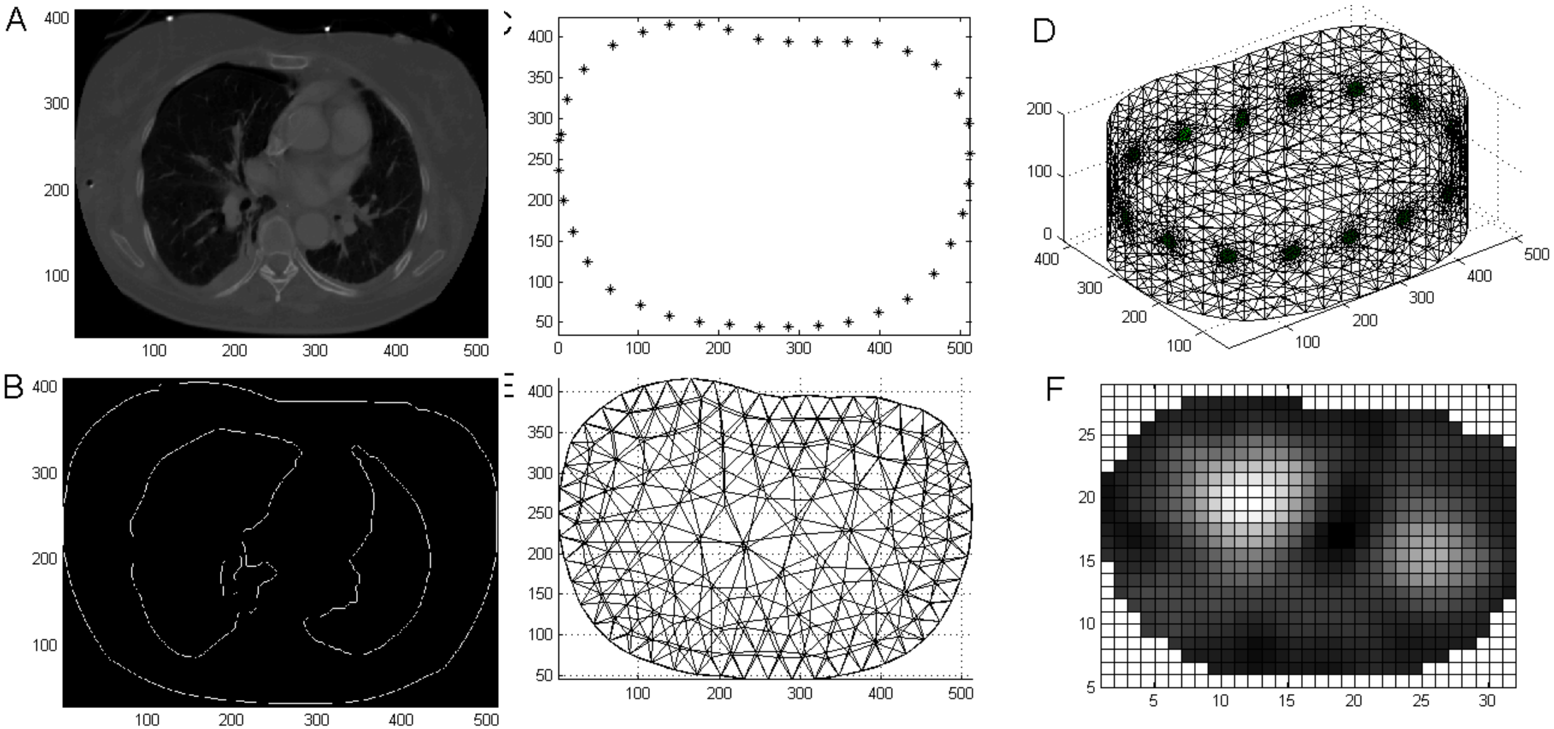
- Horizontal motion of Lung tissue or Thorax resp. can be compensated quite easily.
- By minimizing AAM the Thorax extension during a breath can be estimated.
- Exact tracking allow to determine the Thorax-motion and can be used to verify alternative measurement methods such a stretch sensors.

Introduction

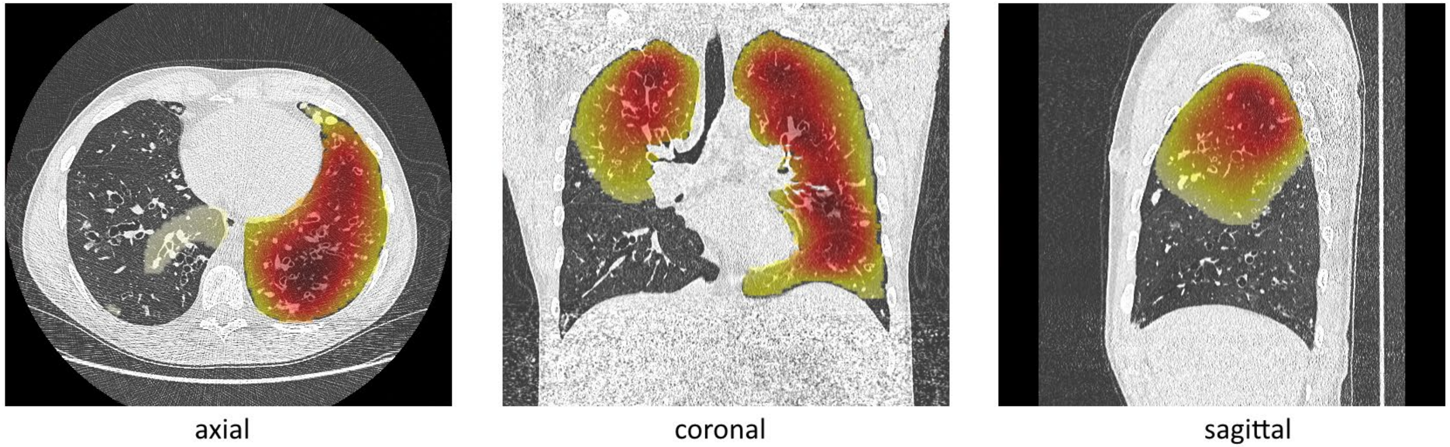
EIT algorithms to provide information from impedance measurements to physicians

1. Methods to improve image reconstruction
   - I. Faster optimization (Sparse solver, Reduction of degrees of freedom)
   - II. 3D reconstruction (Multi-layer measurements)
   - III. Incorporation of prior knowledge
2. Methods to analyse and interpret EIT images and video streams
   - I. Preprocessing, e.g. Lung contour estimation, heart region detection
   - II. EIT measures to reduce complexity, e.g. Center of ventilation, GI scores,
   - III. Functional images, e.g. obstruction maps, regional compliance, time delays
   - IV. Segmentation and quantification, e.g. Costa-Algorithm
   - V. Distribution of „perfusion changes“

Individual thorax geometry



3D DCT-EIT reconstruction with CT prior



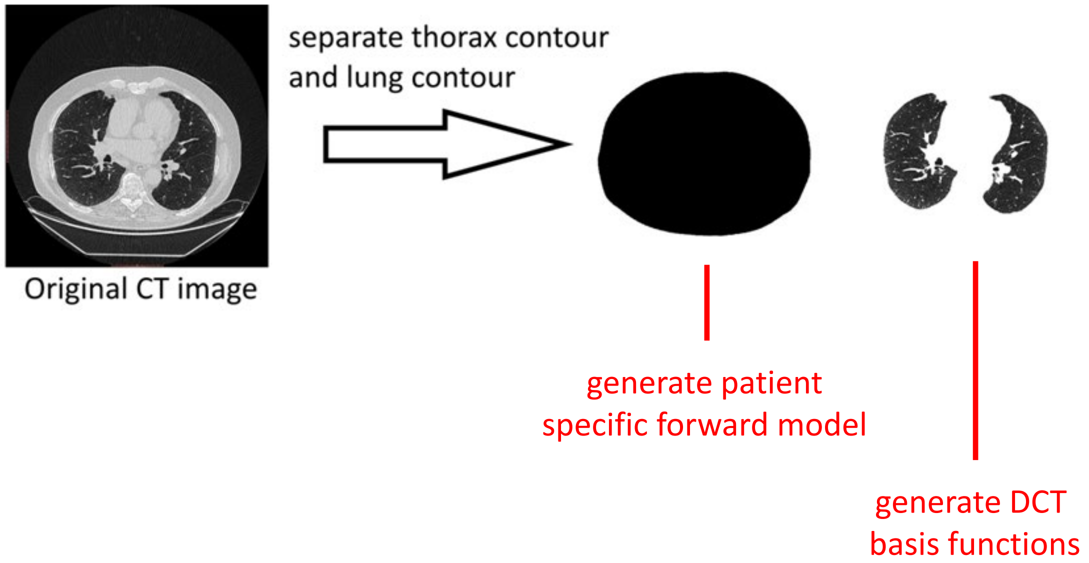
Schullcke B. et al. Scientific Reports, 2016 ,   Chen, R. et al. Plos One, 2022

Integration of *prior*-Knowledge

- General priors in regularization
  - Smoothness of solution (Laplace prior, TV regularization)
    Gong B, et al., *IFAC papers online,* 2017
  - Sparseness
    Javaherian A, et al., *Physiol Meas.* 2015
    Javaherian A, et al., *Med Biol Eng Comput.* 2016

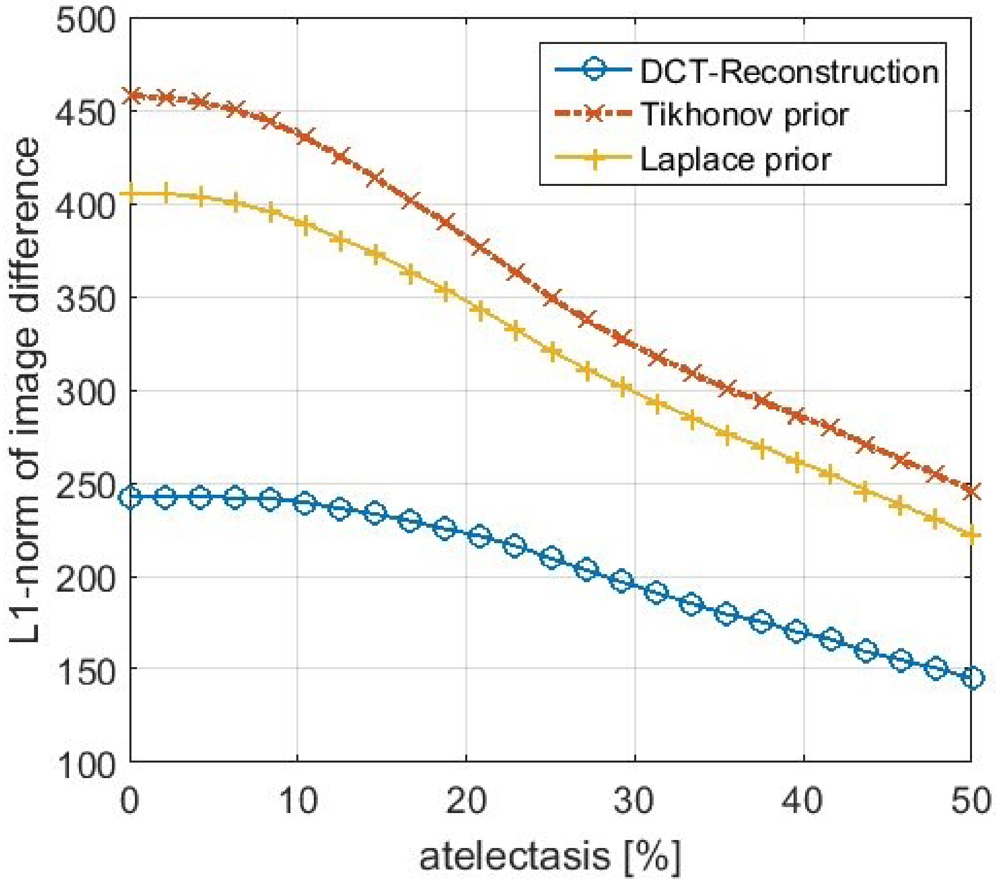
- Patient specific
  - Contour information or more detailled anatomical structures
    Schullcke B, et al., *Scientific Reports,* 2017
    Chen R. et al., Plos One, 2022
  - Reduction of degrees of freedoms in reconstruction
    DCT:
    Schullcke B, et al., *Med. Physics,* 2017
    Schullcke B, et al., *Scientific Reports,* 2017
    Clustering:
    Gong B, et al., *Physiol Meas* 2016
    Spectral Graph Wavelets:
    Gong B, et al., *IEEE Trans. Medical Imaging* 2017

DCT: Discrete Cosine Transformation

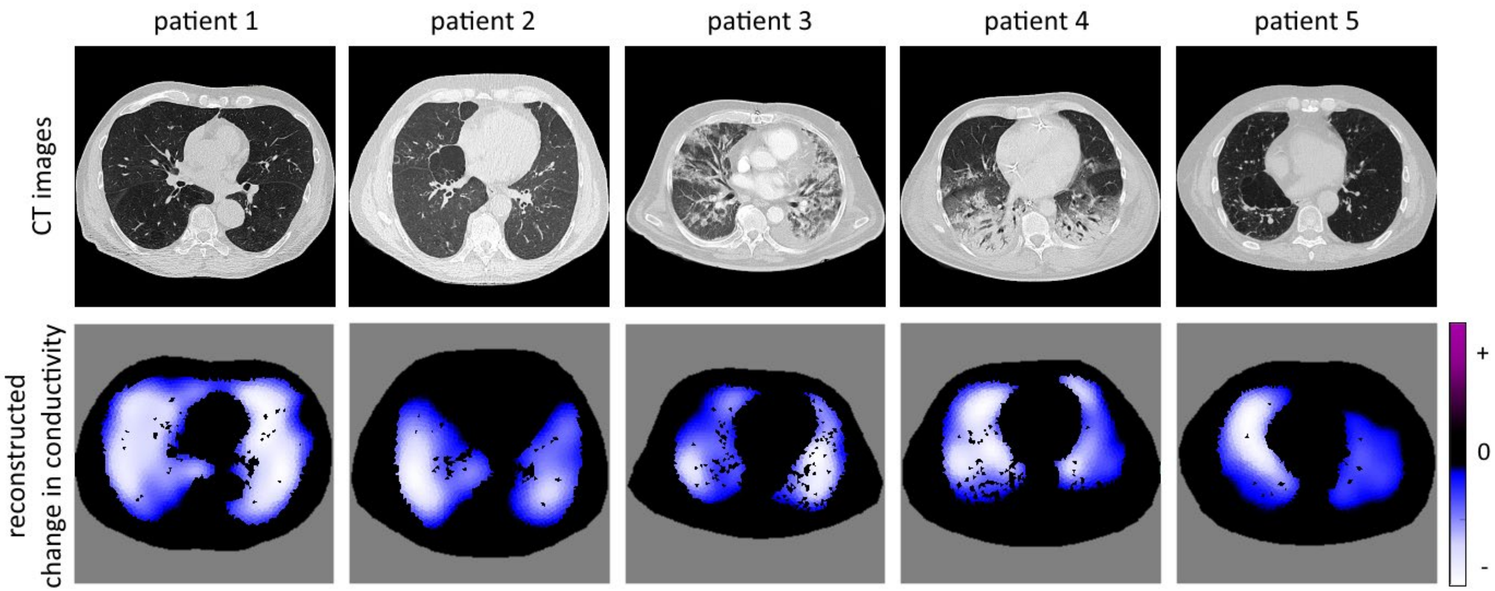


Schullcke B, et al., *Scientific Reports,* 2017, Chen R, et al., *PlosOne*, 2022

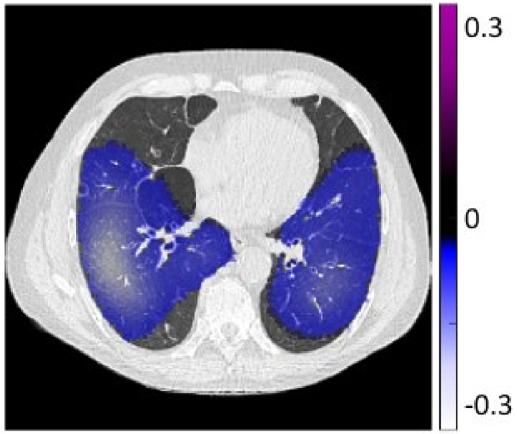
Comparison to different priors



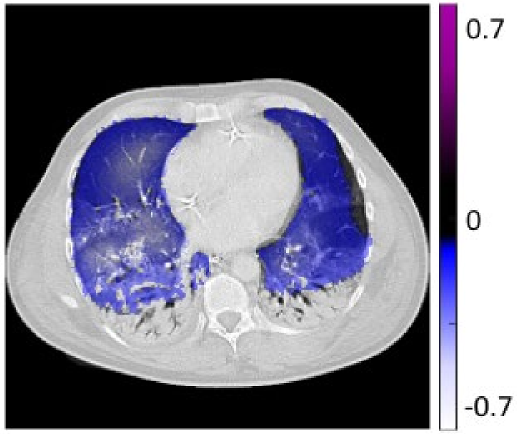
Patient data reconstructed



DCT- Patient Data

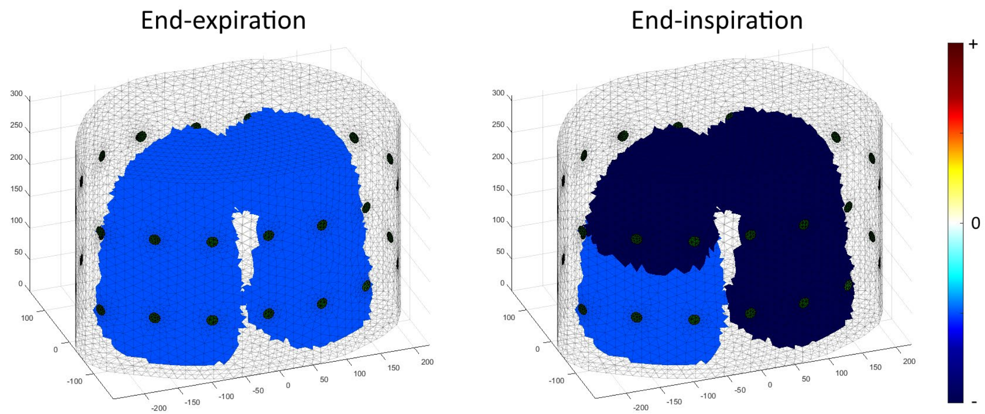


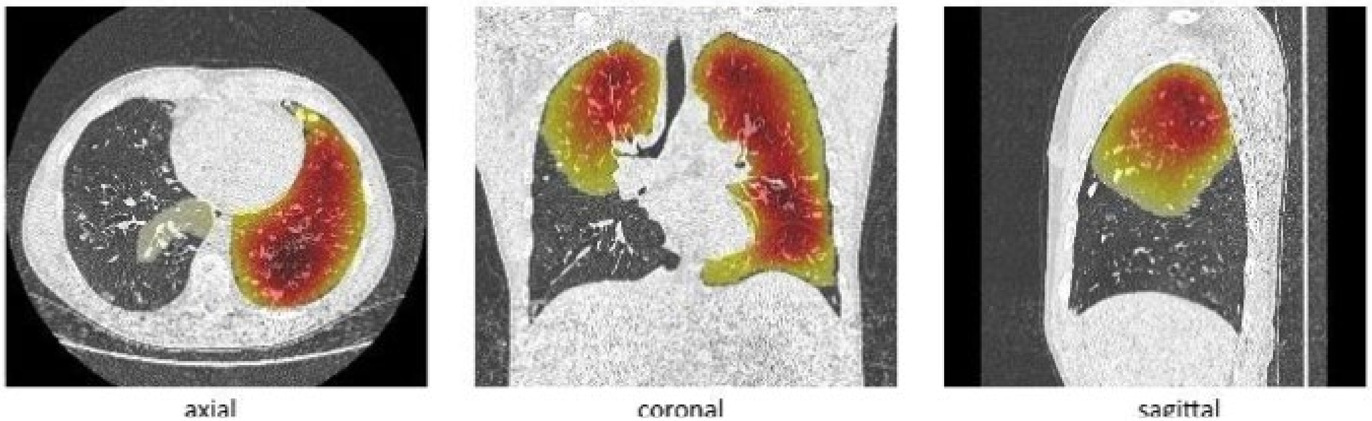
emphysema in ventral lung



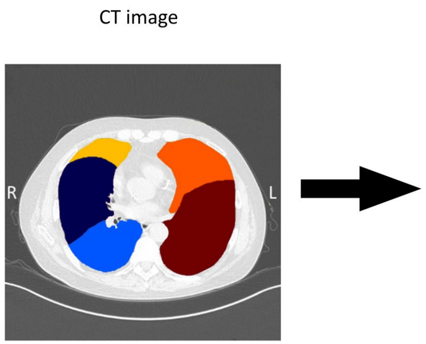
atelectasis in dorsal lung

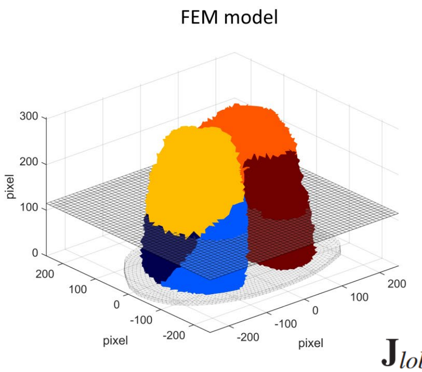
3D DCT Simulation





Lobe reconstruction - method





$$\mathbf{J}_{lobe} = \mathbf{J}\mathbf{L}$$

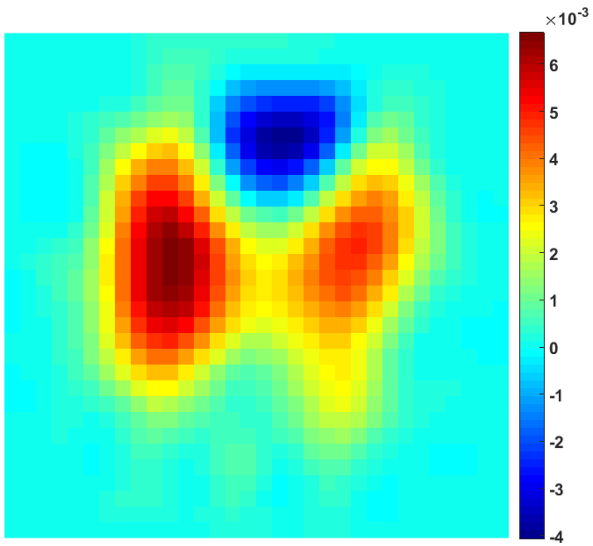
$$L_{i,j} = \begin{cases} 1, & \textit{if element i belongs to lobe j} \\ 0, & \textit{else} \end{cases}$$

$$\hat{\mathbf{x}}_{lobe} = (\mathbf{J}_{lobe}^{\mathrm{T}}\mathbf{J}_{lobe})^{-1}\mathbf{J}_{lobe}^{\mathrm{T}}\mathbf{z} = \mathbf{B}_{lobe}\mathbf{z}$$

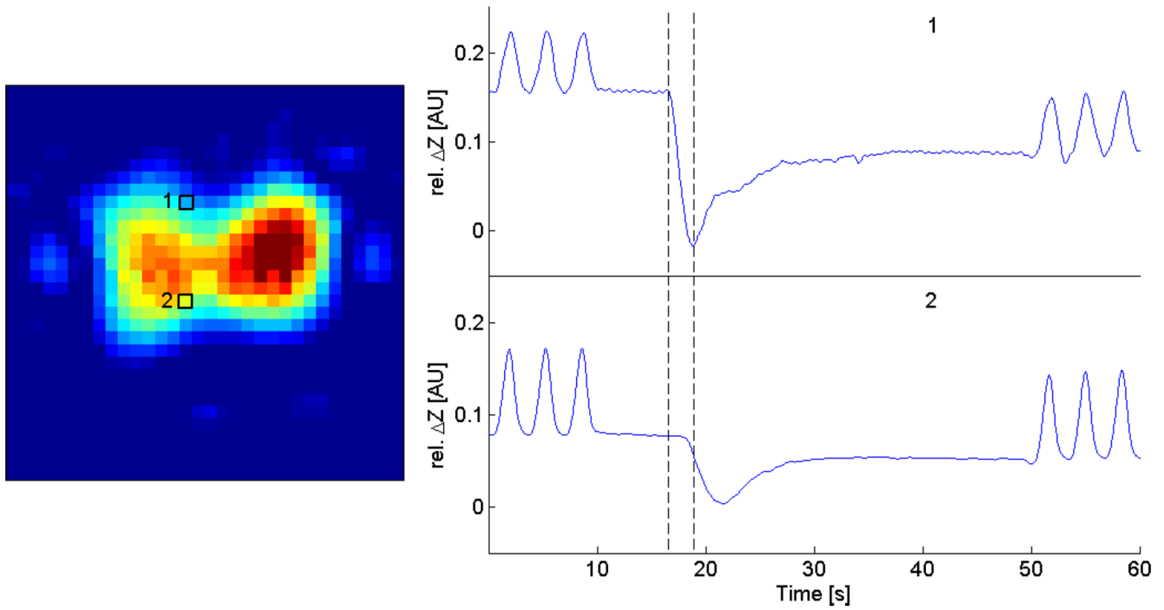
Schullcke B, et al., *Med. Physics,* 2017

Pulsatile, Cardiac related EIT Signal

- 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
- pulsatile impedance changes can be obtained by different methods:
  - frequency filtering
  - PCA
  - ECG gating
  - Harmonic Analysis
  - breath holding
  - use of contrast agents



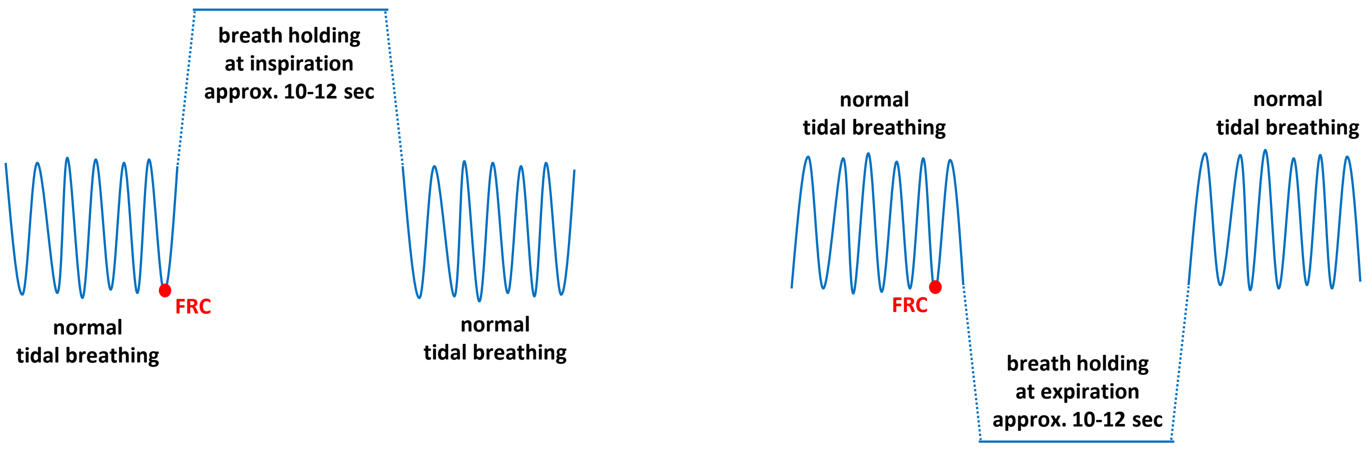
Contrast agent (Saline Bolus)



Methods

- one lung healthy volunteer (male, 29 years, 184 cm, 77 kg)
- Body plethysmography: normal tidal breathing, shutter maneuvers, breath holding
- EIT: 16-electrode belt at the 5th intercostal space, frame rate 50 Hz, current injection 8 mA, 89 kHz

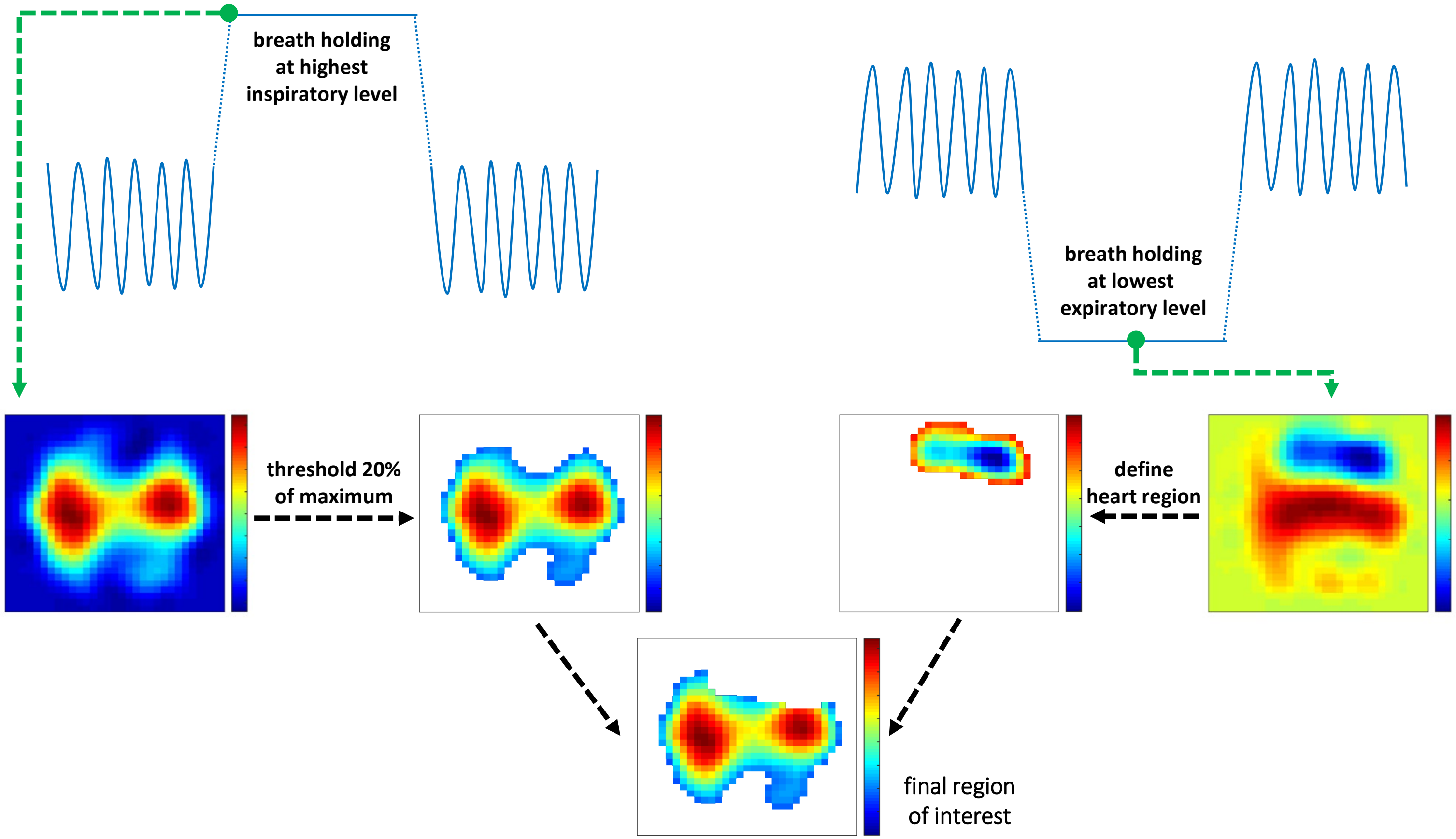
Breathing patterns:



→ 3 various inspiratory and expiratory levels

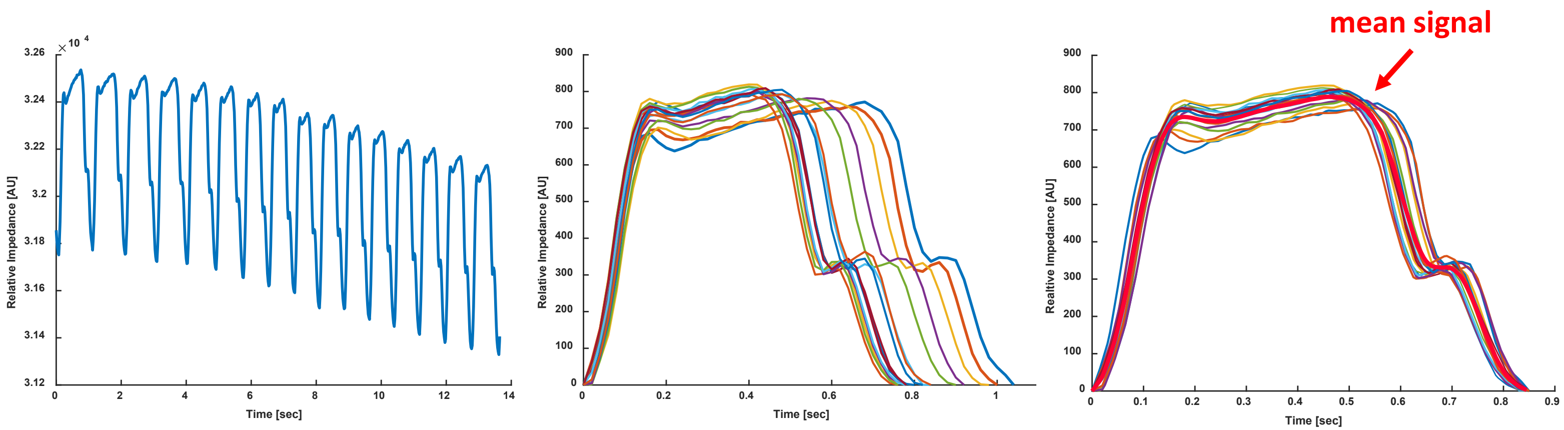
Methods

→ a region of interest was defined by including lung tissue and excluding the heart

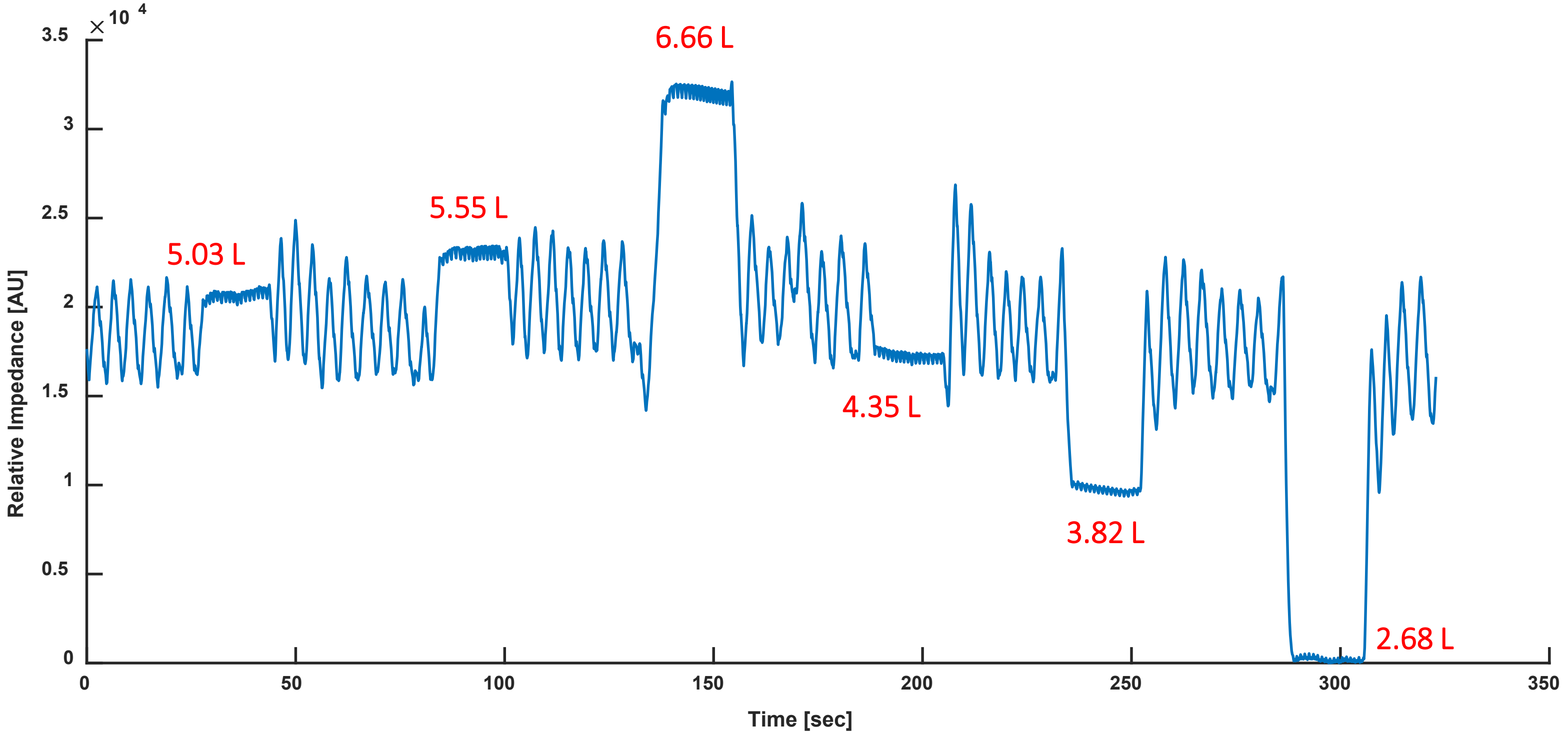


Methods

- the EIT signal measured during the phase of breath holding was subdivided in signal sections corresponding to the period of one heartbeat
- removal of linear trend from all signal sections
- rescaling of the time span of each signal section to the mean time span of all sections
- calculation of the mean signal of all sections

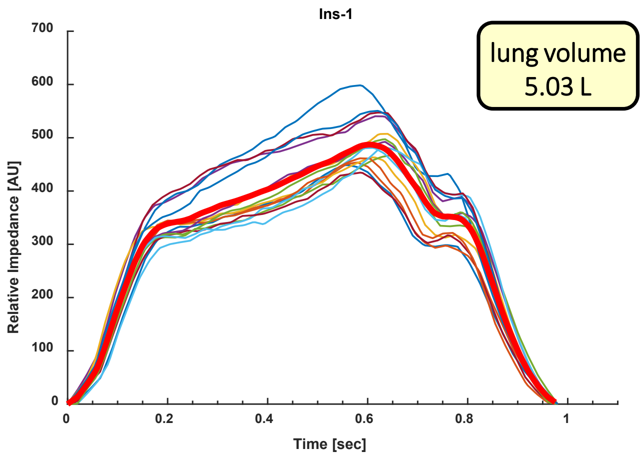


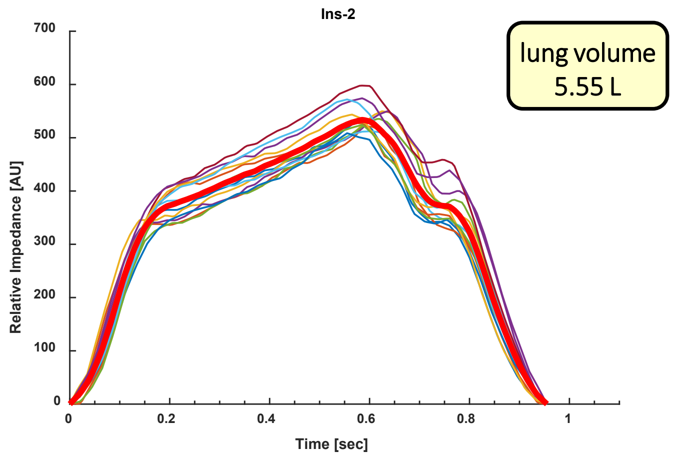
Results – global EIT signal

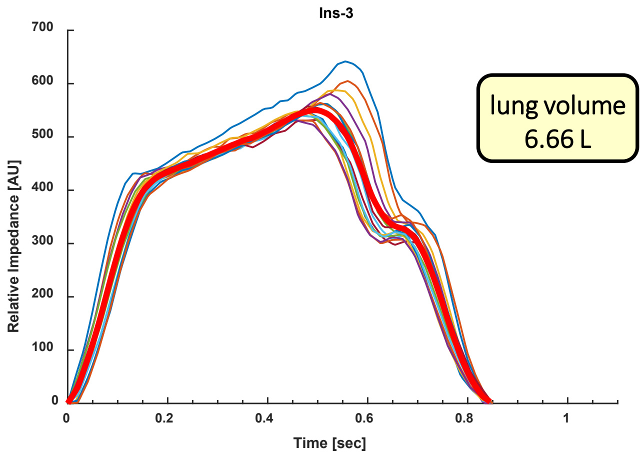


→ lung volume during breath holding

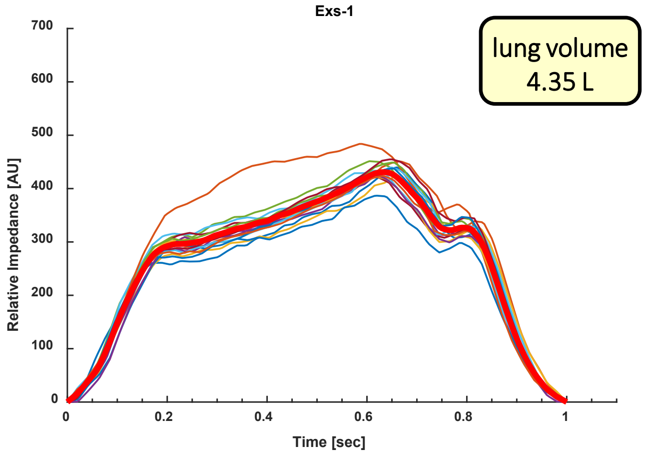
Results – inspiratory levels

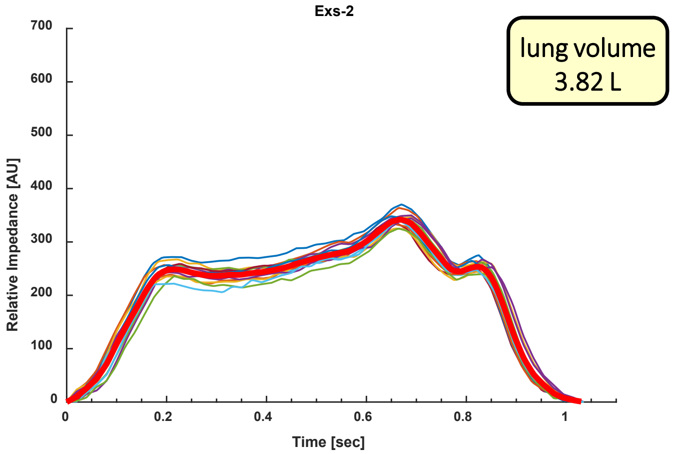


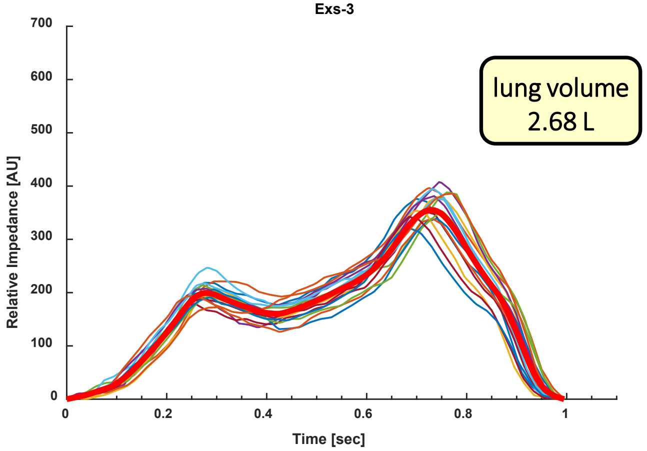




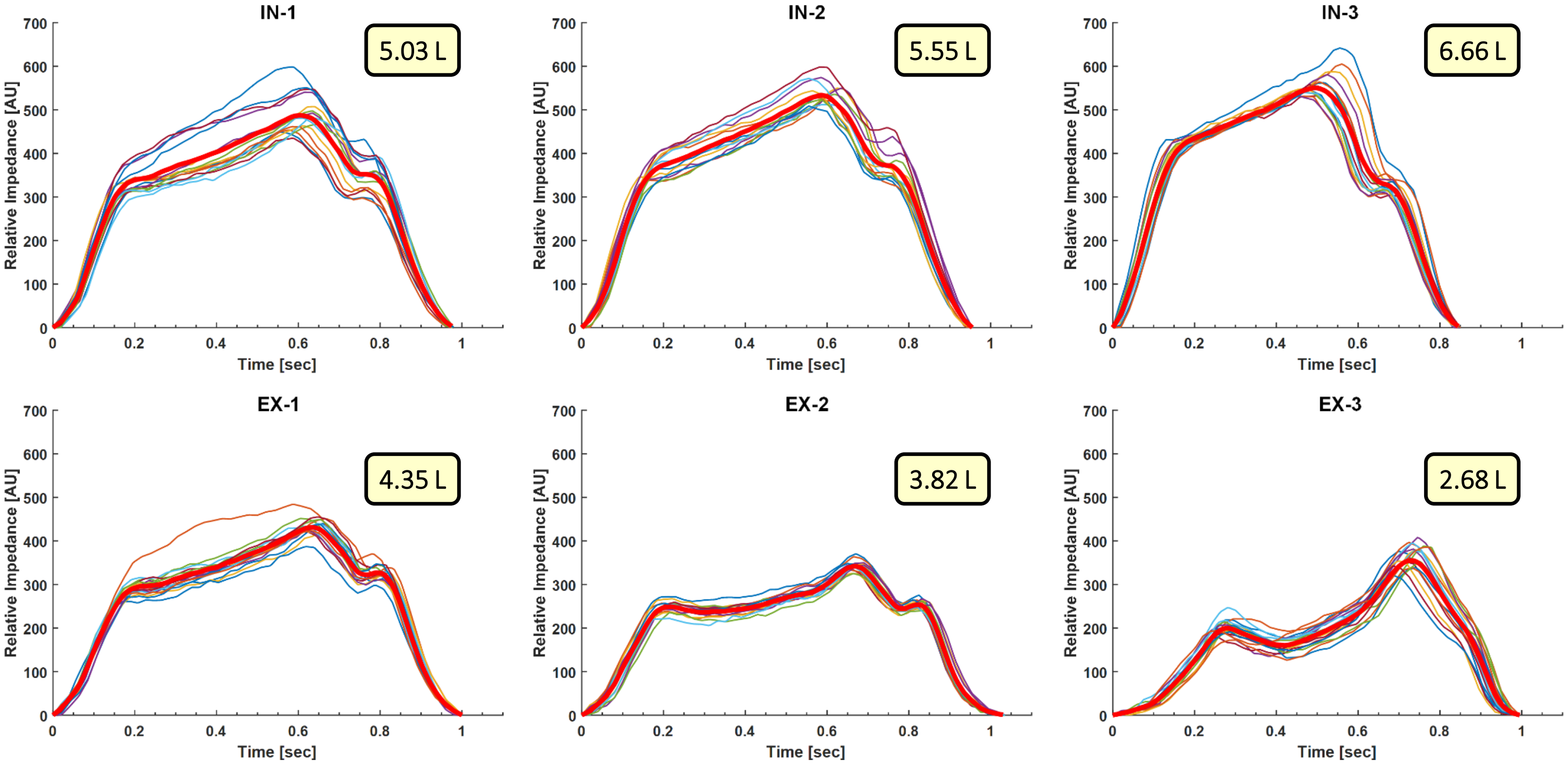
Results – expiratory levels







Results – overview all levels



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.

Three general uses of thoracic EIT have been proposed in adult patients:

- Monitoring of mechanical ventilation
- Monitoring of heart activity and lung prefusion
- Pulmonary function testing

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.

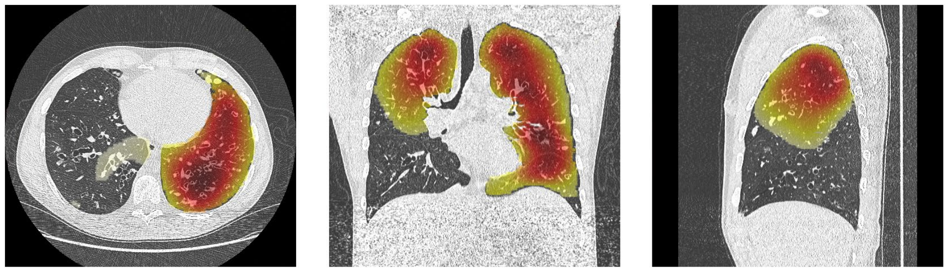
BUT….

Summary -2

- Low signal to noise ratio
- Ill-posed problem, that REQUIRES prior knowledge
- Different forms of priors can be incorporated
  - General constraints
  - Patient specific e.g. anatomical (static) priors or dynamic prior
  - Bayesian embedding
- PRIORS can be misleading if (no longer) correct.
- Priors may dominate over the information content of measured signals.

Future developments to visualize ventilation heterogeneity in patients

- EIT measurements using prior knowledge in all stages
  - Temporal priors in addition to image regularization
  - Validity check of priors
- 'Patient specific EIT imaging'
  - e.g. using patient specific anatomical information in the reconstruction process
- 3D EIT reconstruction
- Multi-frequency EIT
- Absolute EIT
- Lung blood pressure estimates from perfusion velocity (PTT)



axial coronal sagittal

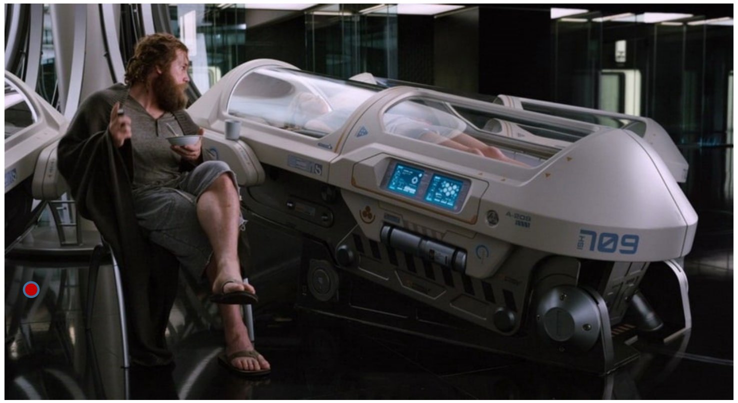
Future Developments

Novel approaches with some potential e.g.

- Contactfree EIT via capacitive or electromagnetic coupling
- combinations of image modalities like PET/EIT or MRI/EIT…

- Widen applicability of **TD EIT** by using (mechanical) stimulation to enhance contrast in static settings
- Multipath problem ? Structured Input?

Still a long way to go…



Acknowledgements
(ventilation related projects)

Motif-A (FKZ: 1781X08)
WiMVent (FKZ: 01IB10002D)
PulMoDS (FKZ: 01DR12095)
MOSES (FKZ: 13FH038I3)
DACAPO (FKZ: 13FH5I01IA)
BIKEM (FKZ: 01DR17024)
MOVE (FKZ: 13FH628IX6)
IRMA (FKZ: 13FH5I05IA)

PAR:Protective Ventilation (GZ: MO 579/1-2)
TAP: TissueAnalysis Plattform (GZ: INST 897/10-1)

ETiME (FP7: PIRSES-GA-318943)
DCPM (H2020 : 872488-DCPM)
PER-Fluid (ERA PerMed 2522FSB903)

PulmoTrack (KK5151903BM1)
EMID (KF2444501FR9)

Julius Von Haast Fellowship of the Royal Society of NZ

SPONSORED BY THE
Federal Ministry of Education and Research

FORSCHUNG AN FACHHOCHSCHULEN

Deutsche Forschungsgemeinschaft
DFG

Bundesministerium für Wirtschaft und Technologie