Electrical Impedance Tomography: Benefits and Limitations

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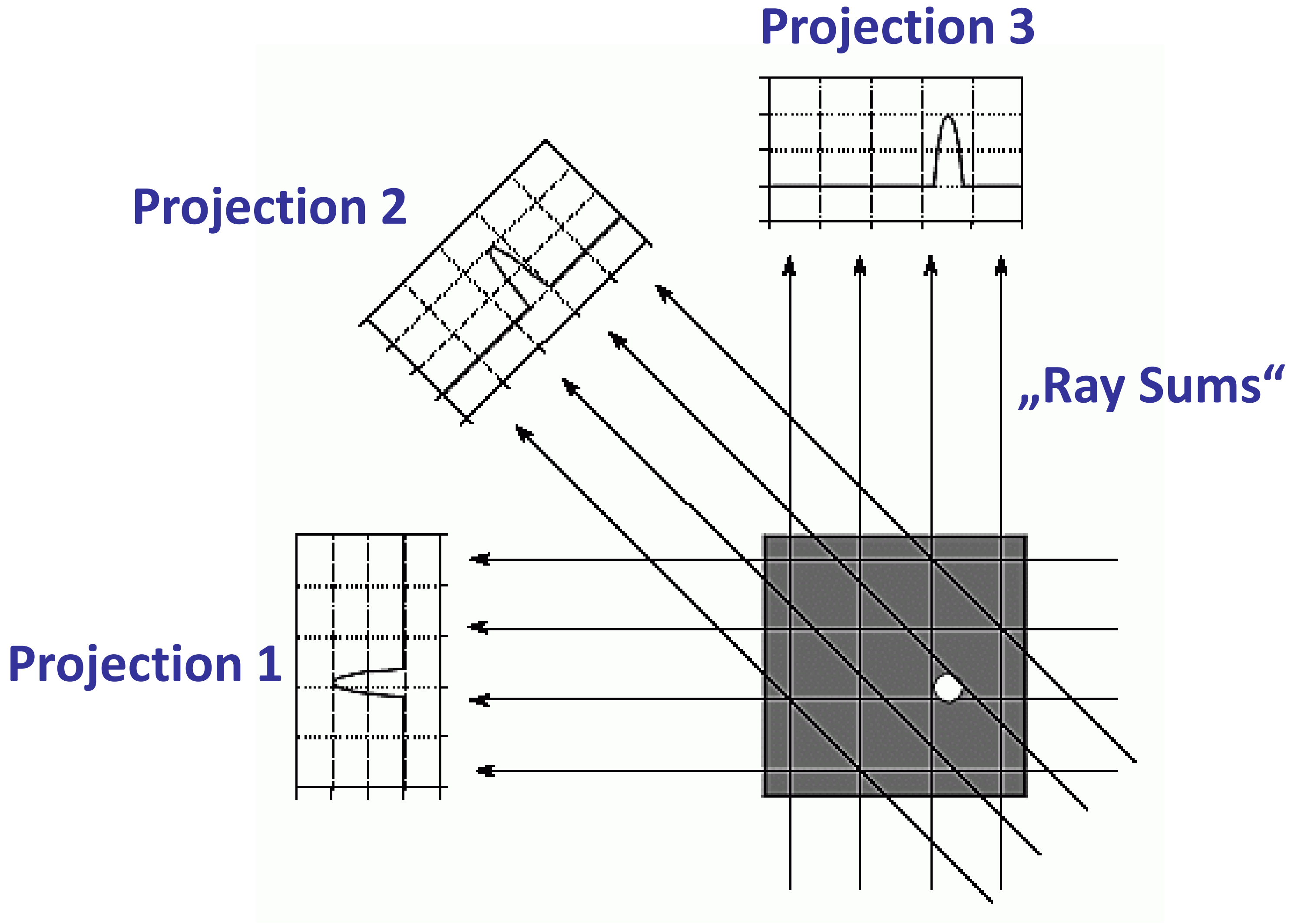
NON-CONVENTIONAL VENTILATORY TEAM
WWW.VENTILATION.CZ

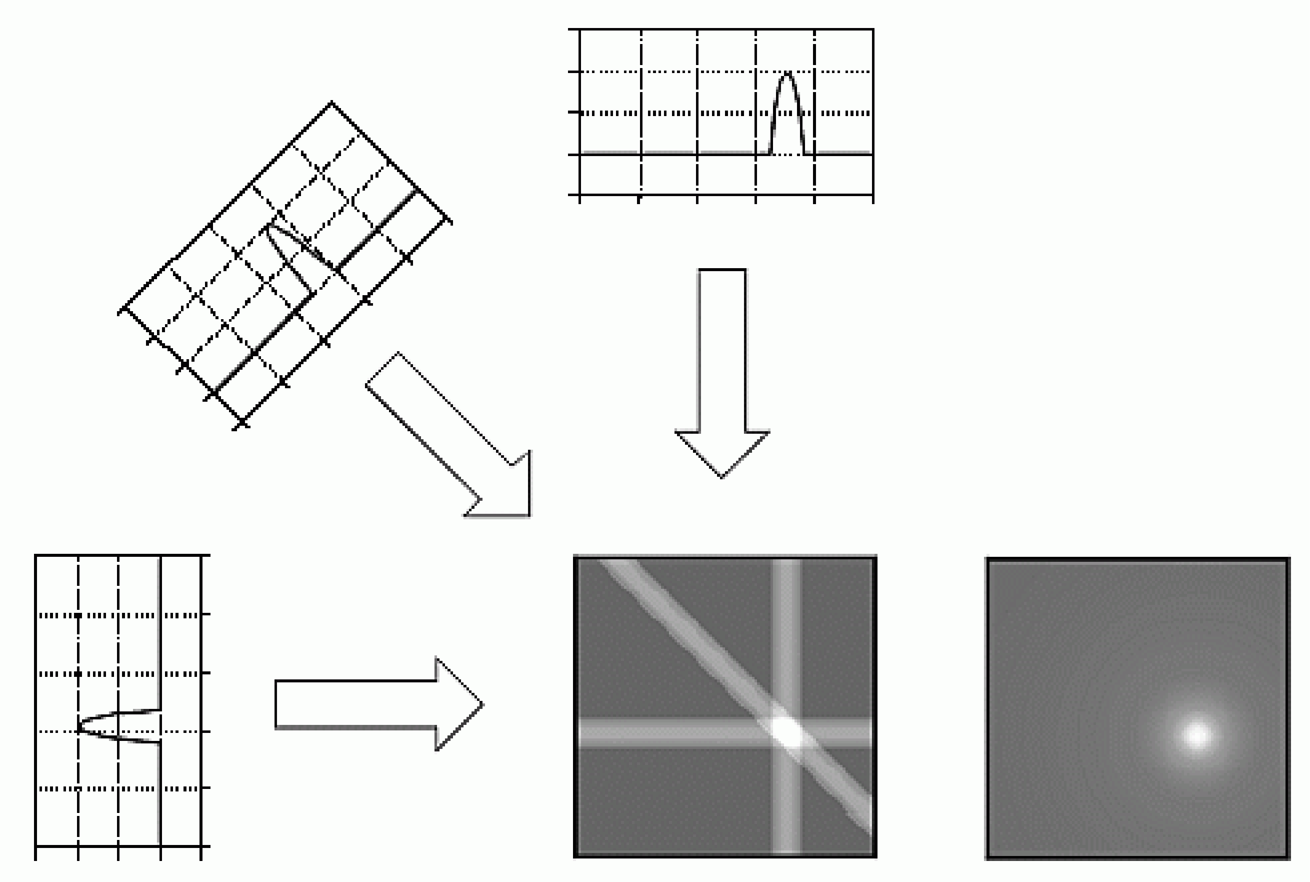
EIT – analogy to the Computed tomography ...

Projections



EIT – analogy to the Computed tomography ...

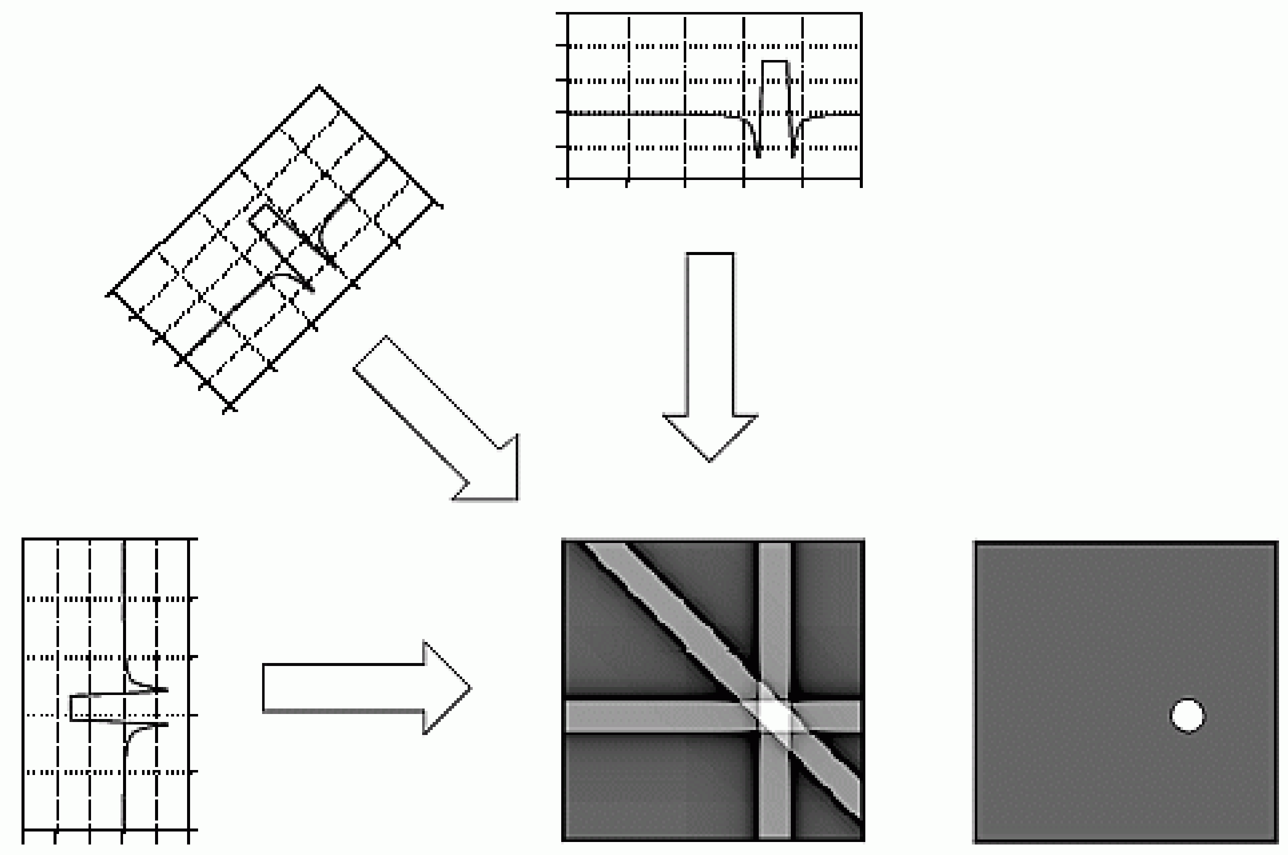
The Back Projection Algorithm



Blurred and distorted reconstructed image

EIT – analogy to the Computed tomography ...

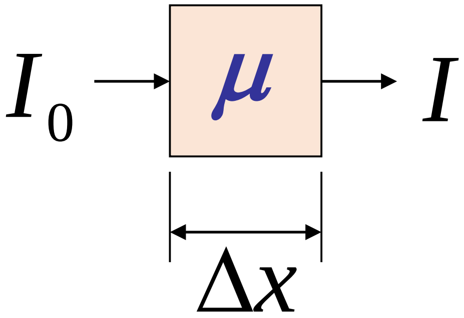
The Filtered Back Projection Algorithm



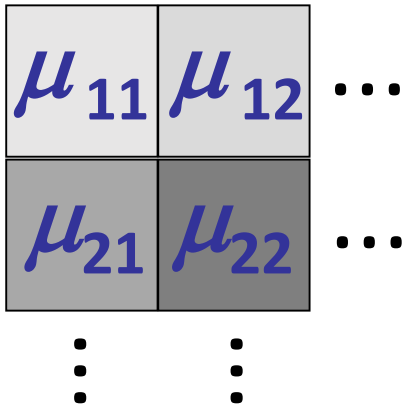
Improved contrast,
the star artefact is reduced.
The result is still not identical with the original image.

EIT – analogy to the Computed tomography ...

CT:



$$I = I_0 \cdot e^{-\underline{\mu} \cdot \Delta x}$$



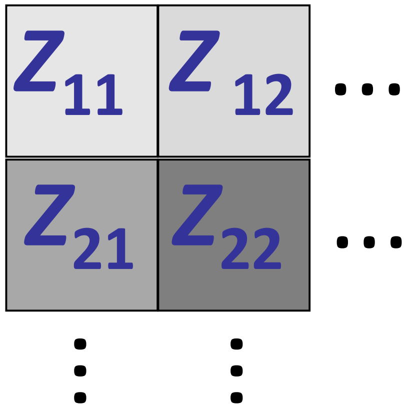
Computed Tomography (CT) uses X-ray radiation and its attenuation.

Linear attenuation coefficient (μ) is a constant that describes the fraction of attenuated incident photons in a monoenergetic beam per unit thickness of a material.

CT image: a matrix of $\mu_{i,j}$ encoded in brightness modulation.

EIT – analogy to the Computed tomography ...

EIT:



Electrical impedance tomography (EIT) uses the electric current to measure the tissue impedance.

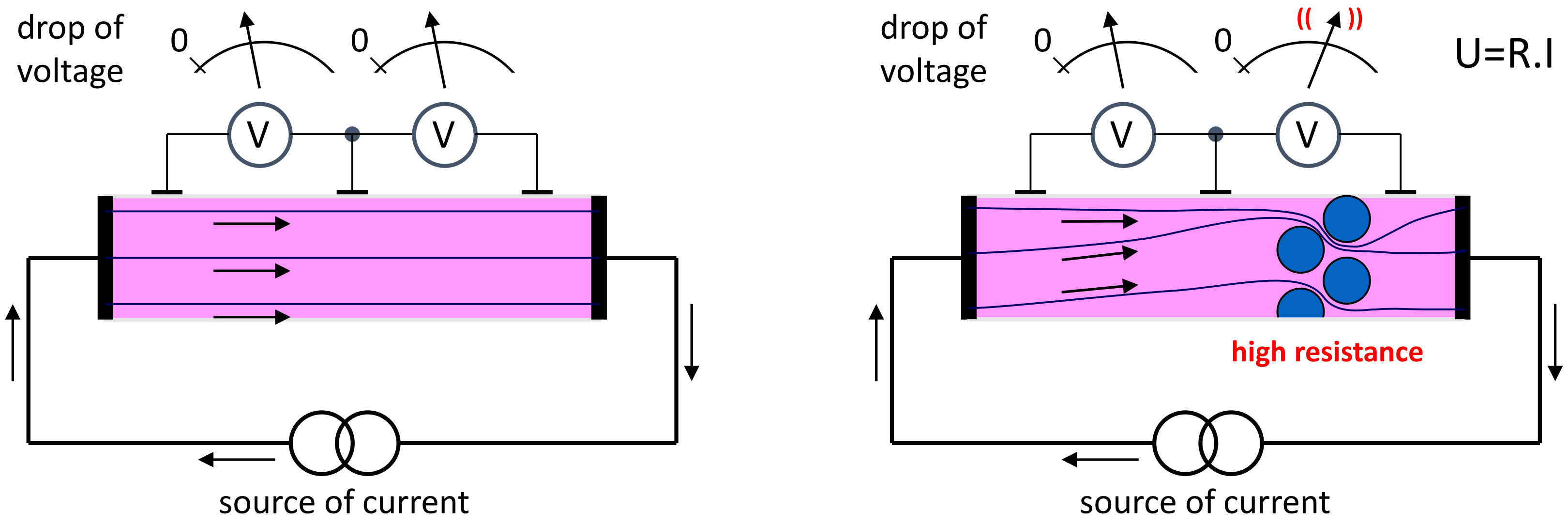
Impedance (Z) is an the effective resistance of an electric circuit or component to alternating current, arising from the combined effects of ohmic resistance and reactance.

EIT image: a matrix of $Z_{i,j}$ encoded in brightness modulation (or using a color scale).

EIT – measurement of impedance

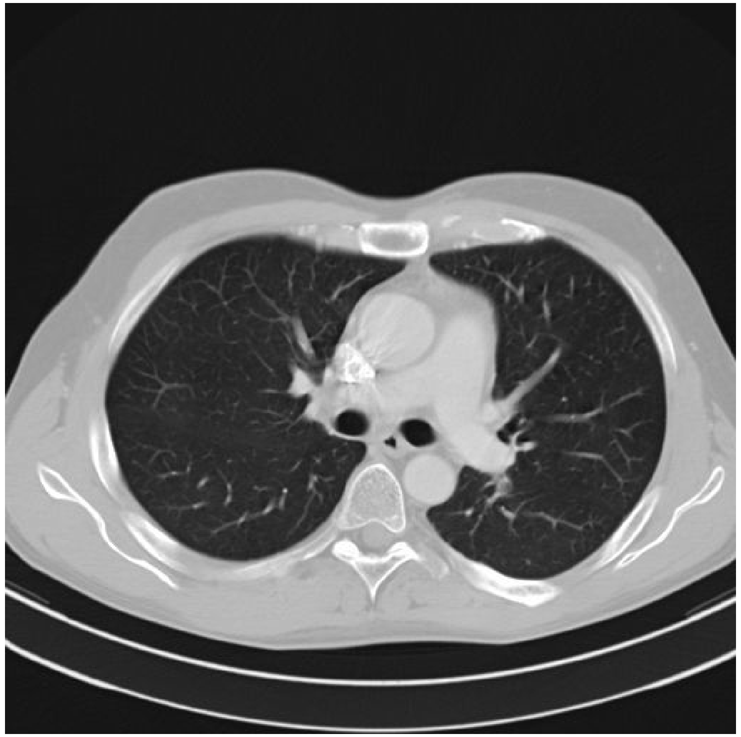
A high contrast in lungs: Conductivity of lungs is strongly affected by presence of gas. The more gas in the lungs, the higher the lung resistance.

Is gas a bad conductor? ☺

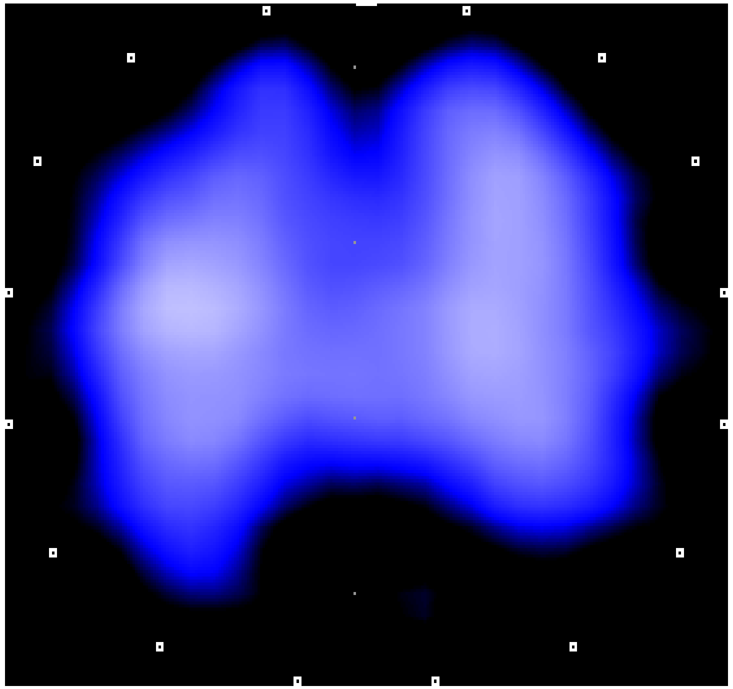


Comparison of CT and EIT

CT scan



EIT image



EIT:

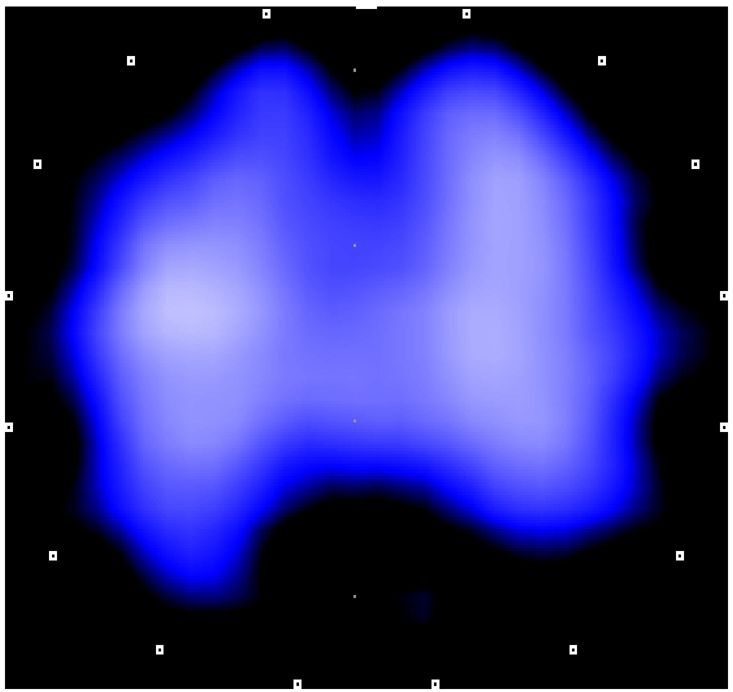
- **low spatial resolution**
- **good temporal resolution**
- **functional imaging system**

Contrast in the lung EIT image is directly proportional to the changes of the lung volume. These changes in EIT image can be directly recalculated to changes in the lung volume.

COULOMBE, N. et al. Physiol. Meas. 2005, 26, pp. 401-411

Questions about EIT

EIT image



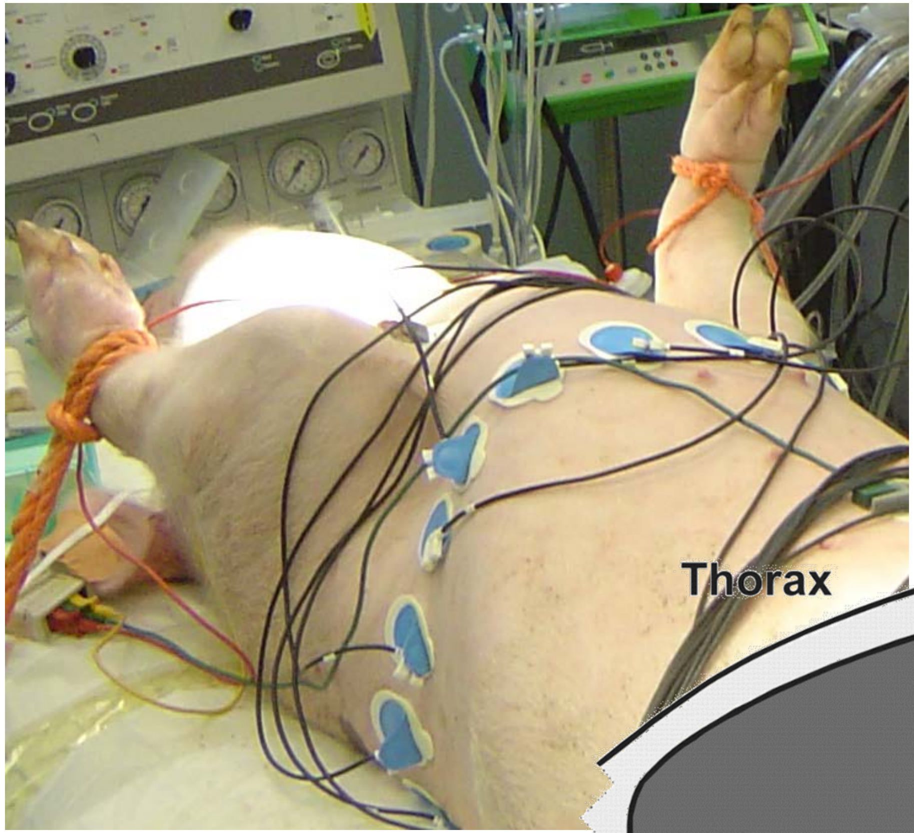
Contrast in the lung EIT image is directly proportional to the changes of the lung volume.
These changes in EIT image can be directly recalculated to changes in the lung volume.

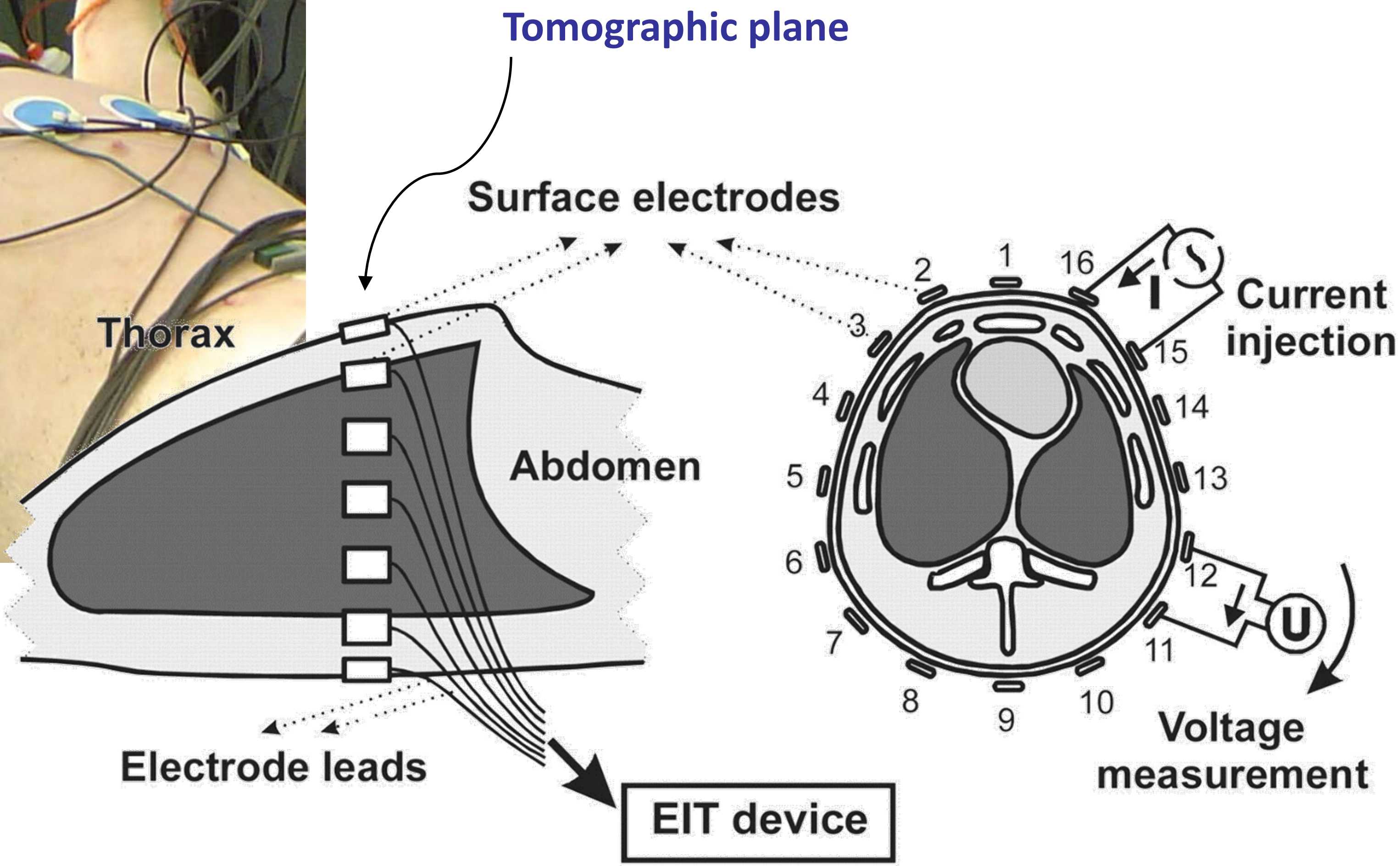
... always? If not, why?

Can the spatial resolution be increased?

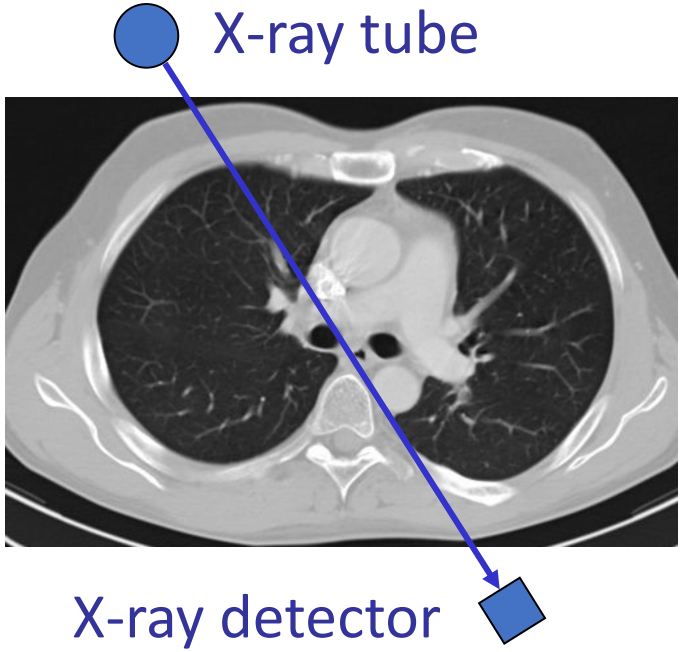
...

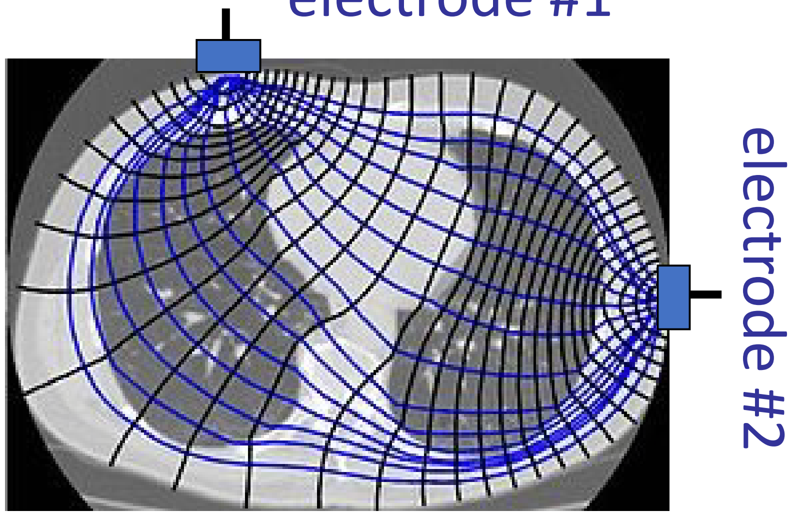
EIT – measurement of impedance





EIT – measurement of impedance - limitations

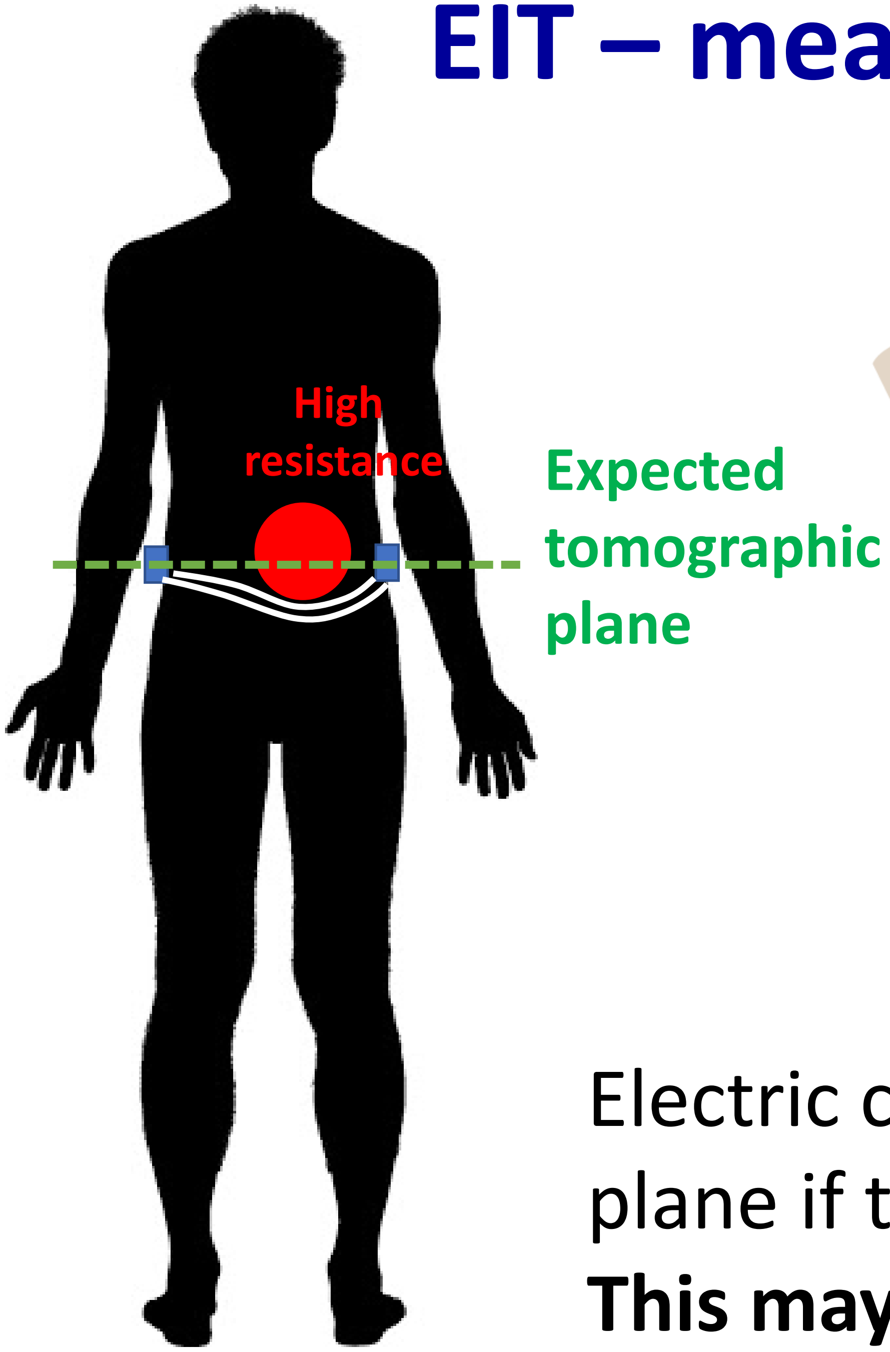


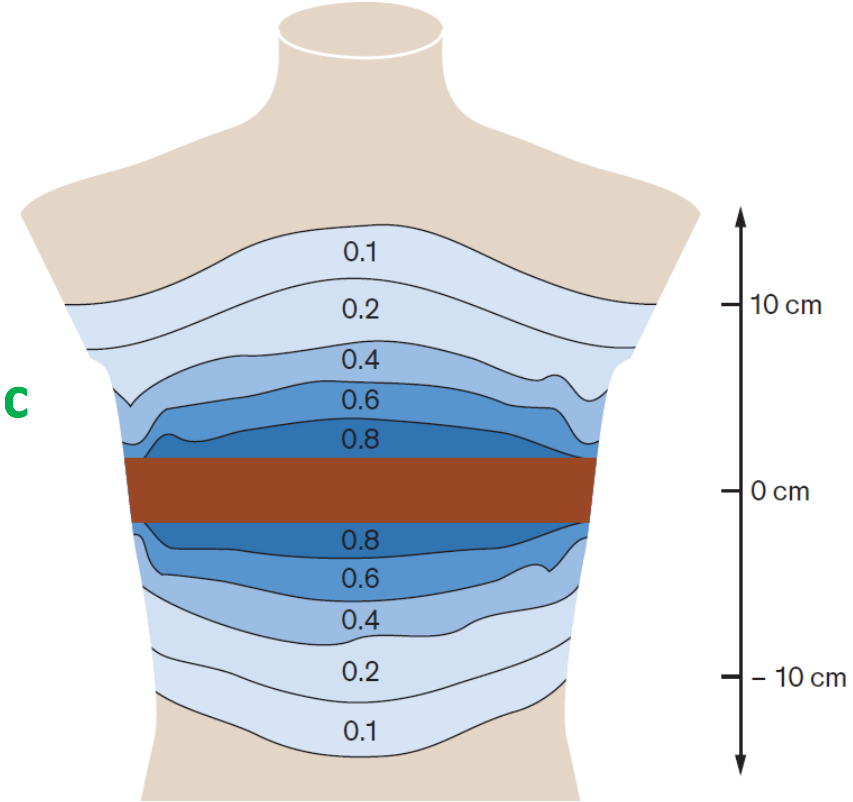


Low spatial resolution:
Further increase in number of electrodes will not improve the spatial image resolution significantly.

Electric current preferably flows through regions with lowest resistance.
This effect limits the spatial resolution.
Resolution towards the center of the image decreases.

EIT – measurement of impedance





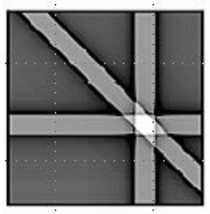
Stolen from Drëger.

Stolen from NSA.

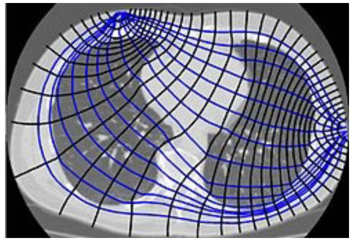
Electric current may flow outside the tomographic plane if there are structures with a high impedance.

This may contaminate EIT signal by other structures.

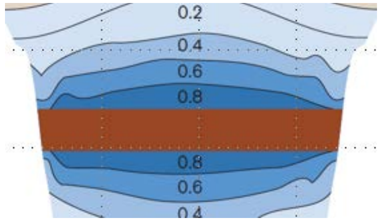
EIT – errors and additional errors compared to CT



Reconstruction algorithms have always some errors. Their corrections presume a certain type of images.

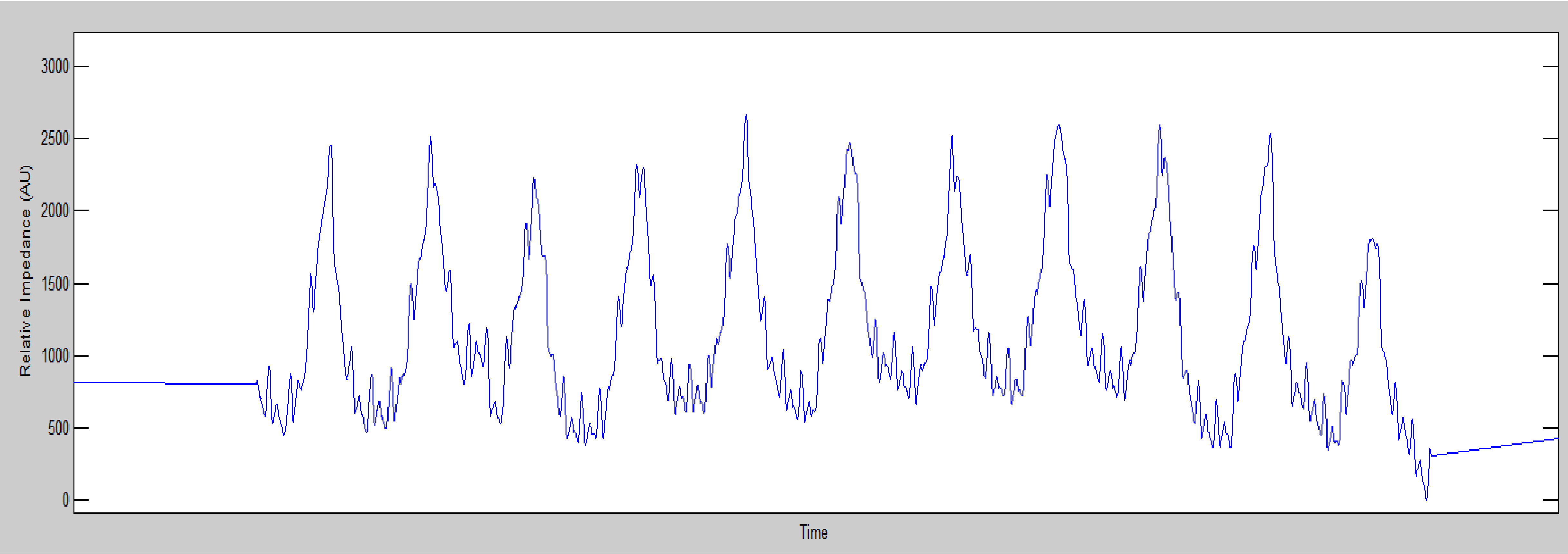


The spatial resolution is low, especially in the center. The electric current does not flow straight.



There is not a true tomographic plane;
a tomographic layer is more appropriate. The layer may be distorted significantly and signals from organs outside the tomographic plain contribute to the EIT signal.

EIT of the thorax



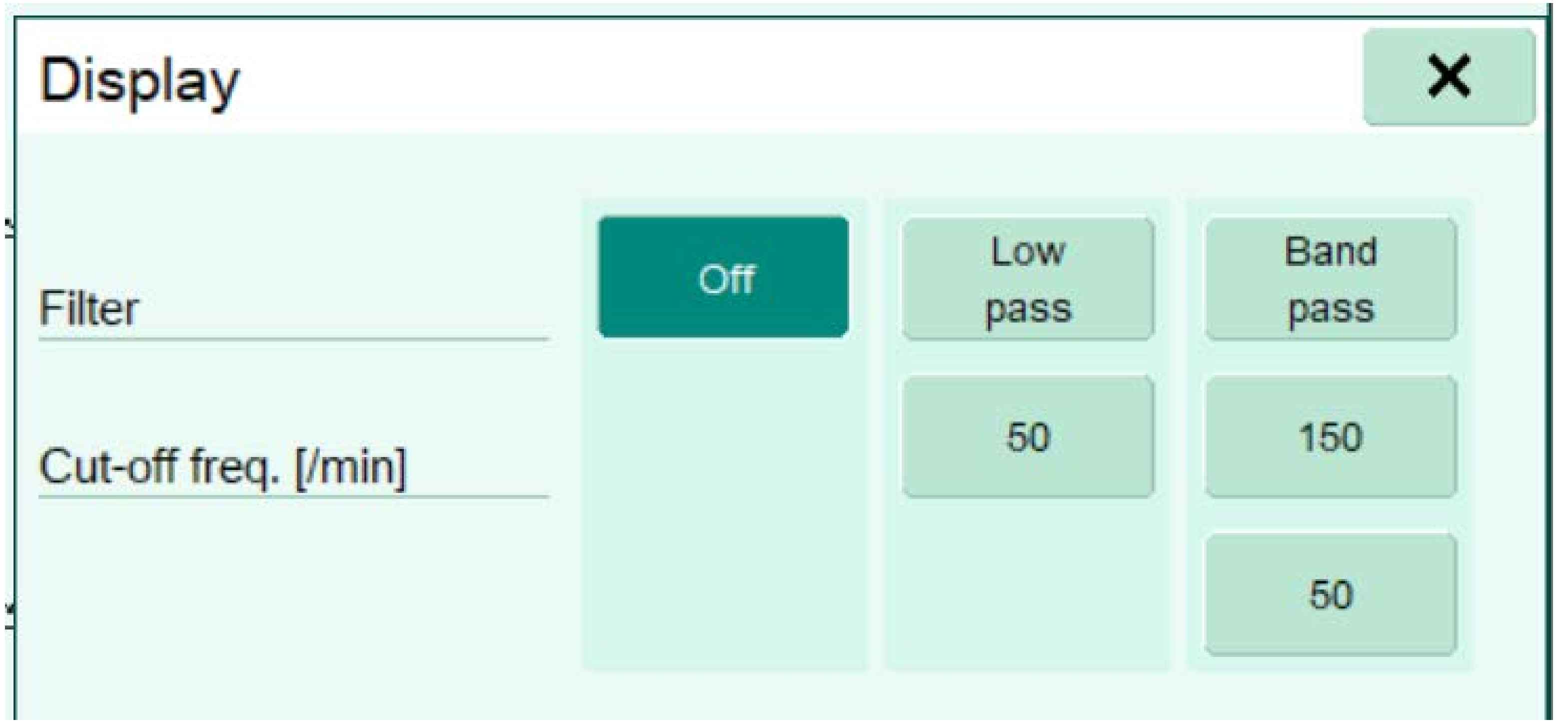
The signal consists of two main components: ventilation and perfusion. They differ in amplitude (1:10 – 1:100) and frequency. **They are mixed even though the tomographic plane is selected properly.**

Separation of ventilation and perfusion

In practice, the ventilation and perfusion EIT signals are usually separated using a Low-pass and a Band-pass filters:

Ventilation:
Low-pass: 50 min^{-1}

Perfusion:
Band-pass: 50–150 min^{-1}



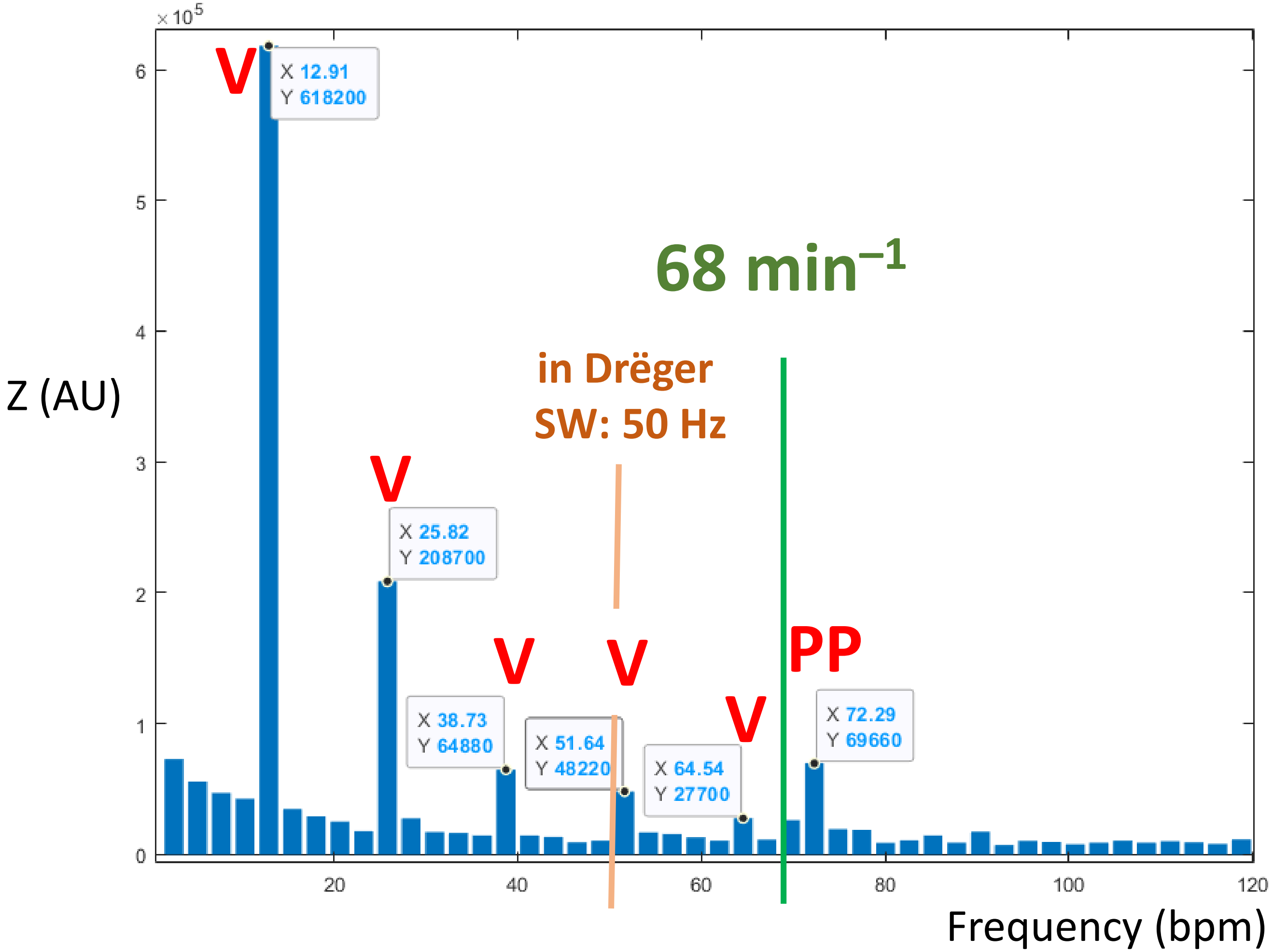
Filtering in Draeger EIT Analysis Tool 6.1, Drëger, Germany

Separation of ventilation and perfusion

Are the spectral components of ventilation and perfusion different?
i.e.: Are the components in the different spectral bands?

V – spectral components of ventilation
basic: 13 min^{-1}
harmonics: 26, 39, ... $n \cdot 13$ min^{-1}

P – spectral components of perfusion
basic: 72 min^{-1}
harmonics: $n \cdot 72$ min^{-1}



(a patient before laparoscopic surgery, volume control ventilation)

Separation of ventilation and perfusion

Are the spectral components of ventilation and perfusion in different spectral bands?

No: The signals cannot be separated using a low-pass and a band-pass filters.

V – spectral components of ventilation

basic: 20 min^{-1}

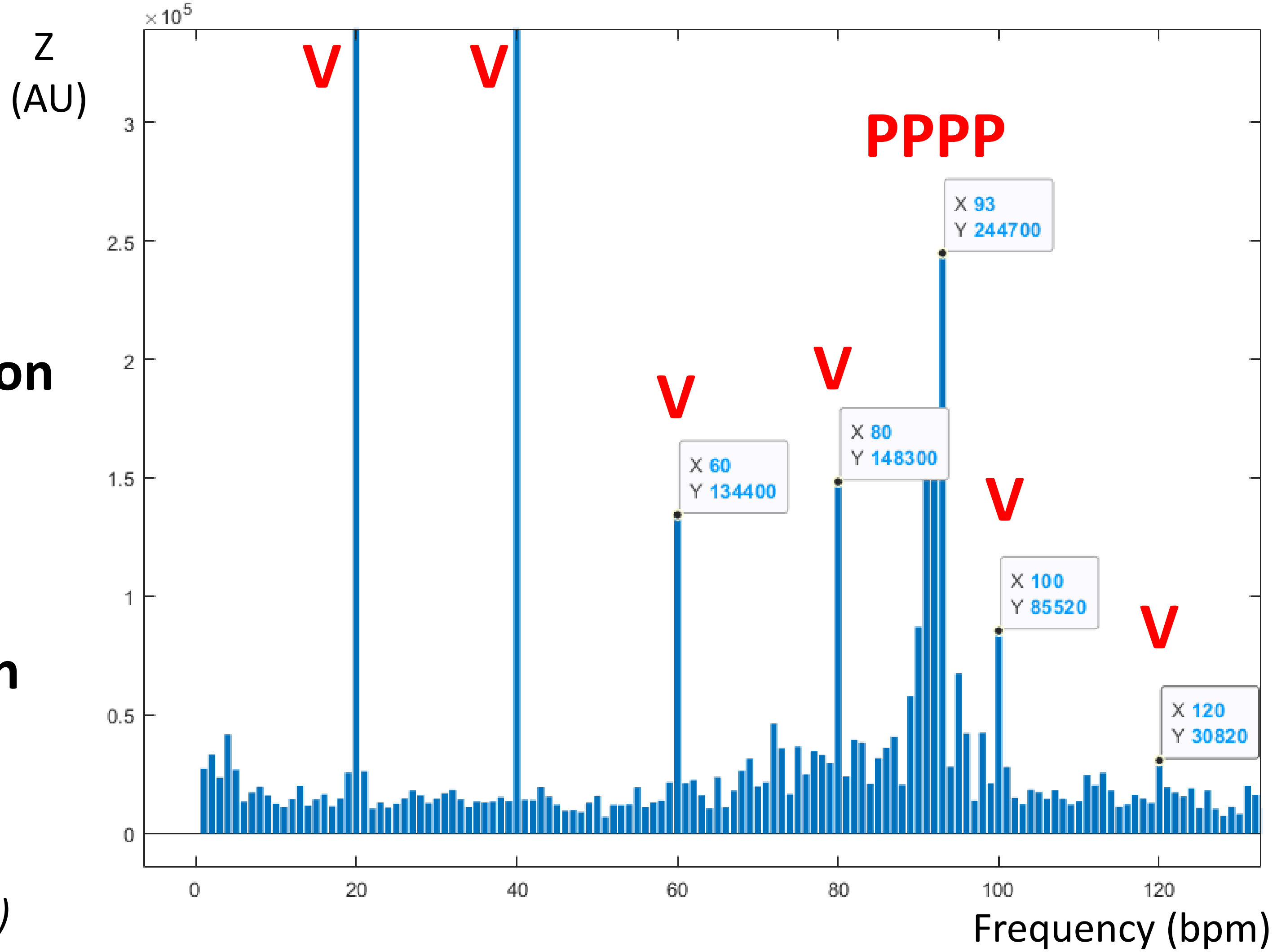
harmonics: 40, 60, 80, 100, 120, ... n·20 min^{-1}

P – spectral components of perfusion

basic: 93 min^{-1}

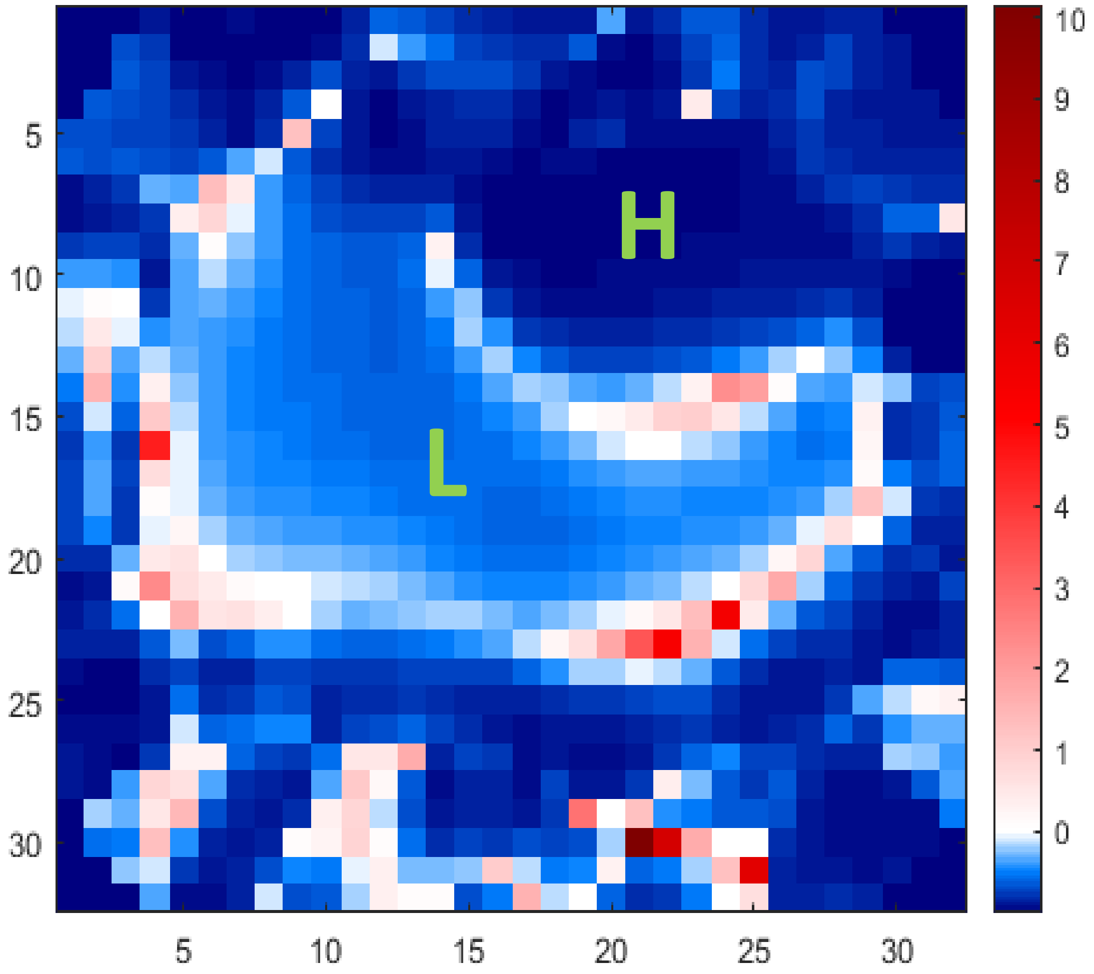
harmonics: n·93 min^{-1}

(Sus Scrofa Domestica, volume control ventilation)



Separation of ventilation and perfusion

Spectral leakage of ventilation components into the perfusion band is regionally dependent.

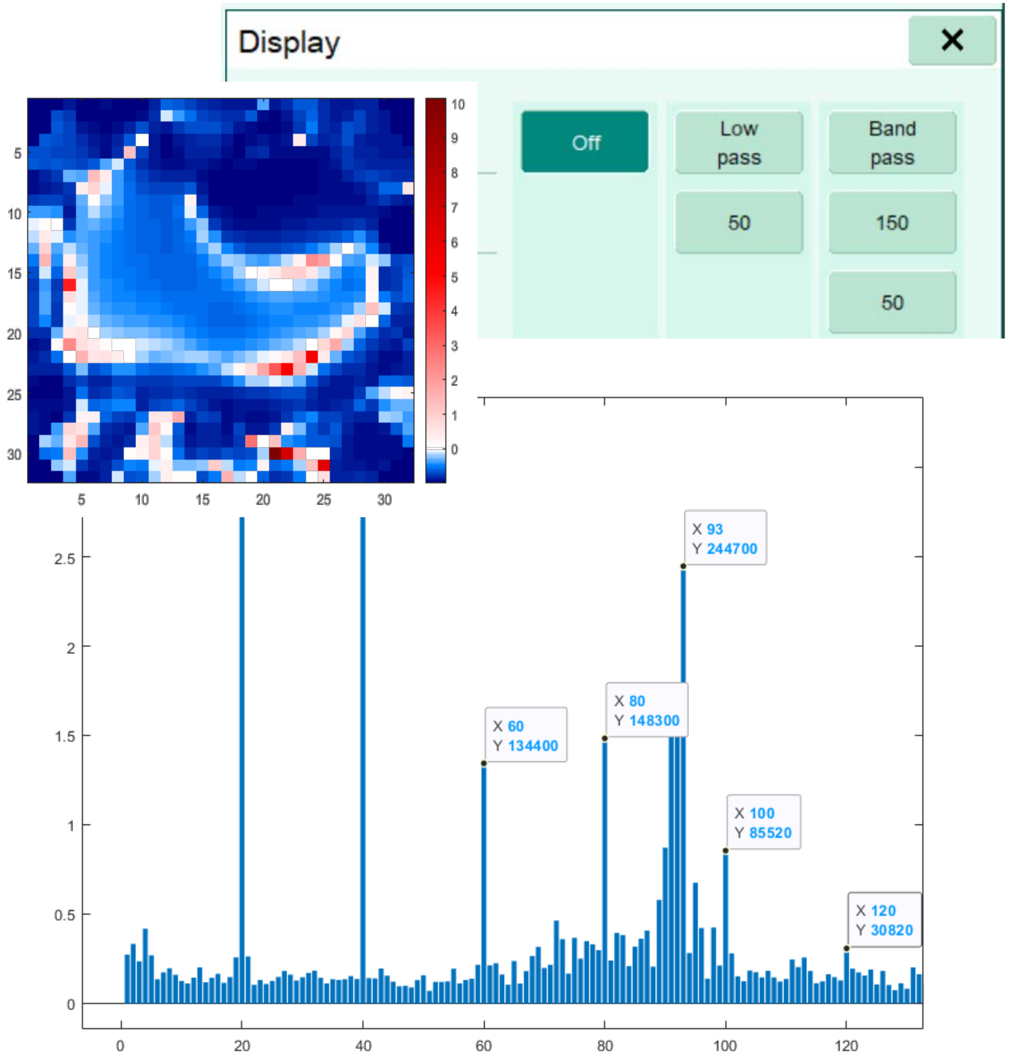


The color scale encodes the relation between ventilation and perfusion components **in the perfusion band**.

- Values < 0 ... perfusion signal dominates.
- Values > 0 ... ventilation signal dominated.
- The value of 0 means that that the amplitudes of ventilation and perfusion signals are equal.

H ... heart, **L** ... Lungs

Separation of ventilation and perfusion



Ventilation signal can be easily obtained (not affected by perfusion but sometimes slightly distorted).

To obtain perfusion signal, a proper method and parameters should be selected. The is a strong iter-individual variability.

A simple bandpass filtering to obtain the perfusion signal may not work well and sometimes does not work at all.

The cut-off frequency should be selected correctly, or, a better algorithm of separation should be applied (ECG gating, Pattern filtering PCA, ...)

Always: do the visual inspection of your results!

Practical applications

Contrast in the lung EIT image is directly proportional to the changes of the lung volume.

These changes in EIT image can be directly recalculated to changes in the lung volume.

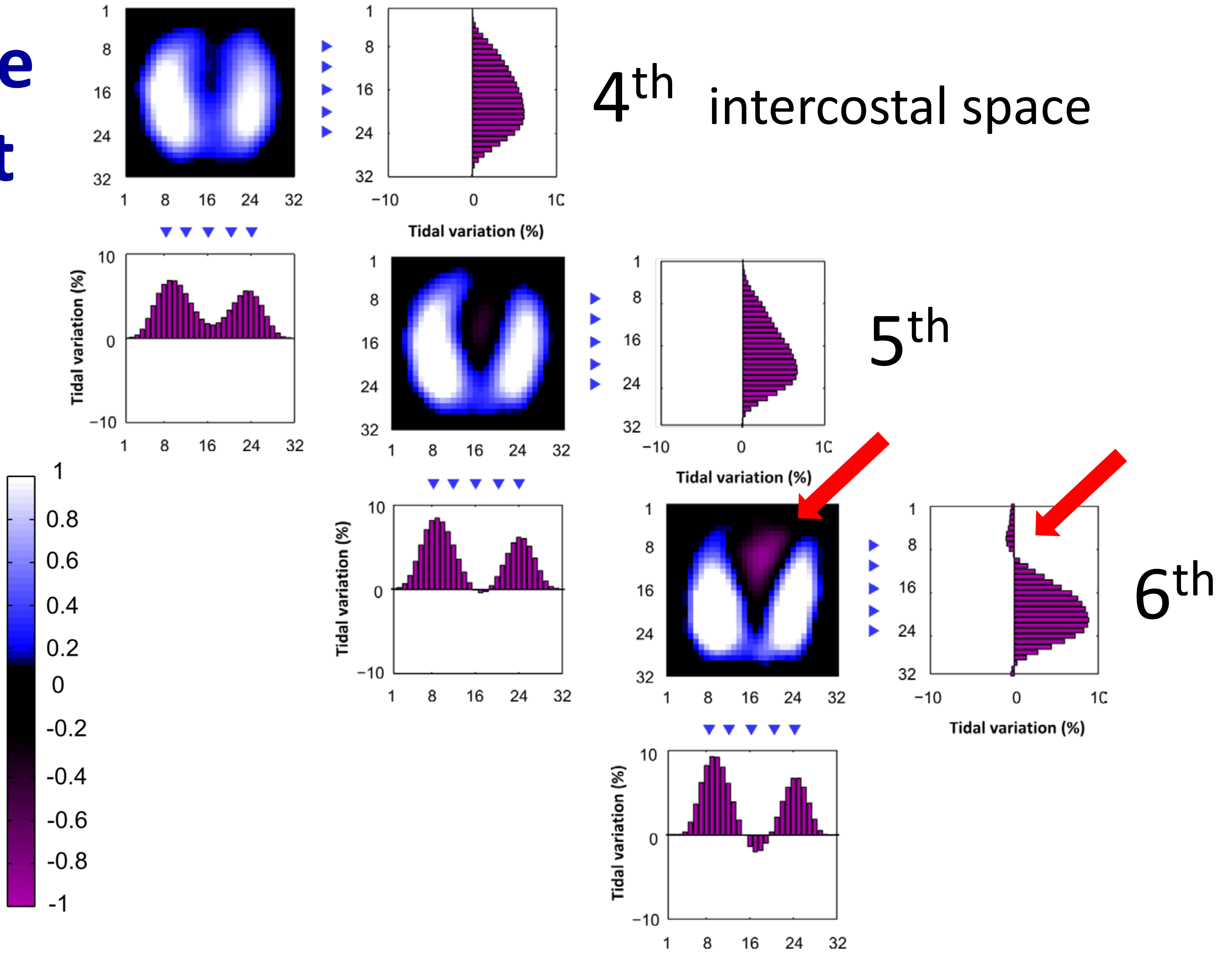
Position of the electrode belt

Spontaneous breathing

Electrode belt placed around the thorax in three different transversal planes - 4th, 5th, 6th intercostal space - all within the area specified by the manufacturer

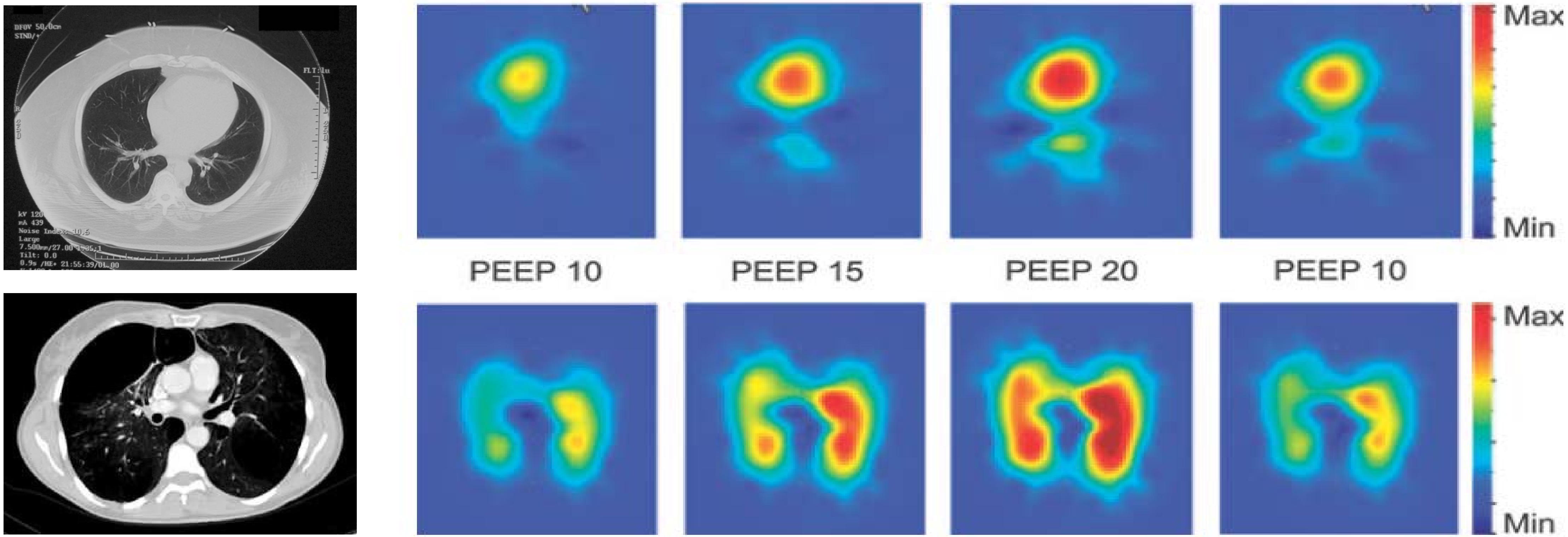
Supine position with the arms along the body

Spirometry recorded



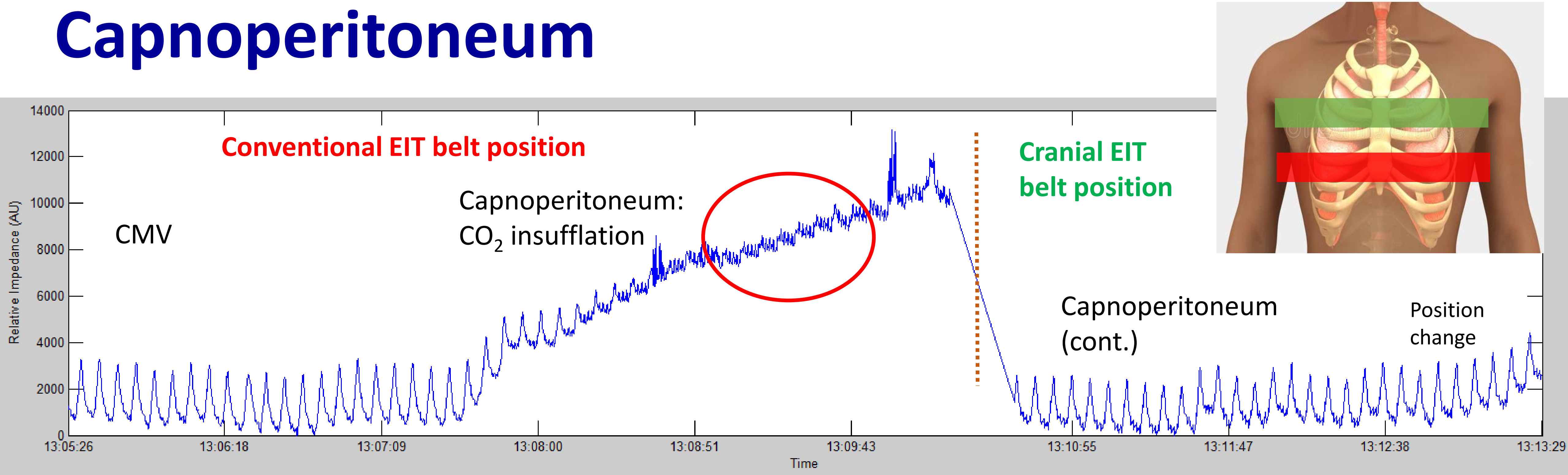
EIT in morbidly obese patients

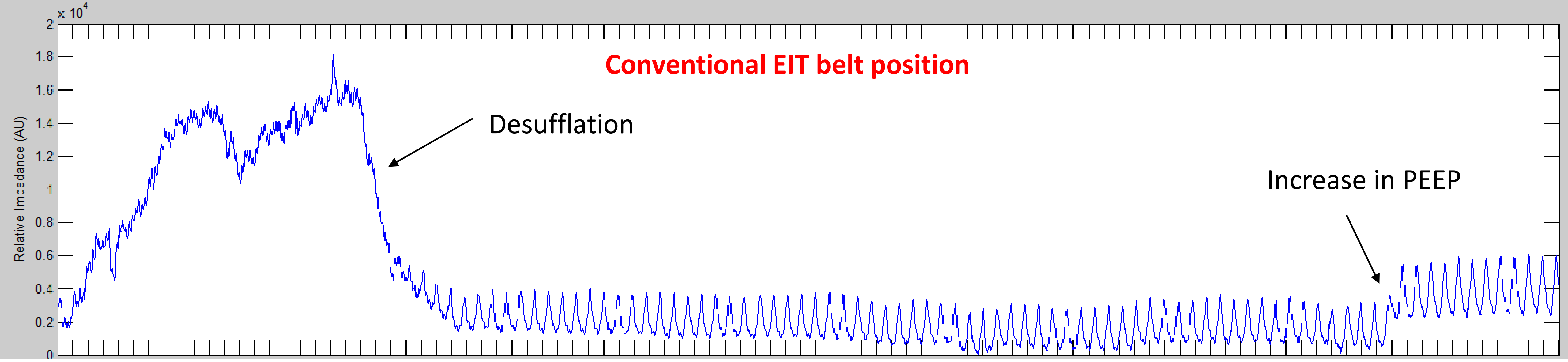
Distorted EIT images from a morbidly obese patient (top) at different PEEP levels and corresponding images from a normal weight patient (bottom).



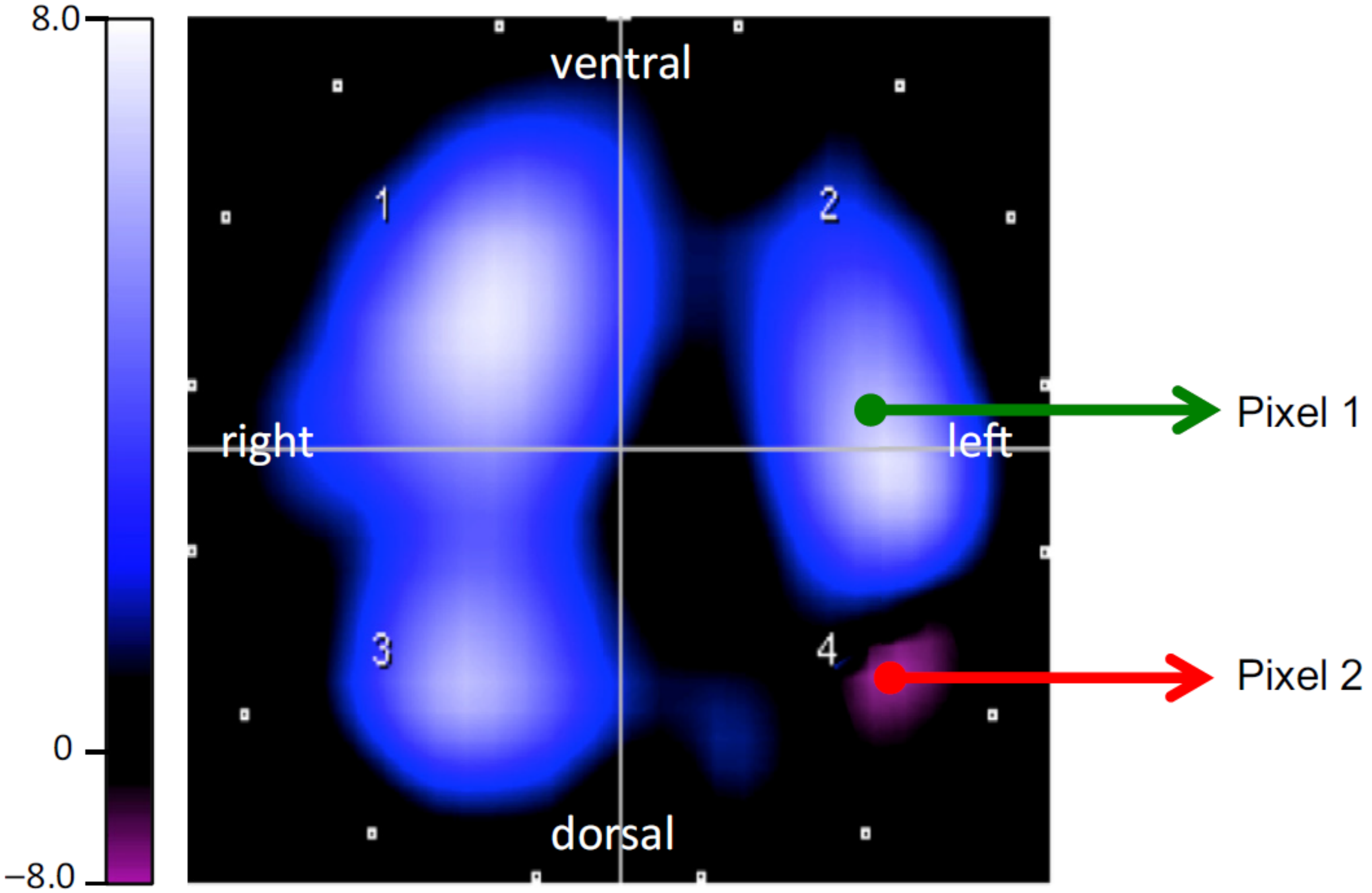
ERLANDSSON, K. et al. Acta Anaesthesiol. Scand. 2006, 50, pp. 833-839

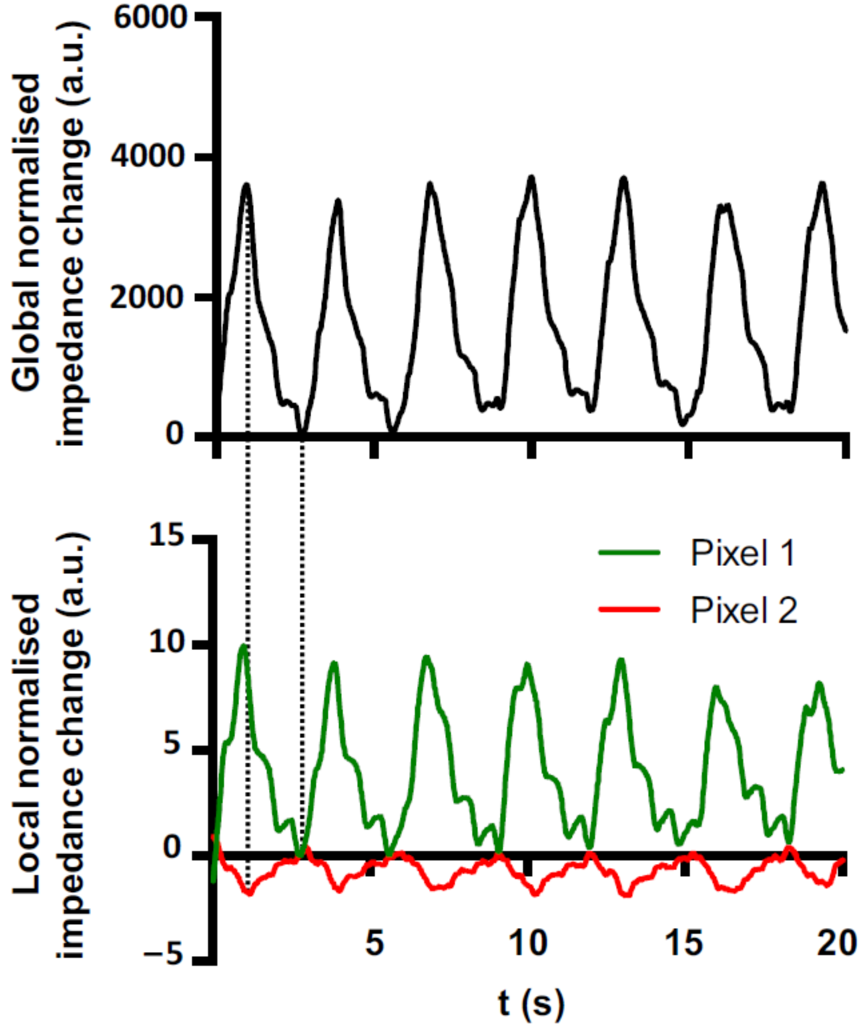
Capnoperitoneum





Pleural effusion



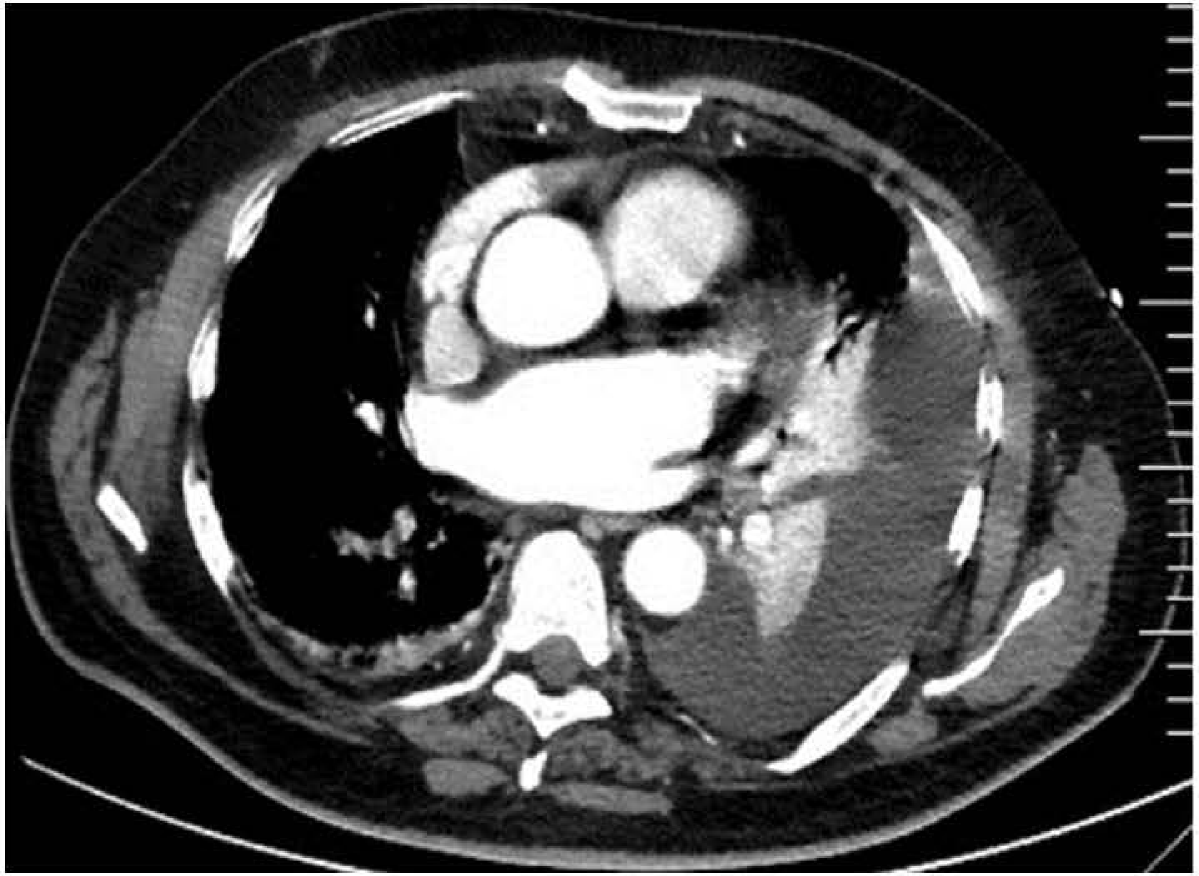


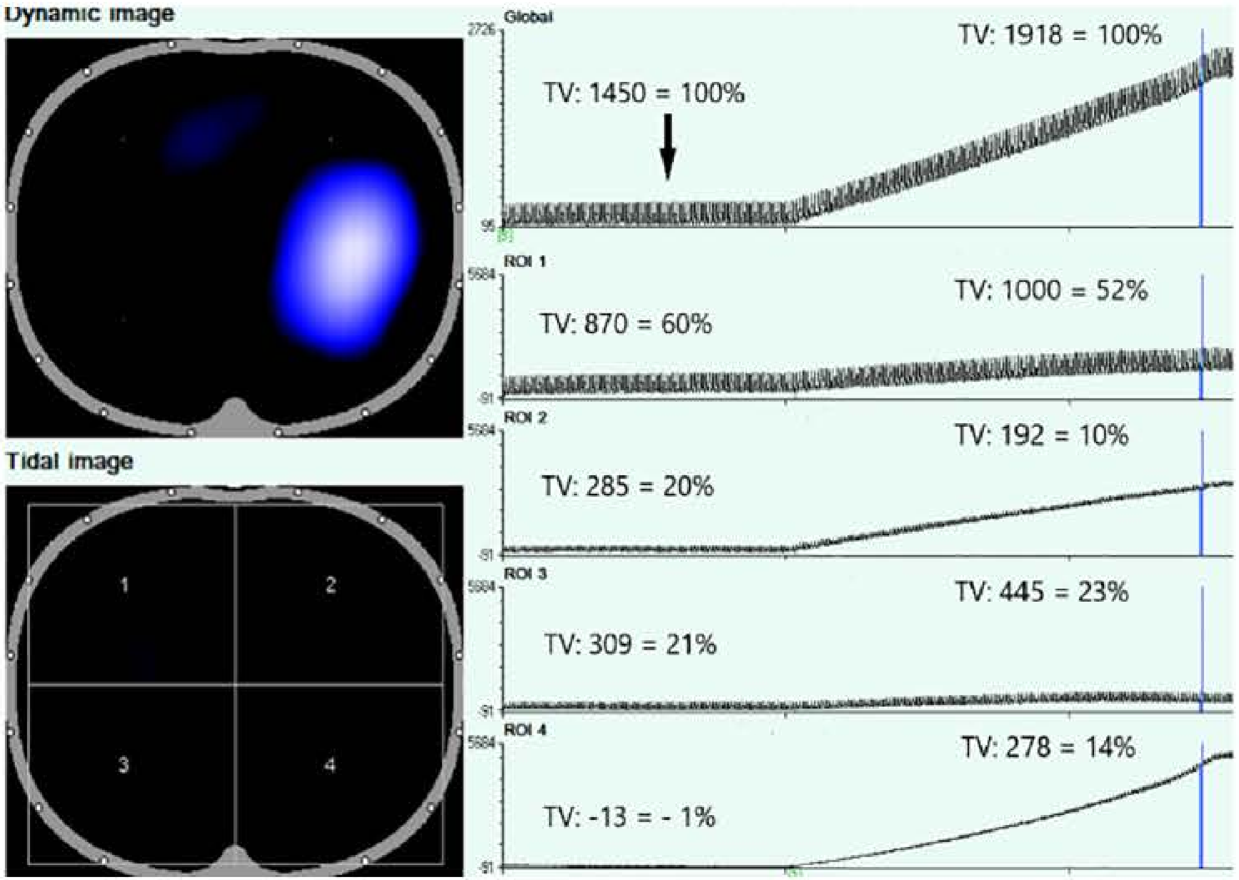
In-phase (pixel 1) and **out-of-phase** (pixel 2) **impedance changes** in a representative patient suffering from left-sided pleural effusion.

!!!

Becher T. et al.: Characteristic pattern of pleural effusion in electrical impedance tomography images of critically ill patients. BJA, 2018.

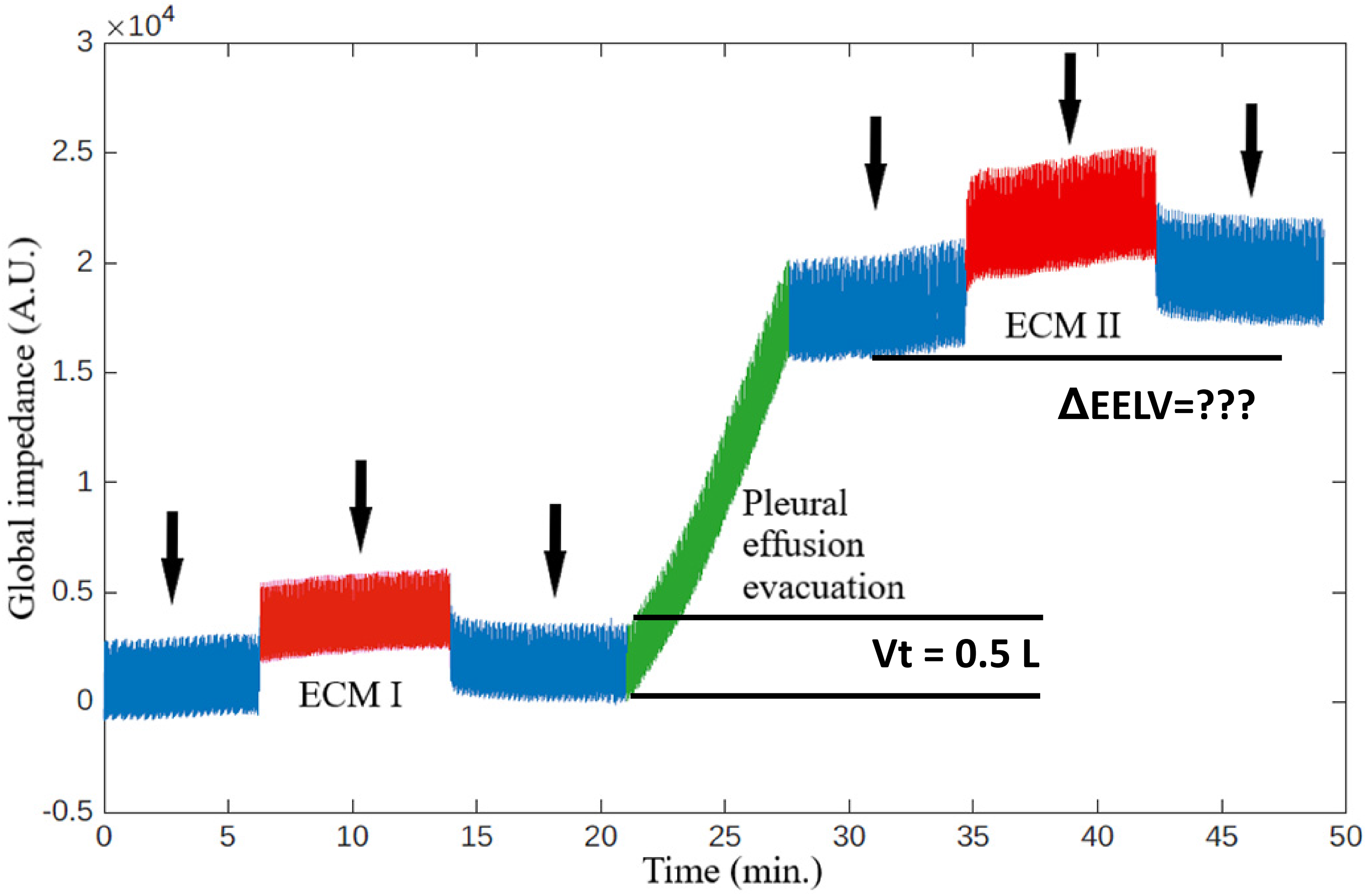
Pleural effusion and its evacuation





Rara, A., Roubik, K., Tyll, T. Effects of pleural effusion drainage in the mechanically ventilated patient as monitored by electrical impedance tomography and end-expiratory lung volume: A pilot study. *Journal of Critical Care*, 59, October 2020, pp. 76-80.

Pleural effusion and its evacuation



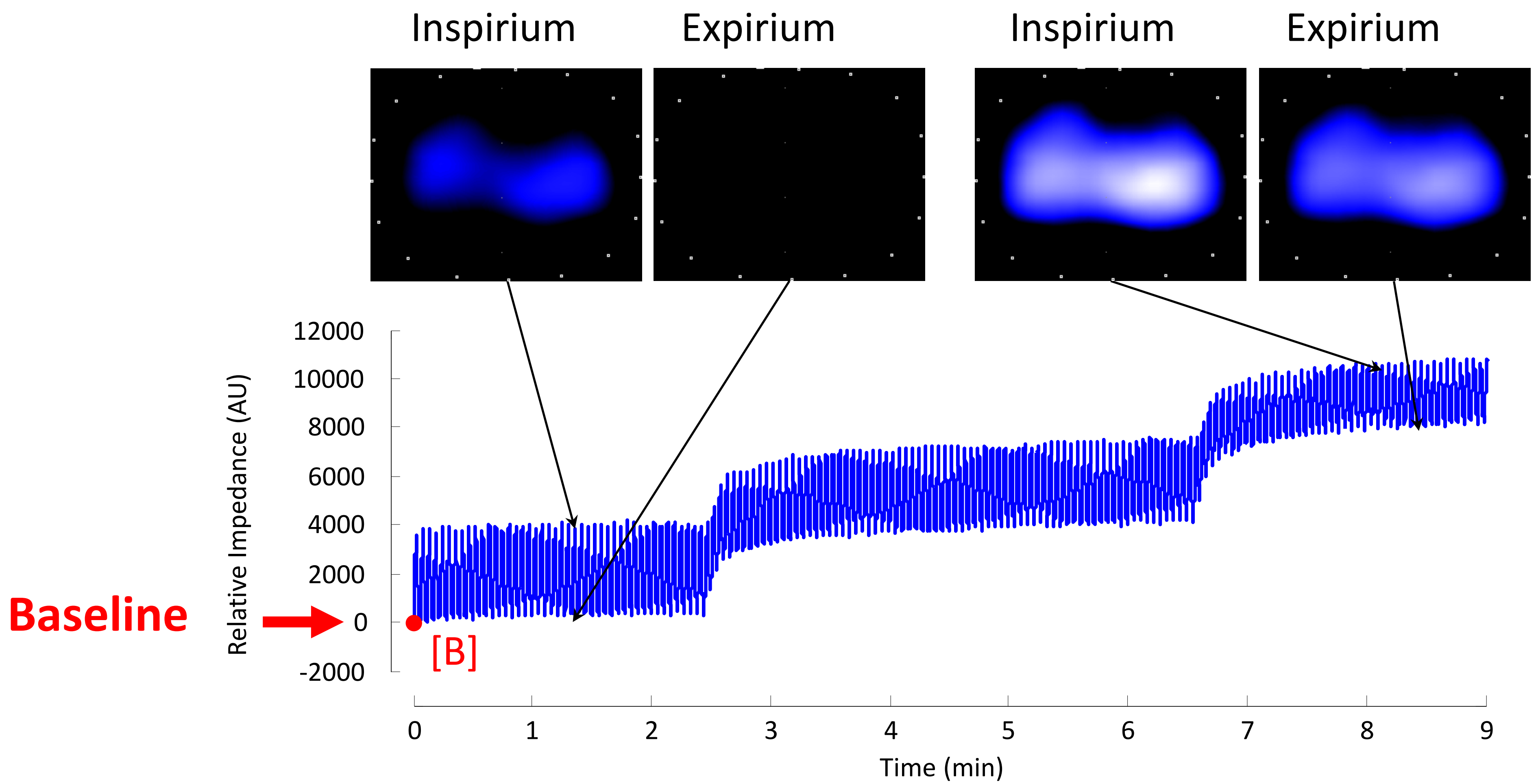
EIT record of global impedance.
ECM: EIT calibration maneuvers.

Re-airation, ΔEELV cannot be calculated...

Rara, A., Roubik, K., Tyll, T. Effects of pleural effusion drainage in the mechanically ventilated patient as monitored by electrical impedance tomography and end-expiratory lung volume: A pilot study. *Journal of Critical Care*, 59, October 2020, pp. 76-80.

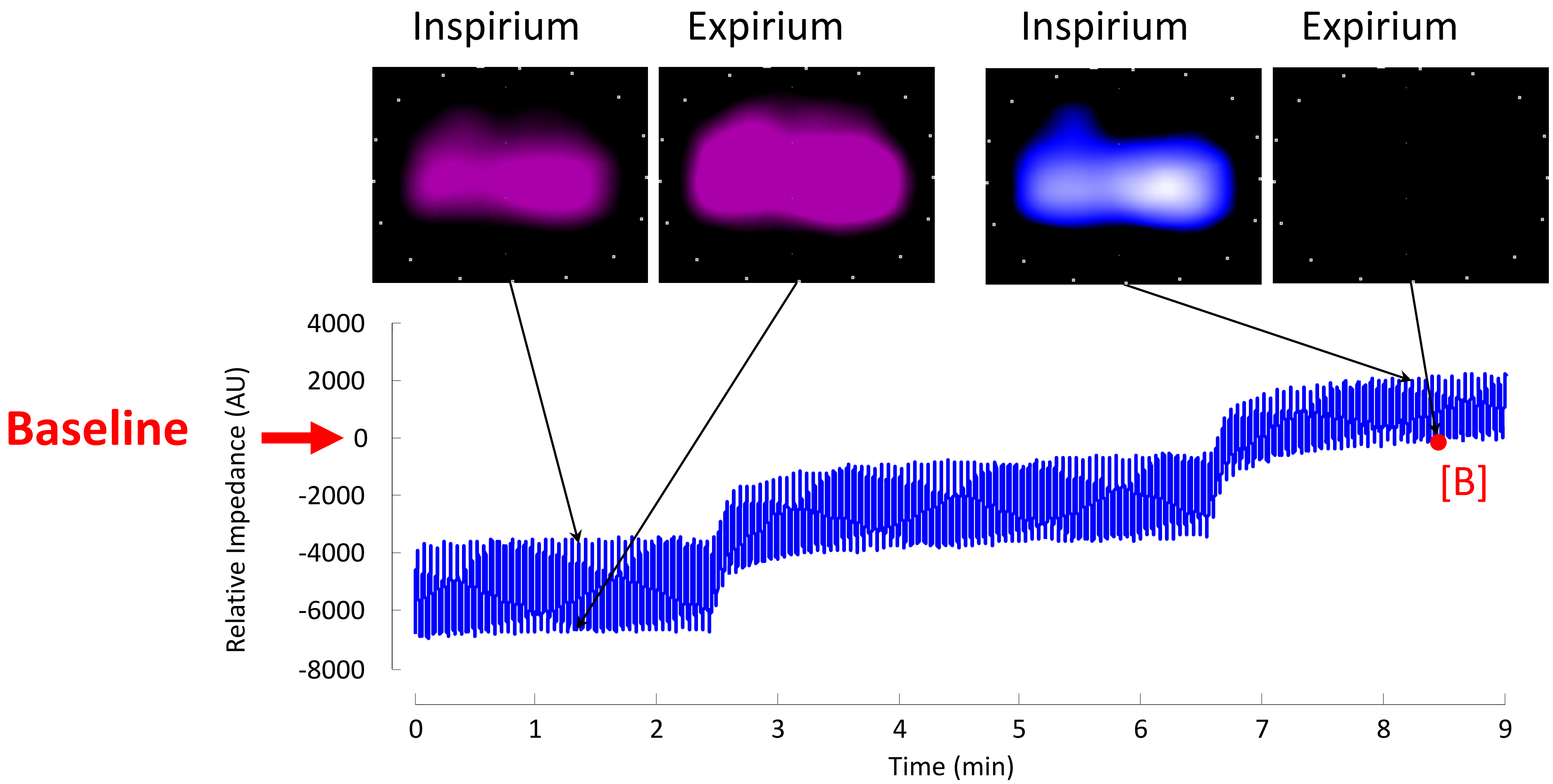
Selection of the baseline frame

Change of color scale during PEEP steps—baseline at the beginning

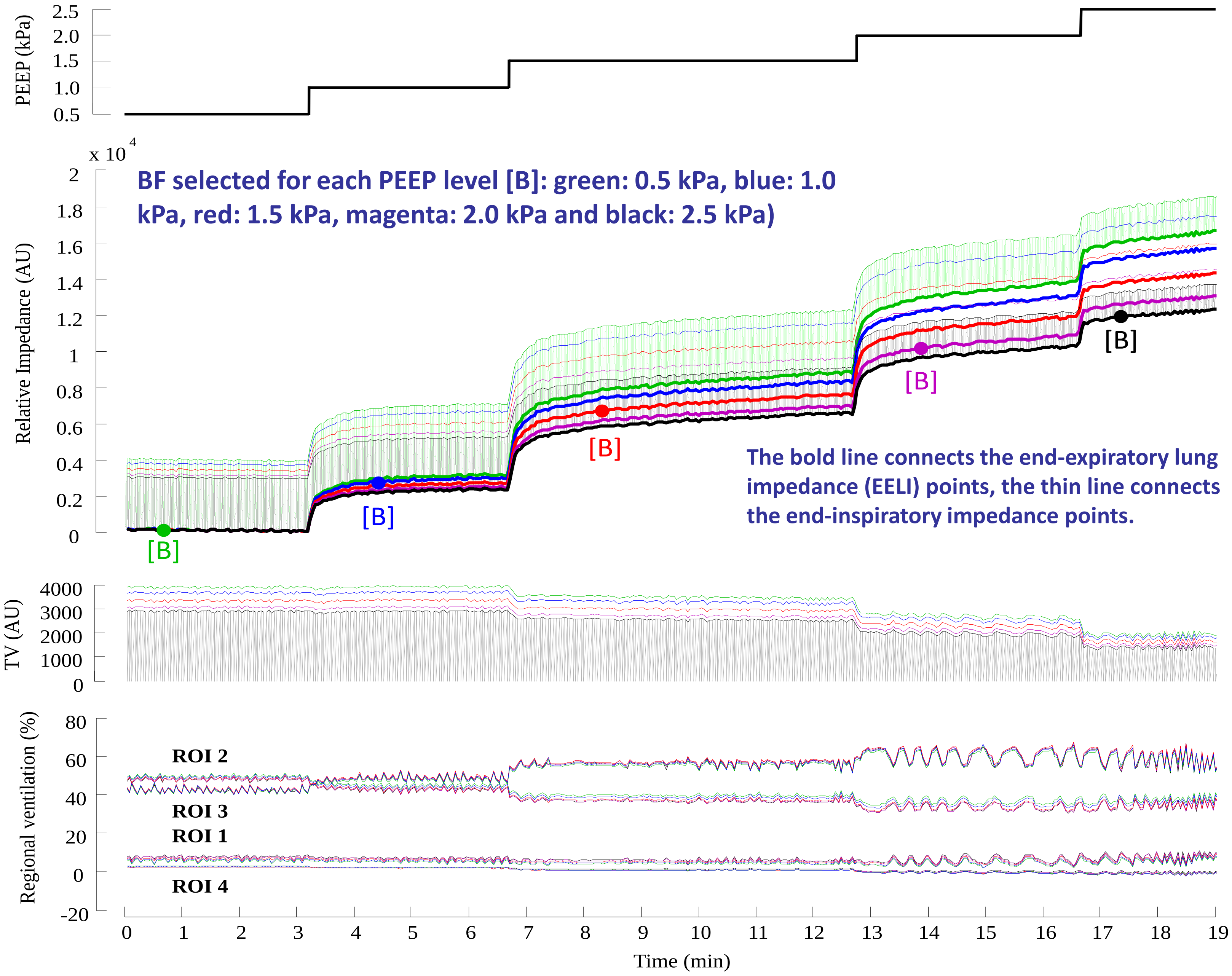


Selection of the baseline frame

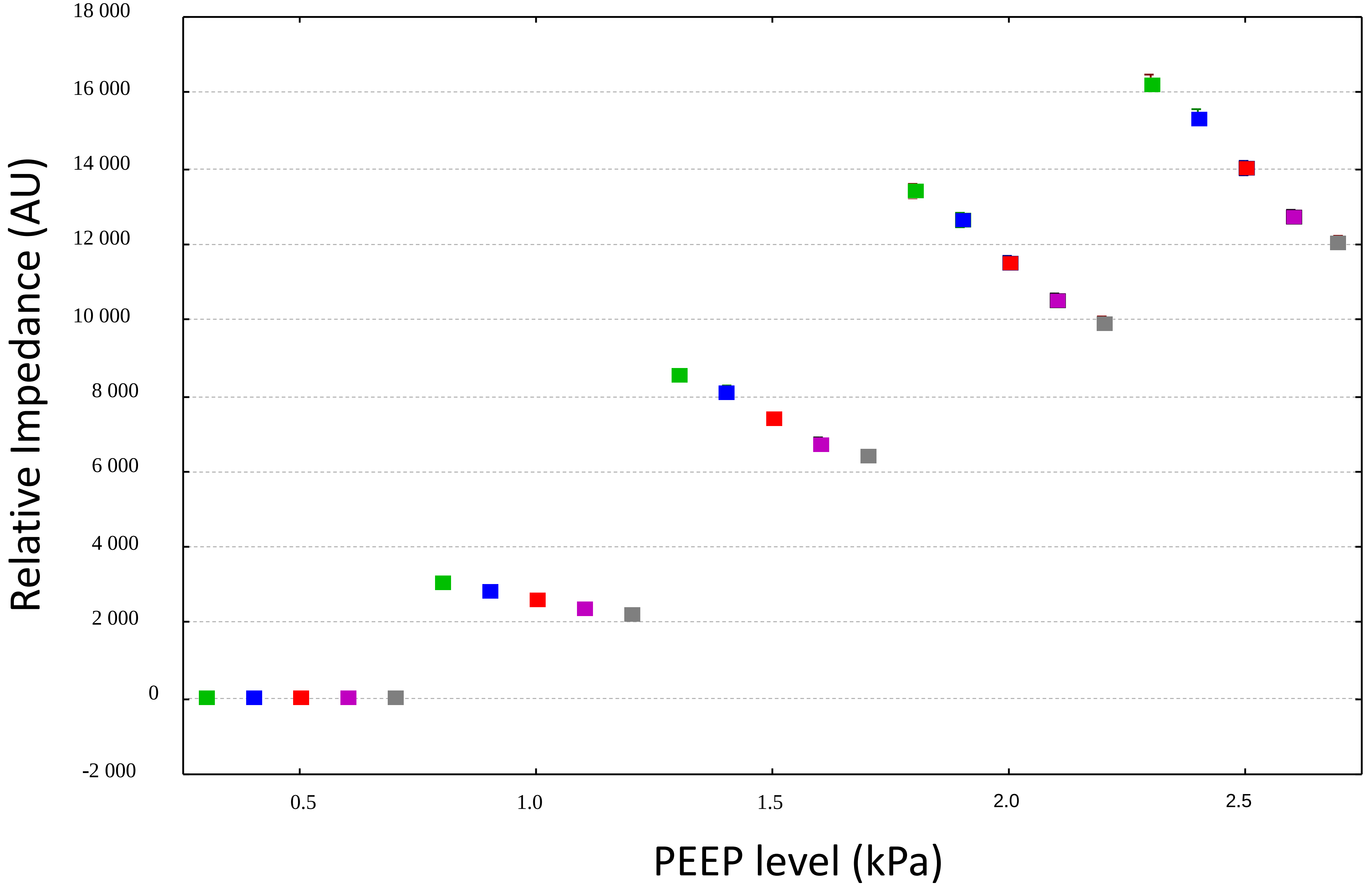
Change of color scale during PEEP steps—baseline at the end



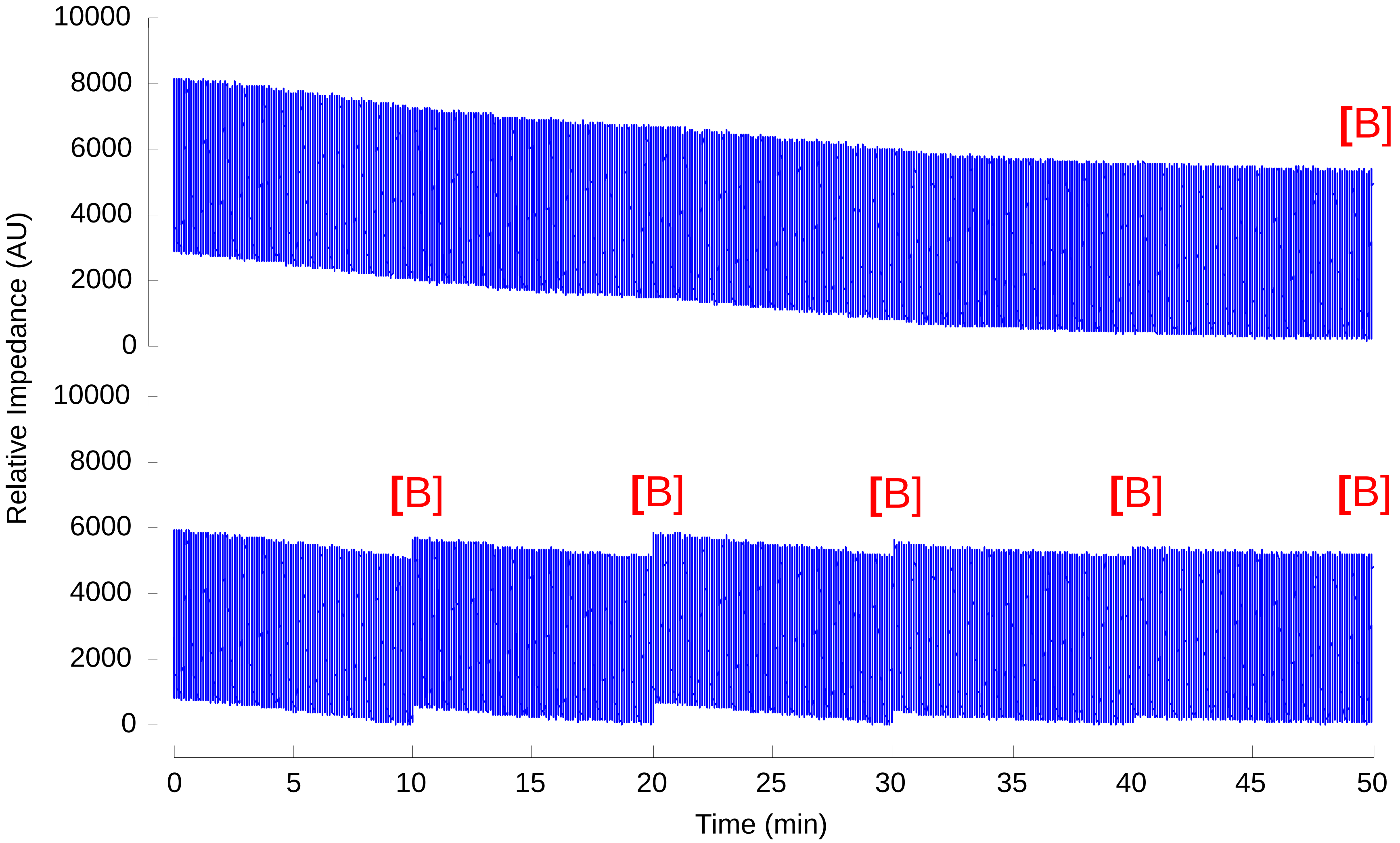
Baseline Frame selection effects



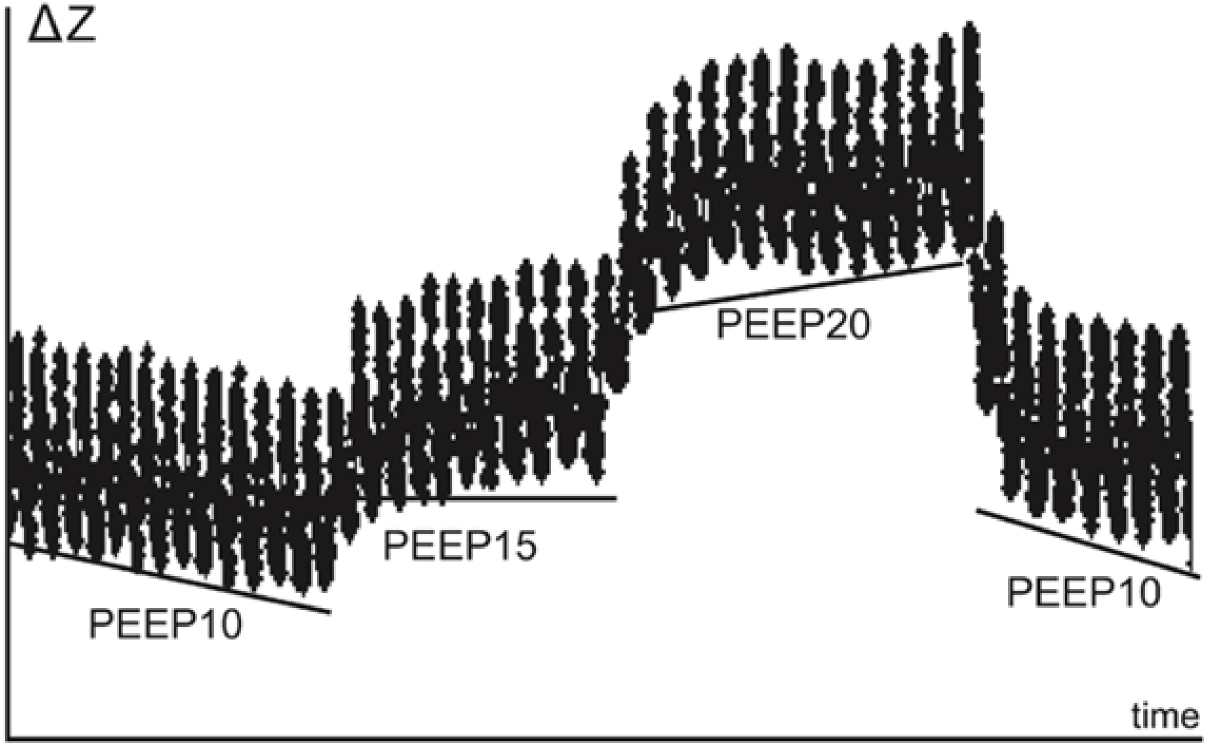
Baseline Frame selection effects



Baseline frame selection in a long-time recording



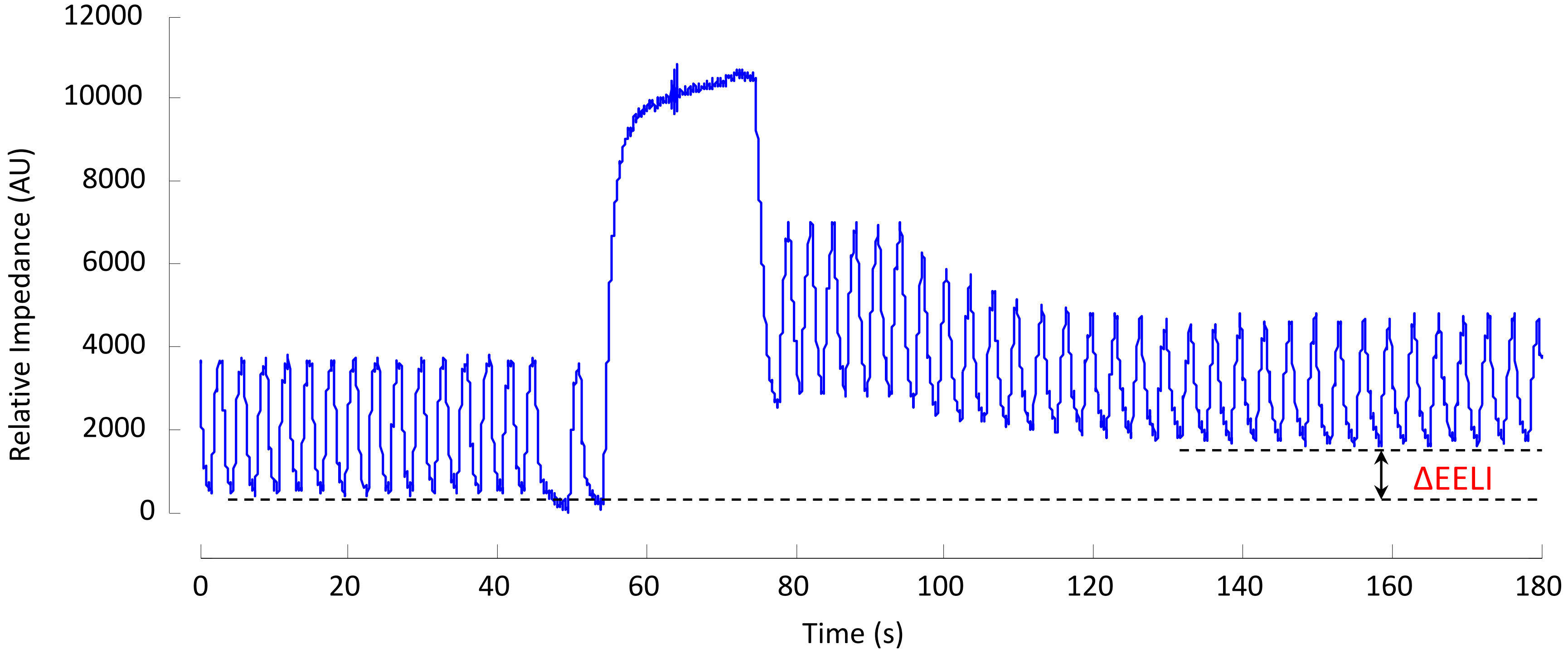
Monitoring of RM efficiency and stability



Erlandsson, K. et al: Positive end-expiratory pressure optimization using electric impedance tomography in morbidly obese patients during laparoscopic gastric bypass surgery. *Acta Anaesthesiol. Scand.* **50,** 833–9 (2006).

Evaluation of lung recruitment

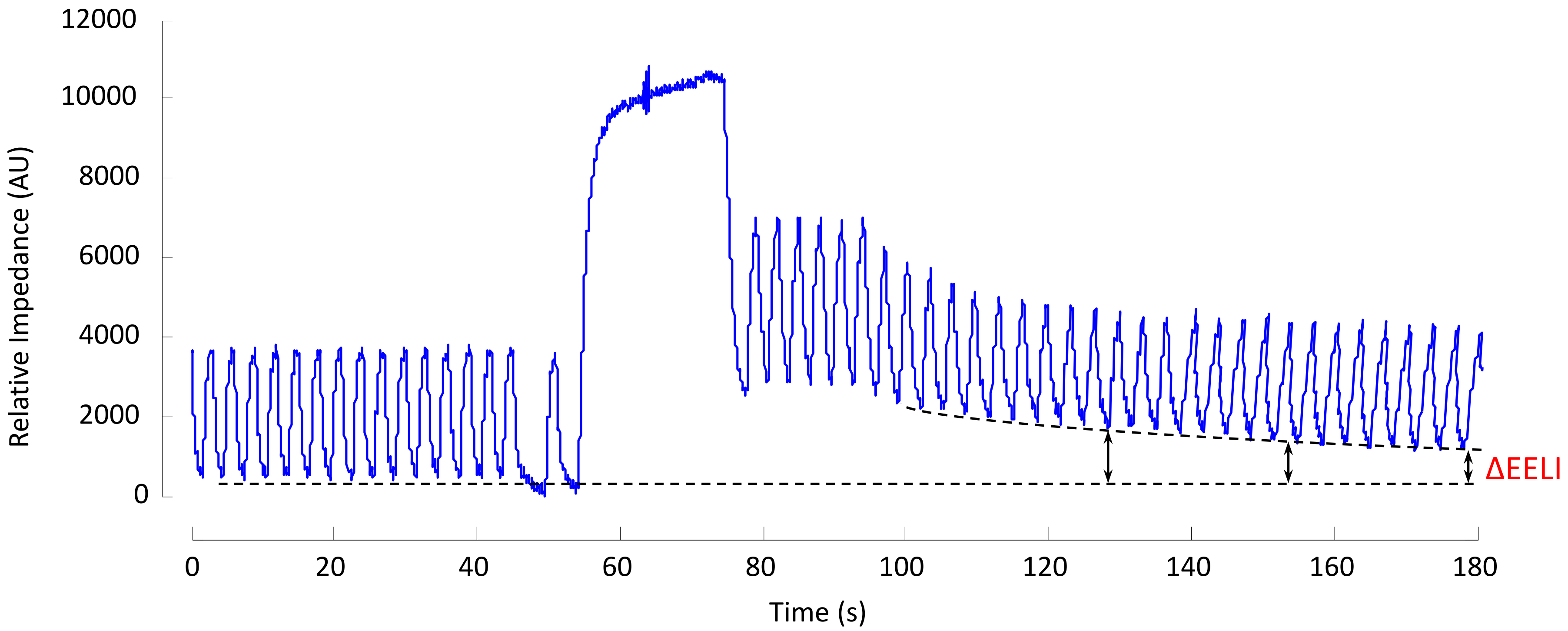
Example of recruitment maneuver. The difference in End-Expiratory Lung Impedance (EELI) corresponds to the recruited parts of the lungs.



Evaluation of lung recruitment

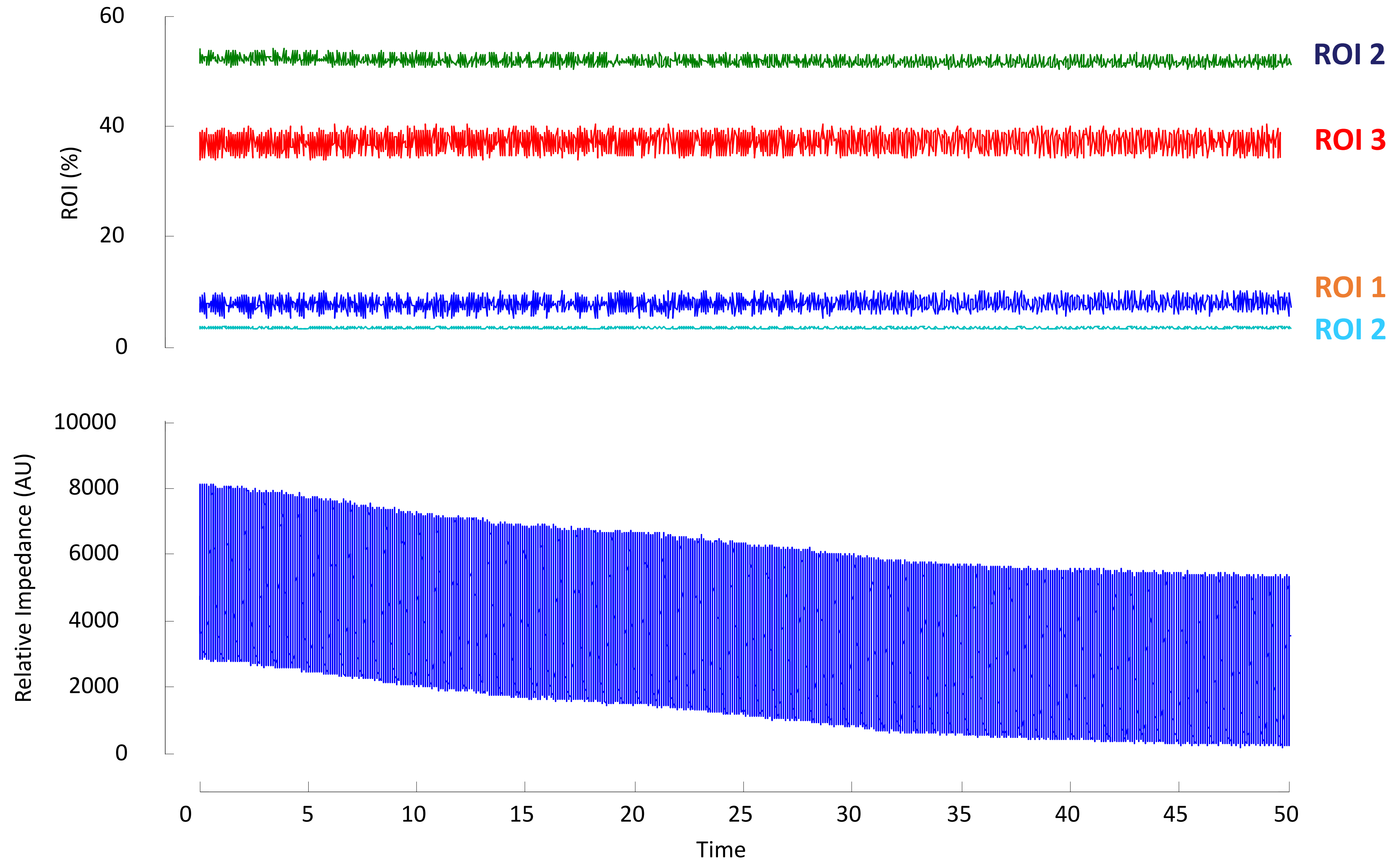
Example of recruitment maneuver **failure**.

Probably insufficient PEEP unable to keep the lungs open.

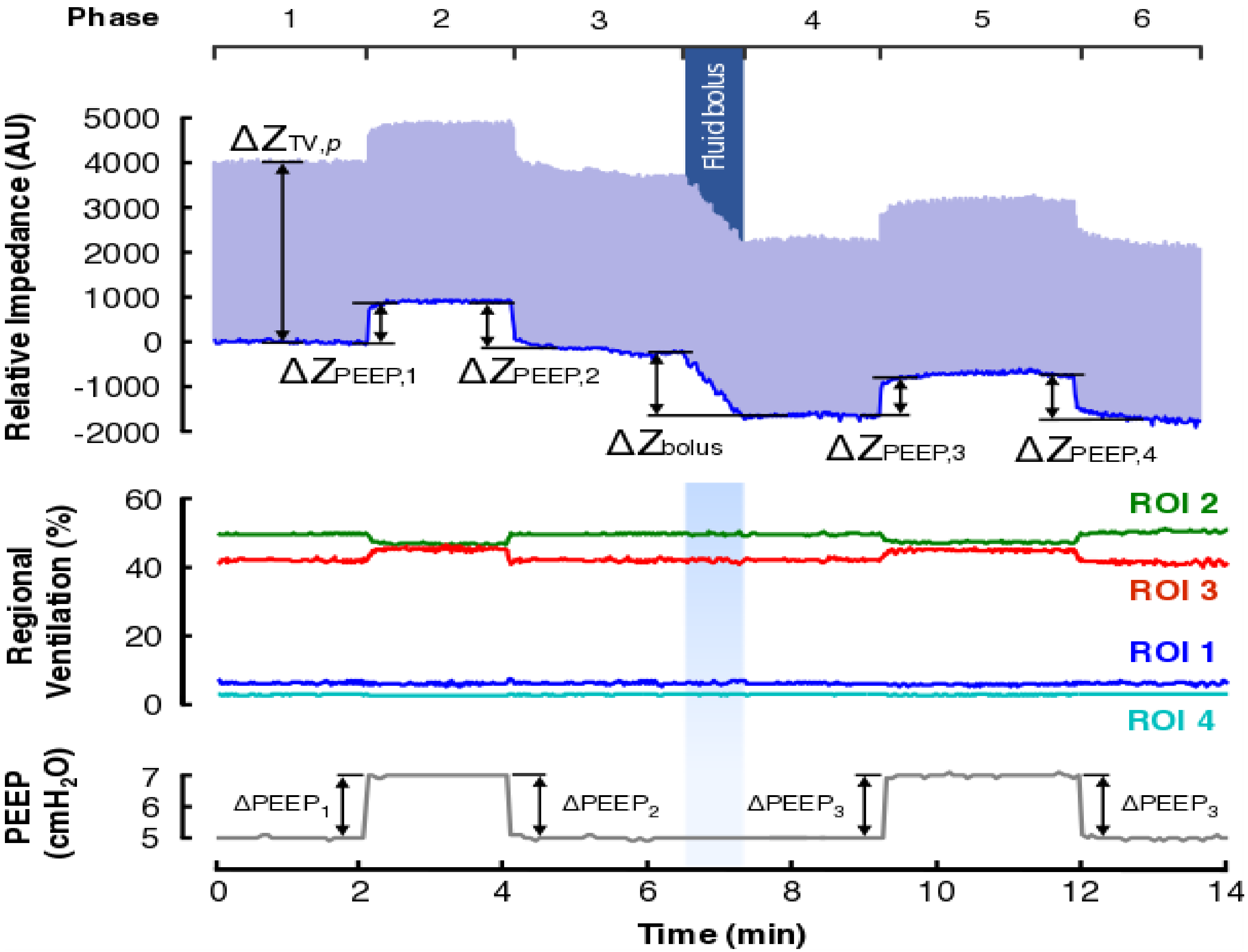


(Not a real recording; changed in Paintbrush artificially)

Continuous drift not caused by atelectasis



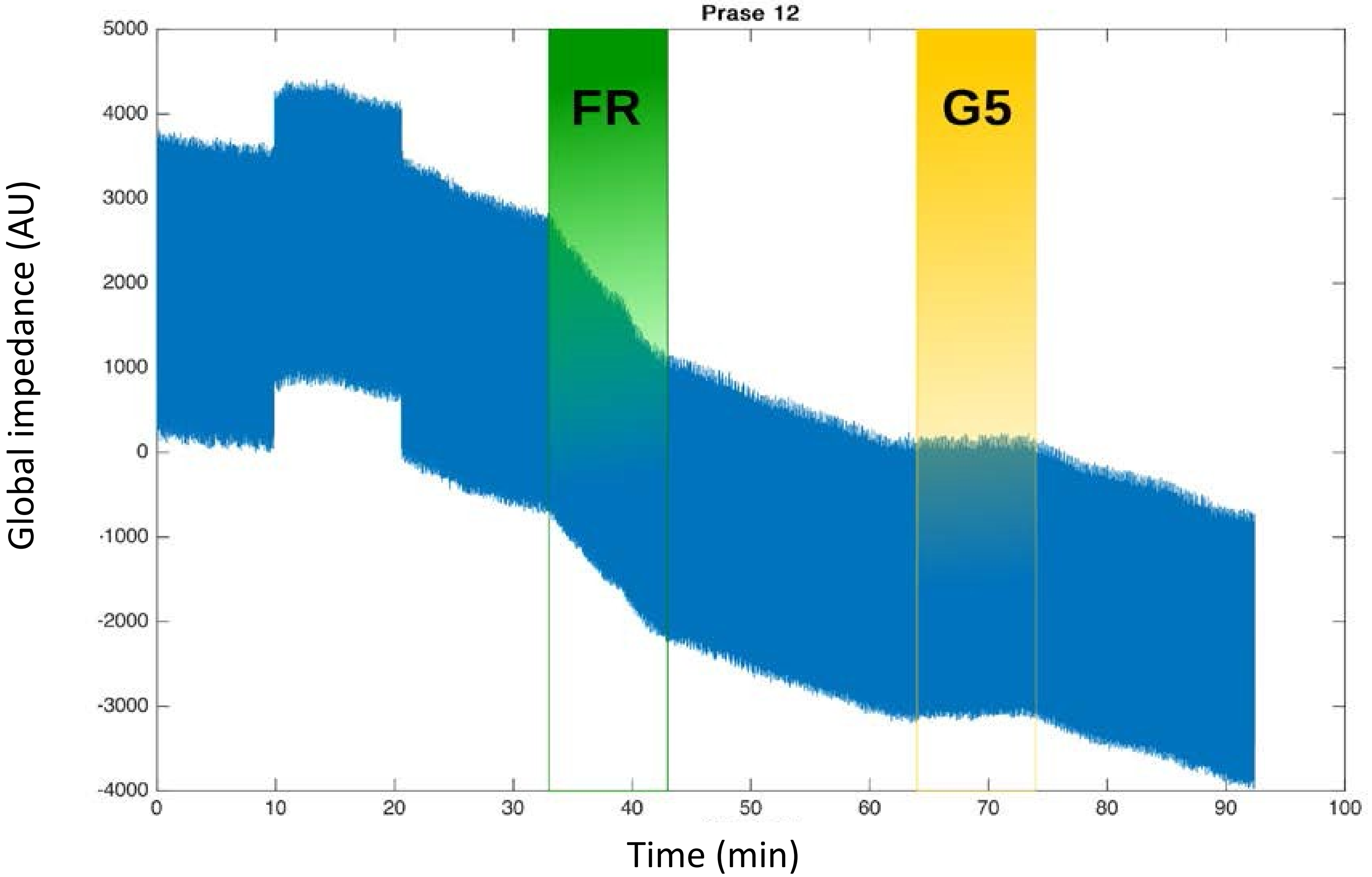
Intravenous administration of fluid



Fluid bolus: 500 mL i.v.

Sobota V, et al.: Intravenous administration of normal saline may be misinterpreted as a change of end-expiratory lung volume when using electrical impedance tomography. Scientific Reports. 2019 Apr 8;9(1):5775.

Intravenous administration of fluids – false derecruitment



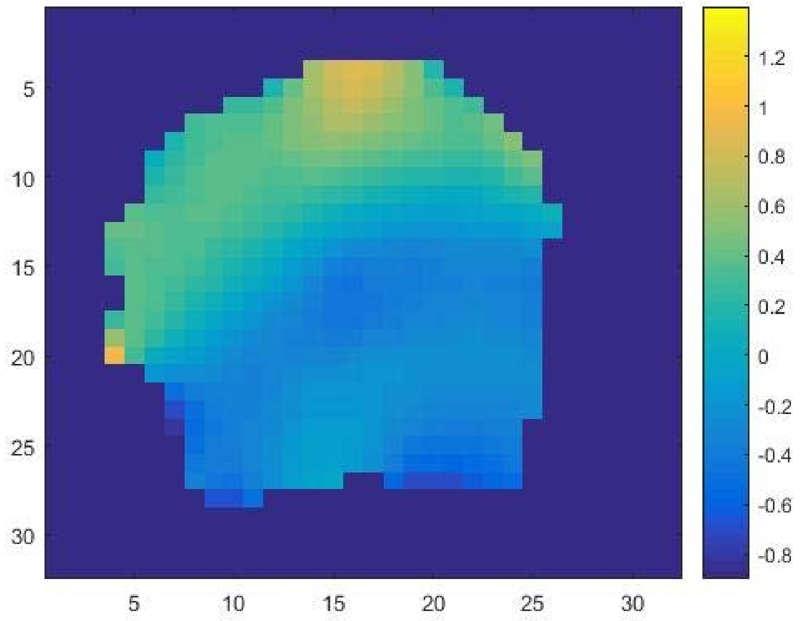
FR – Physiological solution, NS

G5 – Glucose

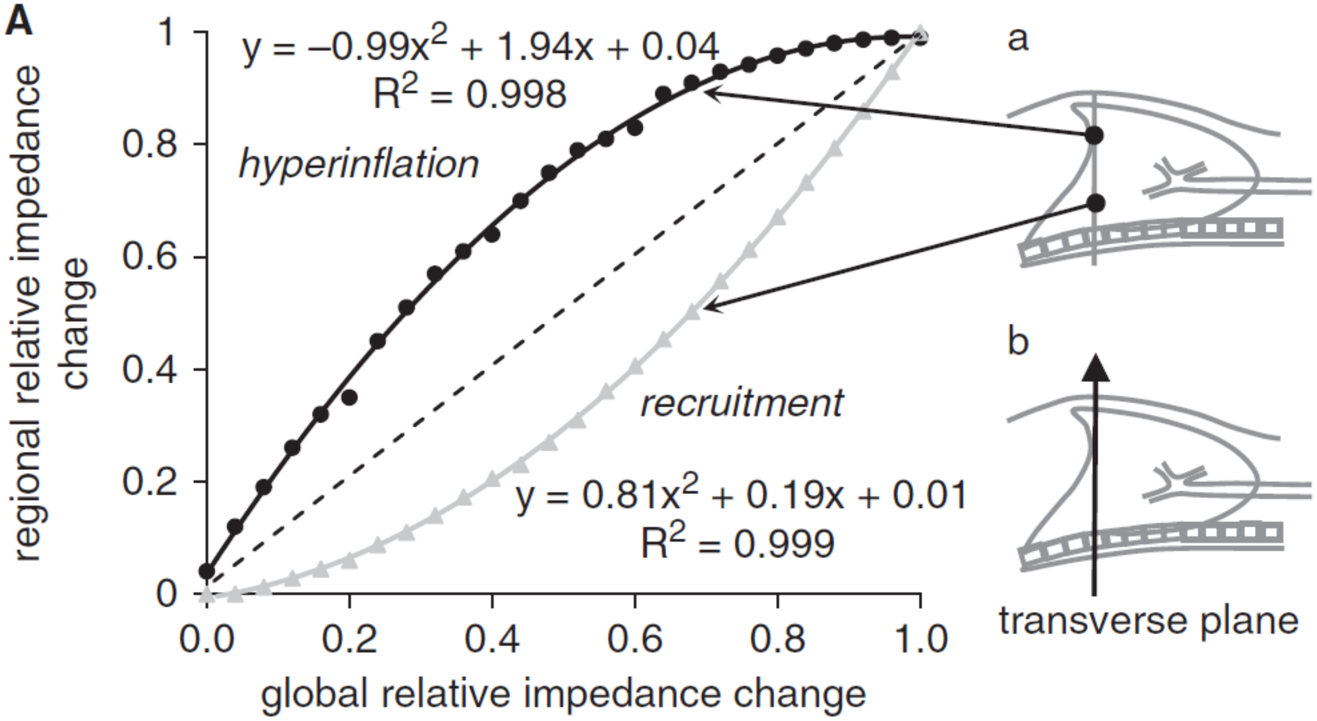
This is a possibility to monitor the fluid balance.

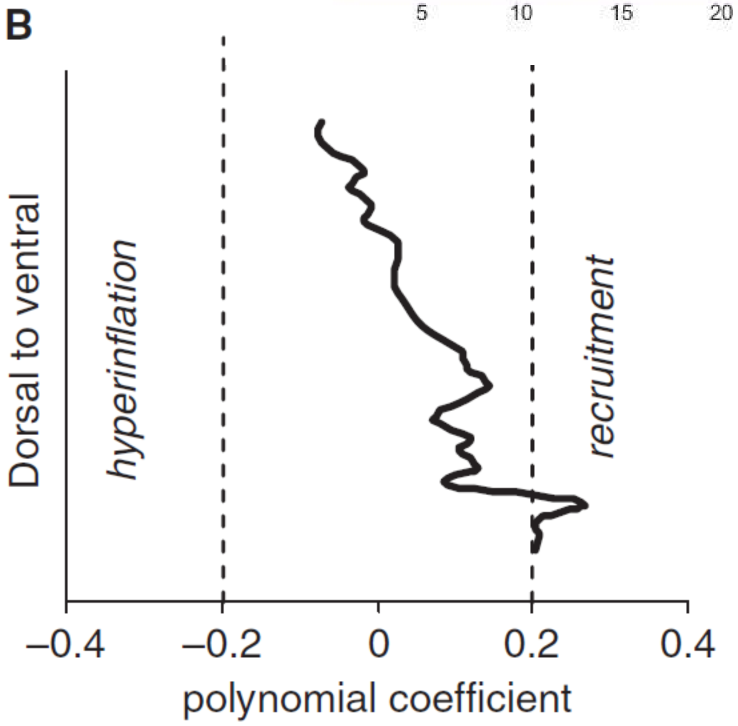
Sobota V, et al.: Intravenous administration of normal saline may be misinterpreted as a change of end-expiratory lung volume when using electrical impedance tomography. Scientific Reports. 2019 Apr 8;9(1):5775.

Maps of polynomial coefficients



Examples of relative impedance change in two individual pixels compared with the relative impedance change of all selected pixels representing the lungs. Both regional and global relative impedance change were calculated as a fraction of 1.

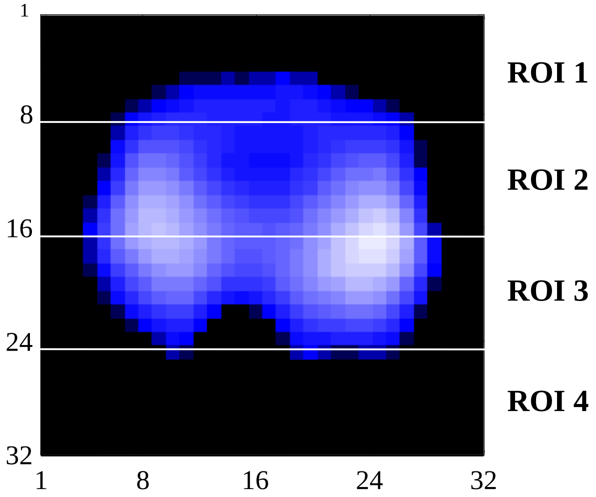




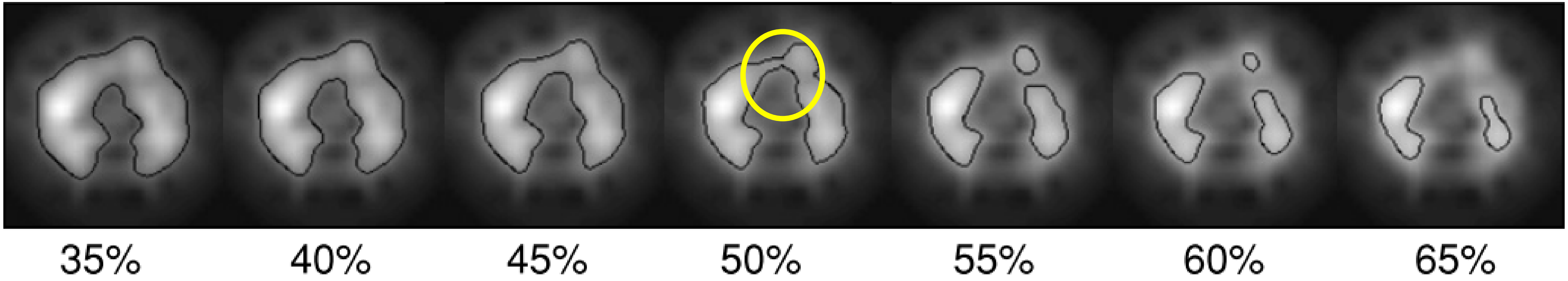
van Heerde et al.: Acta Anaesthesio-logica Svandinavica 2010; 54(10); 1248-1256

Methods of functional ROI determination

ROIs vs. Functional ROI



The edge criteria depend on the regional ventilatory function of the lungs



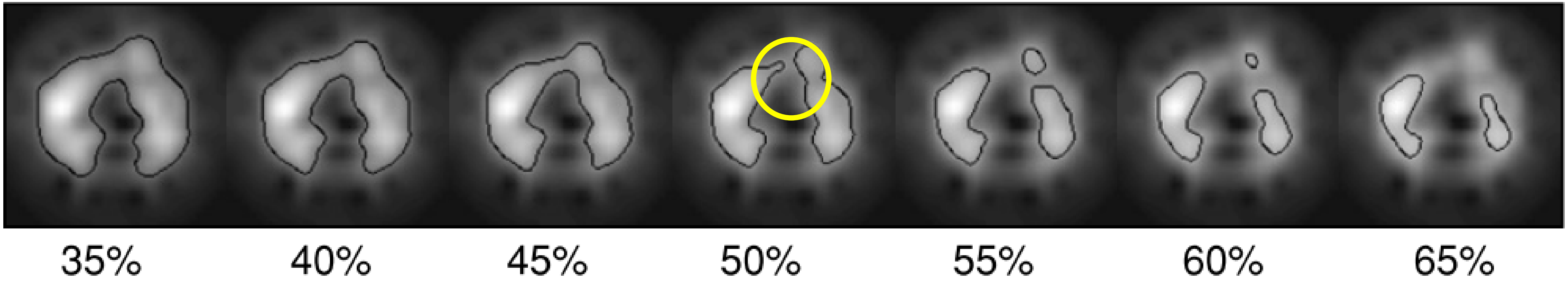
Standard deviation of relative impedance change of each pixel.

The higher the SD, the brighter the grey color.

PULLETZ, S. et al. Physiol Meas 2006, 27, S115-127

Methods of functional ROI determination

The edge criteria depend on the regional ventilatory function of the lungs

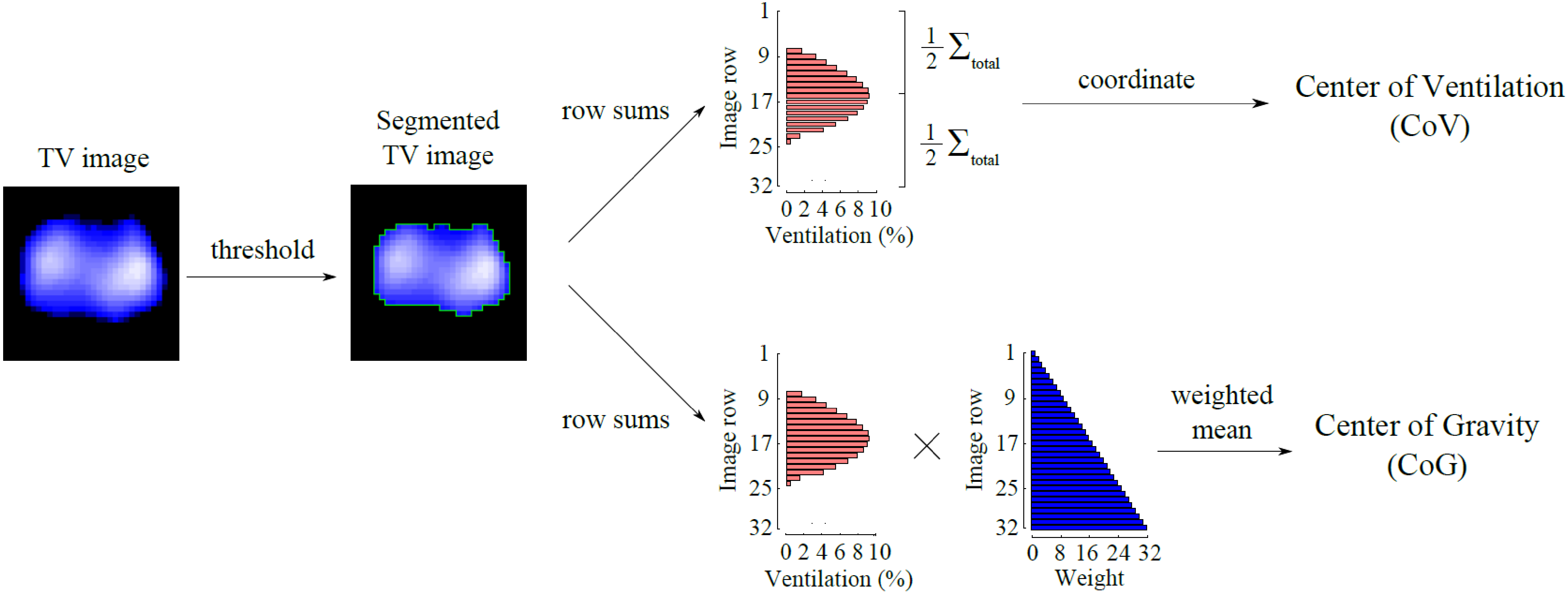


Values of linear regression coefficient calculated in each image with pixel data as dependent variable and global (average) data as independent variable.

The higher the value of the regression coefficient, the brighter the grey color.

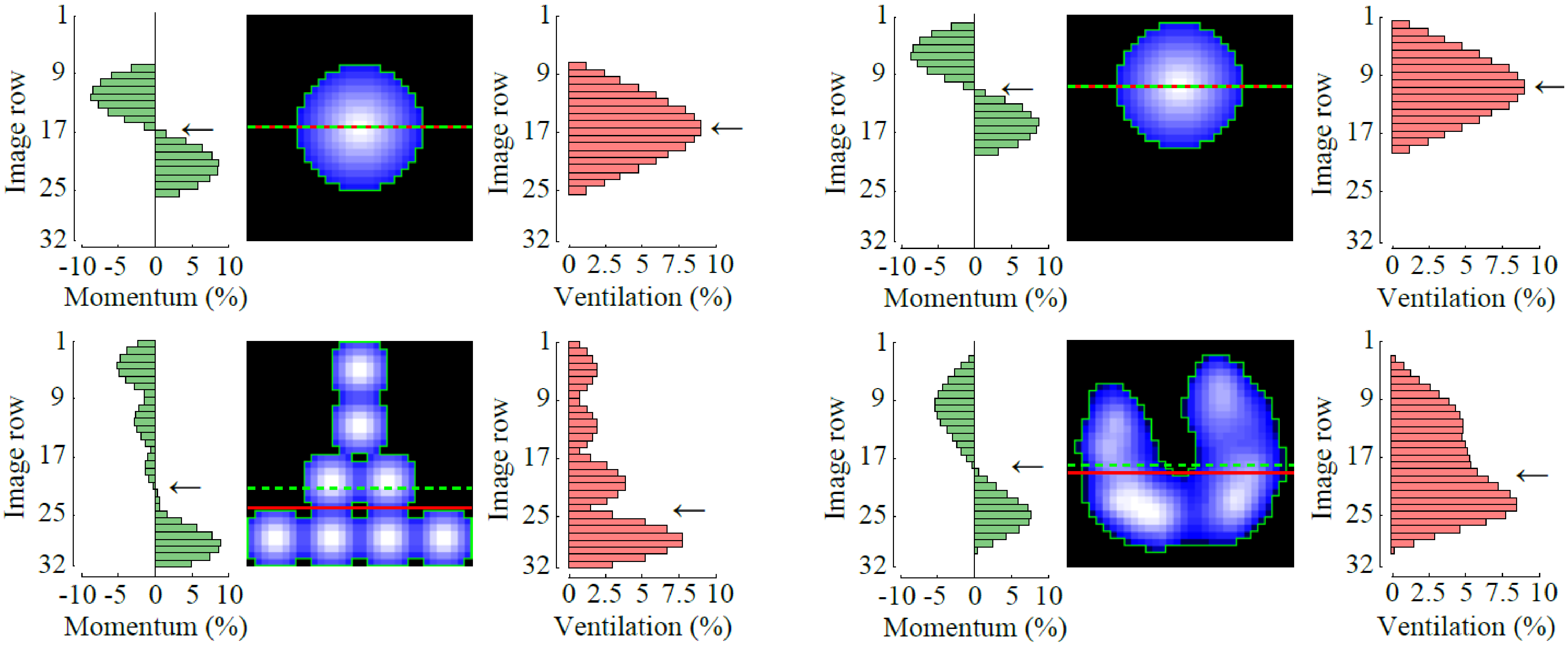
PULLETZ, S. et al. Physiol Meas 2006, 27, S115-127

Center of Ventilation, Center of Gravity



Row sums were calculated from the segmented TV image. CoV was calculated as a coordinate that divides row sums in two equal halves. CoG as a weighted mean of image row sums.

Center of Ventilation, Center of Gravity

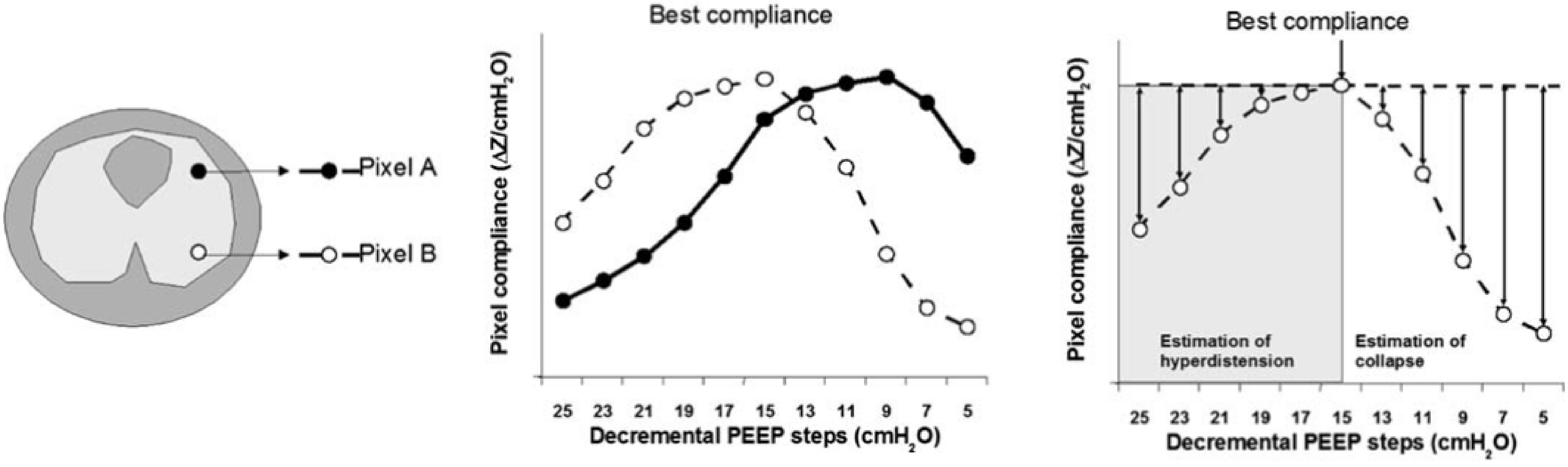


The position of Center of Ventilation (CoV) and Center of Gravity (CoG) for the image structures that are symmetrical (top row) and asymmetrical (bottom row) along vertical axis. For each image, the left bar graph represents the distribution of momentum (weighted means) along vertical axis and the right bar graph shows the row sums in the normalized tidal variation (TV) image. CoV is – red, CoG is -- green.

Sobota, et al.: Center of Ventilation—Methods of Calculation Using Electrical Impedance Tomography and the Influence of Image Segmentation. In *XIV Mediterranean Conference on Medical and Biological Engineering and Computing 2016* (pp. 1258-1269). Springer

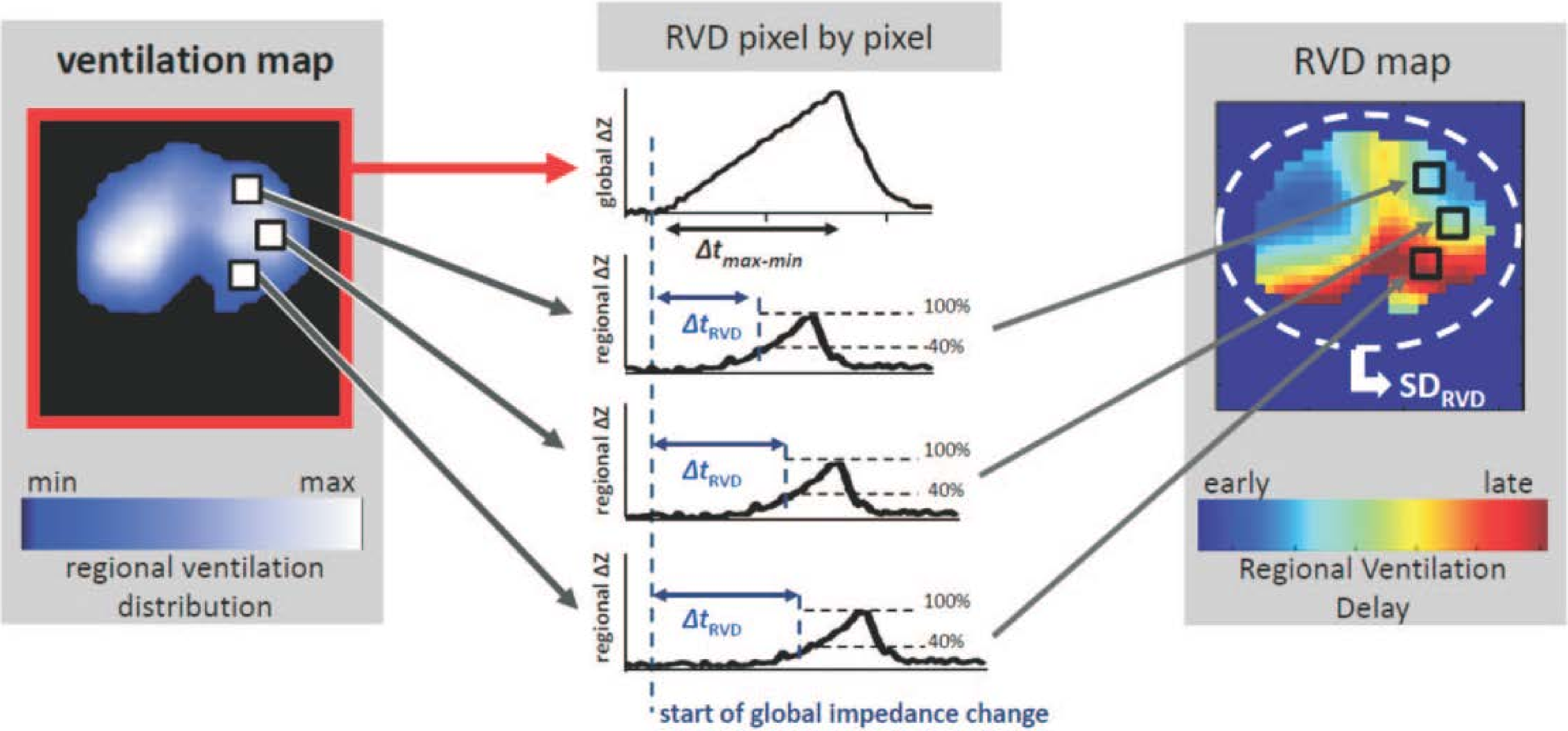
Regional Compliance

Estimation of regional compliance helps to determine regional overdistension or collapse of lungs.



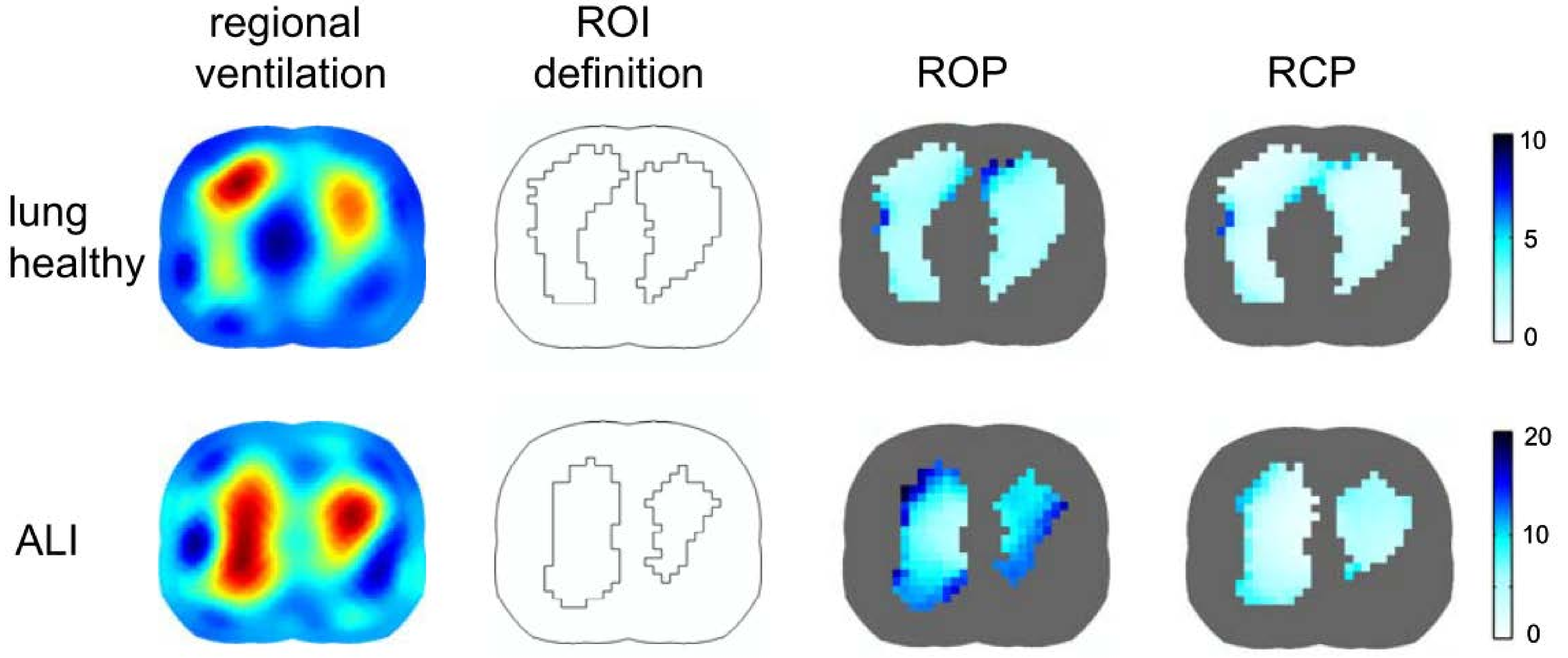
COSTA, E. L. V. et al. Intensive Care Med. 2009, 35, pp. 1132-1137

Regional Ventilation Delay



MUDERS, T. et al. Crit Care Med 2012, Vol. 40, No. 3

Regional Opening and Closing Pressures



PULLETZ, S. et al. J Crit Care. 2012 Jun, 27(3):323.e11-8

Conclusions

- EIT is an interesting and useful ~~imaging~~ monitoring[1] modality offering real time information about lung ventilation. Data processing is necessary.
- EIT data always have to be interpreted depending on the actual conditions, situation and procedure (since EIT is a functional imaging and has several unexpected features).
- Due to the complex processing and recent fast development, a ‘Gold Standard’ of data processing and visualization is still missing.
- 2021: Ventilation, 2022 in Snowbird: Perfusion

[1] based on imaging

Thank you
for your attention

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Materials available at www.ventilation.cz
(https://ventilation.fbmi.cvut.cz/)
in the „For Our Students“ section.