Chest electrical impedance tomography examination, data analysis, terminology, clinical use and recommendations: consensus statement of the TRanslational EIT developmeNt stuDy group

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ONLINE SUPPLEMENT 7

Clinical use of EIT in adult patients

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Introduction

This electronic online supplement (EOS) 7 provides a structured overview of clinical issues pertaining to adult patients examined by EIT in a clinical setting mainly in the fields of mechanical ventilation monitoring and pulmonary function testing as mentioned in the main document. These and other clinical issues are listed in three tables (E7.1-E7.3).

All tables have the same basic structure: they show a brief description how the EIT data specific for each issue need to be acquired and analyzed. In some cases, specific ventilation maneuvers like a positive end-expiratory pressure (PEEP) trial or constant low-flow inflation are needed to generate the information necessary for the clinical issue in question to be answered. These maneuvers are specified when applicable. The typical EIT measures generated by the individual analyses are also provided. Finally, hints on the interpretation of the findings and their use in clinical decision making are made available. The relevant references to clinical studies involving human subjects are provided in the last column of each table.

We only refer to those EIT studies here that were conducted in adult patients. We do not mention studies performed in neonatal and pediatric patients, albeit these often address clinical issues (e.g. EIT-based guidance of mechanical ventilation) relevant for the adult population as well. With this respect, we kindly ask the readers to also consult the EOS8 where the specific information on the EIT use in neonates and children is presented in detail.

The clinical EIT studies carried out in adult subjects most often involved patients suffering from various lung diseases. However, patients with other diseases not involving the respiratory system were examined as well, for instance anesthetized patients undergoing abdominal or cardiac surgery.

The study cohorts in the EIT clinical trials are generally rather small, typically about 10-20 patients. (The exact numbers of studied subjects are stated in the tables.) In addition to the patients´ studies, we provide information and references to studies on healthy volunteers, especially in those cases where clinical trials on patients are lacking or when methodological concepts in EIT data acquisition, analysis and interpretation relevant for the postulated later clinical use were described in these healthy study populations. We also refer to a few pioneering animal experimental studies with clinically relevant findings.

EIT use for monitoring lung ventilation

The use of EIT for monitoring regional lung ventilation has been the most studied clinical EIT application so far. Its major benefit is seen in the continuous bedside assessment of regional lung aeration and ventilation in patients undergoing ventilator therapy. The primary aim of EIT use in these patients is the identification of deleterious phenomena like regional overdistension, derecruitment, cyclic alveolar collapse and EIT-guided optimization of ventilator settings minimizing or eliminating their occurrence and preventing the development of ventilator-associated lung injury. We identify several clinical issues relevant in this context and present the so far proposed and studied EIT approaches to address them in Table E7.1 presented below.

Clinical issue	Method of analysis / EIT measure	Brief description / EIT findings	Maneuvers / interventions besides tidal ventilation	Normal vs. pathological results (if applicable)	Suggested impact on clinical decisions	References / assessment of evidence
Pulmonary ventilation / monitoring of ventilation / ventilator-induced lung injury						
Lung recruitment	Regional tidal ΔZ variation (1-6) with the calculation of U/L ratio, dorsal displacement of the center of ventilation (7-10), increase in regional C_{rs} in the most dependent lung region (10-12), intratidal gas distribution in dorsal lung regions (13)	After an increase in PEEP, P_{insp} or low-flow inflation maneuver, lung recruitment is confirmed by the increase in regional dorsal lung ventilation assessed by different indices of regional ventilation distribution.	Step increments in PEEP with a fixed driving pressure until lung opening pressures are reached. Low-flow inflation maneuver. Open-lung ventilation approach. Assisted ventilation mode.	In lung pathology or with inadequate ventilator settings lung ventilation tends to decrease in dependent lung regions.	EIT offers the potential to monitor lung recruitment and individualize opening pressures at the bedside.	(2) n=16 patients (3) n=20 patients (4) n= 10 patients (7) n=10 patients (13) n=16 patients (14) n=12 patients (5) n=15 patients (6) n=20 patients (10) n=5 patients (1) n=6 pigs (8) n=6 pigs (9) n=16 pigs (11) n=12 pigs (12) n=16 pigs
	Regional delay in ventilation / regional opening and closing pressures	During a low-flow inflation maneuver, the delay until an increase in regional impedance above a set threshold is detected. The time delay between this time point and the actual beginning of the inflation is then calculated in each pixel or ROI. Simultaneous airway pressure measurement allows the assignment of the delay to a respective regional opening pressure.	Constant low-flow inflation (i.e. 2 l/min until 1.5 l are inflated or airway pressure of 50 mbar is reached) (15), step increase and decrease in airway pressure (16)	Normal: synchronous onset of regional filling, pathological: regional delay in ventilation implying recruitment, amount of delay / assignment to parallel pressure measurement indicating recruitability: long delay implies high pressure necessary to recruit, short delay increases the probability of tidal recruitment	Exclude pleural effusion or reversible bronchial occlusion as a reason for delay. Use high PEEP strategy when recruitment occurs early (open up the lung and keep it open) but do not try to open the lungs if the necessary ventilator invasiveness exceeds ARDS network limits.	(15) n=26 patients (16) n=8 patients (17) n=16 pigs (18) n=12 pigs

Clinical issue	Method of analysis / EIT measure	Brief description / EIT findings	Maneuvers / interventions besides tidal ventilation	Normal vs. pathological results (if applicable)	Suggested impact on clinical decisions	References / assessment of evidence
'Best' PEEP	Decreasing or increasing or stable end-expiratory lung impedance change (EELZ)	During an incremental and decremental PEEP trial, the EELZ trend is followed over several breaths. An increase in EELZ reflects ongoing recruitment or overdistension (PEEP too high or too low), a decrease shows derecruitment (PEEP is too low), stable EELZ implies no recruitment or derecruitment (this does not exclude unrecruited, fixed atelectasis or overdistension).	PEEP trial (incremental / decremental)	Normal: steady EELZ, pathological: increasing or decreasing EELZ from breath to breath	Use PEEP with stable EELZ during a decremental PEEP trial	(19) n=10 patients (20) n=12 patients (21) n=15 patients (22) n=20 patients (23) n=1 pig (lavage, surfactant) (1) n=6 pigs (lavage model)
	Homogeneity of ventilation (GI index)	Fall in the GI index along with increased percentage of open lung regions during inflation imply recruitability (24). GI index falls at the high compared with the low PEEP (below LIP) (25).	Constant low-flow inflation (24) Variation in V_T and PEEP (25)	GI index is lower in patients with healthy lung than in patients with ARDS	Use EIT during a constant low-flow inflation to test the lung for recruitability	(24) n=26 patients (25) n=9 patients
	Changes in regional C_{rs} (10, 12, 14, 22, 26), the GI index (22, 27, 28) or CoV (22)	Assessment of changes in regional C_{rs} or regional redistribution of ventilation (homogeneity of ventilation)	Incremental PEEP trial or lung recruitment maneuver and decremental PEEP trial	Regional C_{rs} is lower in dependent lung regions in the pathological case	Set "optimal" PEEP at level which results in lowest GI index value in fixed ROIs or which minimizes the amount of lung collapse (<10%)	(26) n=2 patients (10) n=5 patients (14) n=12 patients (27) n=50 patients (28) n= 10 patients (22) n=20 patients (12) n=16 pigs

Clinical issue	Method of analysis / EIT measure	Brief description / EIT findings	Maneuvers / interventions besides tidal ventilation	Normal vs. pathological results (if applicable)	Suggested impact on clinical decisions	References / assessment of evidence
Atelectasis / lung collapse / derecruit-ment	Changes in regional C_{rs} in dorsal lung regions. Increase in the U/L ventilation ratio or ventral displacement of the center of ventilation.	Assessment of changes in C_{rs} in response to a PEEP step expressed as a percent change in regional (pixel) C_{rs} in relation to the best C_{rs} reached during a PEEP titration trial.	Decremental PEEP trial. Step changes in PEEP, inspiratory pressure or tidal volume	Normal: more homogeneous distribution of ventilation between ventral and dorsal regions of the lung. Pathologic: decreased relative regional ventilation in dorsal lung regions	Helps to identify lung-protective ventilator settings resulting in minimum lung collapse and overdistension.	(26) n=2 patients (4) n=10 patients (29) n=14 patients (12) n=16 pigs (8) n=6 pigs
	Distribution of tidal EIT variation between dependent and non-dependent regions (U/L ventilation ratio)	Increase in U/L ventilation ratio after suctioning implies derecruitment	Open suctioning	Patients with a fall in functional residual capacity after suctioning exhibit an increase in U/L ventilation ratio	Stable U/L ratio after suctioning implies that patients do not require a recruitment maneuver	(30) n= 59 patients
	CoV	CoV shifts towards non-dependent lung regions after the induction of: - general anaesthesia during PSV, PCV and VCV - and pneumoperitoneum	Mechanical ventilation with laryngeal mask or endotracheal tube	Spontaneous breathing and PEEP preserve the preoperative ventilation distribution during general anaesthesia	n.a.	(7) n=10 patients (31) n=30 patients (32) n=32 patients
Homo-geneity or hetero-geneity of regional respiratory system mechanics	Determination of inhomogeneous respiratory system mechanics, calculation of EIT-derived measures like the GI index, center of ventilation, U/L ventilation ratio.	The inhomogeneity of regional ventilation can be characterized by several gross EIT measures or by indices describing the ventilation distribution in the anteroposterior direction.	PEEP trial, ongoing tidal ventilation	Normal: homogeneous respiratory system mechanics	Inhomogeneity may lead to an adjustment of ventilator settings until homogeneity is reached. Severe un-correctable inhomogeneity may lead to rescue ECMO therapy.	(27) n=50 patients (28) n=10 patients (33) n=2 patients

Clinical issue	Method of analysis / EIT measure	Brief description / EIT findings	Maneuvers / interventions besides tidal ventilation	Normal vs. pathological results (if applicable)	Suggested impact on clinical decisions	References / assessment of evidence
	Spatial and temporal heterogeneity of ventilation during pulmonary function testing measured by EIT	Regional IVC, FEV_1, FVC, FEV_1/FVC and expiration times needed to exhale set percentages of FVC. The heterogeneity of their spatial distribution characterized by the CV or GI indices	Full inspiration to TLC and forced full expiration to RV	Pathological: higher spatial and temporal ventilation heterogeneity	n.a.	(34) n=33 patients and n=26 healthy human subjects (35) n=7 patients and n= 7 healthy subjects (36) n=14 patients and n=14 healthy subjects
	Assessment of homo-geneity/heterogeneity of ventilation distri-bution (PSV and NAVA: (37), HFOV: (38-41), CMV (42)) by various EIT measures	Regional distribution/changes in ventilation or lung volume in set regions of interest during various modes of mechanical ventilation.	Measurement during CMV, HFOV, PSV, NAVA	n.a.	Set mechanical ventilation settings to ensure homogeneous distribution of ventilation/lung volume in set regions of interest	(37) n=10 patients (39) n=10 patients (40) n=1 patient (42) n=10 patients (38) n=9 pigs (41) n=18 pigs
Regional compliance / regional impedance-pressure curves	Estimation of regional ΔZ/ΔP (26) or fractional V_T/ΔP (10, 12); construction of regional ΔZ-P curves (43-45)	Assumption of uniform pressure distribution in the ventilated lung.	C_{rs}: step changes in PEEP under constant ventilator settings. Regional ΔZ-P curves or fractional V_T: constant low-flow lung inflation (and deflation). Step increases/decrea-ses in airway pressure.	Normal: homogenous ΔZ/ΔP	Optimal PEEP selection. Detection of regional lung recruitment, overdistension and collapse.	(26) n=2 patients (44) n=9 patients (10) n=10 pigs (12, 43) n=16 pigs (45) n=9 pigs (46) n=12 pigs

Clinical issue	Method of analysis / EIT measure	Brief description / EIT findings	Maneuvers / interventions besides tidal ventilation	Normal vs. pathological results (if applicable)	Suggested impact on clinical decisions	References / assessment of evidence
Effect of high frequency oscillatory ventilation	Homogenization of lung volume distribution during HFOV, assessment of regional lung volume distribution during HFOV	After calibration of tidal impedance to tidal air volume.	calibration	Normal: homogeneous lung volume distribution	Change of CDP and oscillation frequency	(39) n=10 patients (38) n=8 pigs (lavage injury)
Effect of sighs	Distribution of ΔEELZ and tidal ΔZ variation	Sigh increases EELZ and decreases ventilation heterogeneity	Sigh: 35 cm H_2O for 3-4 s applied at different rates	Normal: homogeneous lung volume distribution	Sighs reduce strain and ventilation heterogeneity during assisted ventilation in ARDS	(47) n=20 patients
Over-distension	Regional pressure-volume (ΔZ) curves	Determination of regional UIP by an automatic algorithm.	parallel measurement of airway pressure, better: transpulmonary pressure; low-flow inflation maneuver	Normal: homogenous UIP	Reduction of mean airway pressure	(44) n=9 patients
	Deterioration of ventilation in lung units	Decrease in pixel C_{rs} as surrogate for amount of alveolar collapse within that pixel. Weighted average at each PEEP step gives an estimate of cumulative collapse.	Lung recruitment maneuver and decremental PEEP trial	n.a.	Set PEEP at level with lowest cumulated collapse	(26) n=2 patients

Clinical issue	Method of analysis / EIT measure	Brief description / EIT findings	Maneuvers / interventions besides tidal ventilation	Normal vs. pathological results (if applicable)	Suggested impact on clinical decisions	References / assessment of evidence
Regional gas flow	Determination of regional pulmonary gas flow	First derivative of regional ΔZ(t) is proportional to regional flow. V(t) can be imaged after calibration of ΔZ(t)	Measurement during tidal ventilation or during forced full expiration/ recruitment maneuver	Normal: homogenous distribution of regional gas flow	None at the moment	(36) n=14 patients and n=14 healthy adults (35) n=7 patients and n=7 healthy adults (48) n=5 patients (49) n=13 pigs
EIT-guided lung-protective ventilation	Use of EIT ventilation indices to reduce heterogeneity of ventilation distribution or optimize regional C_{rs} (11, 50), EIT determined center of ventilation calculated in a Fuzzy controller (8)	Regional EIT-derived C_{rs} used to maximize recruit-ment of the dependent and minimize overdistention of the nondependent lung areas. EIT proposed in automated (closed-loop) ventilation algorithms to determine the necessity of lung recruitment maneuvers	Incremental PEEP titration	Not applicable	Use EIT-derived C_{rs} to set PEEP at the level which balances dependent lung recruitment and nondependent overdistention.	(11) n=12 pigs (50) n=4 pigs (8) n=6 pigs
Single-lung ventilation	Monitoring qualitatively or quantitatively left and right-sided ventilation	During tidal artificial ventilation, a ROI-based analysis is performed either in a fEIT ventilation tomogram or in the EIT right and left lung waveforms. A loss or gain in ventilation during manipulation of the endotracheal tube shows either SLV or DLV.	Measurement during tidal artificial ventilation	SLV should be avoided during standard situations of ventilations (it can occur due to too deep intubation). But SLV can also be desired (during lung/thorax surgery, ventilation in a patient with a large bronchopleural fistula).	Correct tube position either to induce SLV or DLV whatever is intended	(51) n=10 patients (52) n=40 patients (53) n=5 pigs

Clinical issue	Method of analysis / EIT measure	Brief description / EIT findings	Maneuvers / interventions besides tidal ventilation	Normal vs. pathological results (if applicable)	Suggested impact on clinical decisions	References / assessment of evidence
Monitoring of tidal recruitment of atelectasis	Monitoring: regional determination of tidal recruitment (54-56)	Proof of tidal recruitment is given by fast non-invasive measurement of SpO_2 oscillations, changes in regional V_T, EELZ and gas flow are followed by EIT in different ROIs	Parallel measurement of intratidal changes of gas exchange by fast, non-invasive SpO_2 (54)	Normal: no regional recruitment of atelectasis	Lung recruitment, increase of PEEP, reduction of VT	(56)n=9 patients (54) n=21 pigs (55) n=9 pigs
	Detecting a potential for tidal recruitment: Ventilation delay in the dorsal regions of the lung (17, 18)	During a low-flow inflation the delay until a threshold increase of regional Z in dorsal lung regions is reached (in comparison with global or ventral regions) indicates the late "opening" of lung units that collapsed during expiration.	Low-flow inflation maneuver	Normal: no regional recruitment of atelectasis	Lung recruitment, increase in PEEP, reduction of V_T	(17) n=16 pigs (18) n=12 pigs
	Detection of tidal recruitment by increased C_{rs} in dependent regions on V_T increase (10)	Higher C_{rs} at higher V_T at identical PEEP implies tidal recruitment	Temporary increase in V_T	Regional C_{rs} remains stable when tidal recruitment is noit present	Lung recruitment, increase in PEEP	(10) n=5 patients and 10 pigs

Table E7.1. Clinical issues of EIT use in adult patients focussing on monitoring lung ventilation and guidance of mechanical ventilation.

CDP: continuous distending pressure; CoV: center of ventilation; CMV: controlled mechanical ventilation; CoV: center of ventilation; C_{rs}: respiratory system compliance; CV: coefficient of variation; DLV: double-lung ventilation; EELZ: end-expiratory lung impedance; ΔEELZ: end-expiratory lung impedance change; fEIT: functional EIT; FEV_1: forced expiratory volume in one second; FVC: forced expiratory vital capacity; GI: global inhomogeneity, HFOV: high-frequency oscillatory ventilation; IVC: inspiratory vital capacity; n.a.: not applicable; LIP: lower inflection point of a pressure-volume curve; NAVA: neutrally adjusted ventilation assist; P: pressure; P_{insp}: inspiratory pressure; ΔP: pressure change; PEEP: positive end-expiratory pressure, PCV: pressure-controlled ventilation; PSV: pressure-support ventilation; ROI: region of interest; RV: residual volume; SLV: single-lung ventilation; SpO_2: oxygen saturation; TLC: total lung capacity; UIP: upper inflection point of a pressure-volume curve; U/L: upper-to-lower ventilation ratio; VCV: volume-controlled ventilation; V_T: tidal volume; Z: impedance; ΔZ: impedance change

EIT use for monitoring cardiac activity, lung perfusion and fluid status

It has long been realized that the physiological activity of the heart leads to periodic changes in regional thoracic electrical bioimpedance that can be traced by EIT (57, 58). This information can be used to study for instance the heart performance, by measuring the stroke volume, or lung perfusion. Compared with the ventilation-oriented chest EIT, the cardiovascular aspects of EIT use have been studied less often and the number of involved research groups is lower. The explanation may be that the analysis of EIT data specifically aiming at cardiovascular phenomena in the chest is challenging because of the small amplitude of the corresponding heart-beat related signal variations.

Table E7.2 summarizes the efforts in EIT research focussing on such clinical issues as the assessment of stroke volume, ventricular diastolic performance, pulmonary perfusion, pulmonary hypertension, ventilation-perfusion matching and heart-lung interactions. The table also contains information on a few studies targeting the measurement of the fluid content of the lung tissue using EIT. The clinical issues comprise the diagnosis and monitoring of lung edema development and its therapy and the related assessment of extravascular lung water.

Clinical issue	Method of analysis / EIT measure	Brief description / EIT findings	Maneuvers / interventions besides tidal ventilation	Normal vs. pathological results (if applicable)	Suggested impact on clinical decisions	References / assessment of evidence
Pulmonary perfusion and fluid state						
Pulmonary perfusion	EIT lung pulsatility (59-61) or regional relative distribution of RPBF by hypertonic saline first-past kinetics (62, 63) or indirect assessment of RPBF by EIT measurement of regional O_2 uptake (64)	Cardiac-related impedance changes can be detected by EIT by ECG-triggered measurement, measure-ment during apnea or frequency-domain filtering. The signal is not directly related to stroke volume but more to vessel pulsations. Pulsatility: detects cardiac-related impedance changes related to changes in local blood volume. RPBF: The high conductivity of hypertonic saline makes it suitable for an electric contrast agent. Injected in the right atrium a first-pass kinetics analysis can be performed.	Administration of saline bolus, ECG triggered EIT data sampling, frequency domain filtering. Pulsatility: Frequency domain filtering and/or ECG-gated EIT acquisition. During apnea or tidal ventilation, RPBF distribution: Administration of a small saline bolus into a central vein during apnea.	Normal: homogenous distribution of heart-beat related signal. No interference with inspiration or expiration. Pathology (pulmonary embolism): regional perfusion deficit	None at the moment	(60) n=10 patients (61) n=10 healthy subjects and 20 patients (65) n=8 human subjects (ECG trigger) (64) n=12 patients (59) n=8 pigs (apnea) (62) n=3 pigs (saline bolus) (63) n=6 pigs (saline bolus) (53) n=5 pigs (saline bolus)
Pulmonary hyper-tension	EIT pulsatility amplitude: Maximal impedance change during systole (ΔZsys)	Changes in EIT pulsatility amplitude can be related to the interaction between cardiac-related changes in vascular volume and local vascular mechanics.	Measurement during spontaneous breathing or mechanical ventilation	Patients with IPAH have a reduced volume pulse of the pulmonary vascular bed manifested as a reduced systolic impedance amplitude	Diagnosis screening of IPAH. Evaluation of responses to treatment.	(66) n=21 patients and n=30 healthy human subjects (67) n=8 patients

Clinical issue	Method of analysis / EIT measure	Brief description / EIT findings	Maneuvers / interventions besides tidal ventilation	Normal vs. pathological results (if applicable)	Suggested impact on clinical decisions	References / assessment of evidence
Ventilation-perfusion mismatch	EIT regional ventilation and pulsatility estimated perfusion	Regional mapping of ventilation and perfusion and ventilation-perfusion ratio	Analysis of functional ventilation and perfusion maps	Normal: matched ventilation and perfusion	None at the moment	(68) n=12 healthy subjects (69) n=11 pigs (70) n=6 pigs
Cardiac output	Cyclic variation in Z in the cardiac (ventricular) region, HR derived from the EIT signal	Cyclic variation in Z correlates with SV	No specific interventions (variation in SV in validation studies)	n.a.	None at the moment	(57) n=4 healthy subjects (71) n=10 healthy subjects (72) n=10 healthy subjects (73) n=26 patients and n=10 healthy subjects (74) n=14 pigs
Right ventricular diastolic function	ROI-based analysis of the diastolic part of the heart-beat related EIT waveform	EIT-derived RAEV correlates with MRI findings	No specific interventions			(75) n=27 patients and n=7 healthy subjects
Heart-lung interaction	EIT assessment of pulmonary stroke volume variation	ΔZ pulse arrival time	Mechanical ventilation at different V_T and PEEP settings, hypovolemia	Ventilation induces stroke volume variation that is detected by EIT	n.a.	(76) n=8 pigs

Clinical issue	Method of analysis / EIT measure	Brief description / EIT findings	Maneuvers / interventions besides tidal ventilation	Normal vs. pathological results (if applicable)	Suggested impact on clinical decisions	References / assessment of evidence
Lung edema / extra-vascular lung water	Estimation of extravascular lung water by U/L ventilation ratio (77), reduction in ΔEELZ (78), mean Z (79, 80) or ΔZ during full inspiration (81), fdEIT (82) or aEIT imaging (83), EIT lung water ratio computed from the IM coefficient (84)	EVLW decreases bio-impedance. Increased EVLW can be detected by analysis of ventilation-induced impedance changes in the anterior and posterior parts of the lung (U/L ventilation ratio) or decreased ΔEELZ or reversed slope of IM coefficient during lateral positioning	Normal mechanical ventilation. Calculation of U/L ratio. Fluid administration. Right and left tilt and calculation of imbalance between right and left lung ventilation.	An U/L of 0.64 has a 93% sensitivity and 87% specificity to detect a supranormal EVLW (77). IM coefficients exhibit a negative trend slope in normal lungs during body rotation and a positive one in injured lungs.	Diagnosis of lung edema. Aid in clinical decision making regarding fluid/diuretic therapy. Diagnosis high-altitude pulmonary edema. (Changes in pulmonary fluid content may impact the EIT-derived information on lung aeration and should be taken into account.)	(77) n=14 patients (79) n=9 healthy subjects (80) n=20 patients (83) n=4 patients (81) n=20 healthy subjects (78) n=14 pigs (82) n=3 goats (83) n=5 pigs (84) n=30 pigs

Table E7.2. Clinical issues of EIT use in adult patients focussing on heart activity, lung perfusion and fluid status.

aEIT: absolute EIT imaging; EVLW: extravascular lung water; EELZ: end-expiratory lung impedance; ΔEELZ: end-expiratory lung impedance change; fdEIT: frequency-difference EIT imaging; HR: heart rate; IM: imbalance ventilation coefficient; IPAH: idiopathic pulmonary hypertension; n.a.: not applicable; PEEP: positive end-expiratory pressure, RAEV: right atrium emptying volume; RPBF: regional pulmonary blood flow; SV: stroke volumeU/L: upper-to-lower ventilation ratio; V_T: tidal volume; Z: impedance; ΔZ: impedance change; ΔZsys: maximum impedance change during systole

EIT examinations in specific lung disease

The most widespread clinical use of EIT is noted in critically ill, mechanically ventilated patients. The most frequent lung disease that is assessed and monitored by EIT in these patients is ARDS. Nonetheless, there exist several other pulmonary diseases where EIT has been applied and where the potential for routine clinical use has been identified. These comprise diseases like pneumothorax and pleural effusion that can also be encountered in mechanically ventilated patients but also other diseases where EIT examinations take place during spontaneous breathing. The number of studies focussing on chronic lung diseases like COPD, asthma and cystic fibrosis is increasing, the results imply that EIT might be of benefit, e.g. in disease staging or monitoring of disease progression and therapy effects. EIT has also been applied in patients suffering from pneumonia or lung cancer. A few case reports on EIT examinations in less common diseases, like tracheobronchomalacia and lung transplant, have been reported as well. Table E7.3 gives the detailed information on EIT use in these specific lung diseases.

Clinical issue	Method of analysis / EIT measure	Brief description / EIT findings	Maneuvers / interventions besides tidal ventilation	Normal vs. pathological results (if applicable)	Suggested impact on clinical decisions	References / assessment of evidence
Specific diagnoses						
Pleural effusion/ empyema	Ventilation distribution, ΔEELZ, ventilation asynchrony	R/L lung ventilation asymmetry in unilateral affections, changes in ventilation distribution	Measurement during spontaneous breathing or mechanical ventilation	Ventilation reduced at the affected side of the chest in predominantly unilateral pathology	The improved symmetry of right-to-left lung ventilation distribution can be assessed during aspiration of pleural fluid	(85) n=6 patients (86) n= 10 patients (87) n=22 patients
Pneumo-thorax	Ventilation distribution, ΔEELZ automated algorithm for detection of penumothirax	Online sequential analysis of perturbations seen in the EIT ventilation and aeration change maps constructed from two to three respiratory cycles.	Sequential increase in PEEP with a fixed inspiratory driving pressure (88)	Pneumothoraces as small as 20 mL could be detected with EIT (sensitivity 100%; specificity 95%)	EIT-based algorithm can be used to detect early signs and locations of pneumothoraces in high-risk situations	(88) n=39 pigs (89) n=1 pig
Pneumonia	Ventilation distribution	R/L lung ventilation asymmetry in unilateral disease	Measurement during spontaneous breathing or mechanical ventilation	Ventilation reduced at the affected side of the chest	None at the moment	(90) n=1 patient (91) n=24 patients
Lung cancer	Ventilation distribution	R/L lung ventilation asymmetry in unilateral bronchial carcinoma	Measurement during spontaneous breathing or mechanical ventilation	Ventilation reduced at the affected side of the chest	None at the moment	(90) n=1 patient (92) n=5 patients (93) n=21 patients (94) n=14 patients

Clinical issue	Method of analysis / EIT measure	Brief description / EIT findings	Maneuvers / interventions besides tidal ventilation	Normal vs. pathological results (if applicable)	Suggested impact on clinical decisions	References / assessment of evidence
COPD	Spatial and temporal ventilation homogeneity (quantified by various EIT measures representing regional lung volumes (e.g. V_T, FEV_1, FVC), flow rates (e.g. PEF, FEF_{25-75}) or expiration times)	Ventilation distribution is heterogeneous in COPD, regional responses to bronchodilator administration can be traced by EIT	Measurement during spontaneous breathing (34, 95-97), forced full expiration (34, 97) and mechanical ventilation (39, 98)	Ventilation heterogeneity more pronounced in COPD patients compared with healthy subjects	Regional pulmonary function monitoring, identification of exacerbation and response to therapy and reversibility testing, phenotyping	(34) n=33 patients and n=26 healthy subjects (95) n=12 patients and n=15 healthy subjects (96) n=28 patients (39) n=10 patients (97) n= 35 patients (98) n=1 patient
Asthma	Spatial and temporal ventilation homogeneity (quantified by various EIT measures representing regional lung volumes (e.g. V_T, FEV_1, FVC), expiratory flows (PEF, FEF_{25-75}) or expiration times)	Ventilation distribution is heterogeneous in patients with chronic history of asthma, it improves after bronchodilator reversibility testing	Measurement during spontaneous breathing and forced full expiration	Ventilation heterogeneity is more pronounced in asthma patients compared with age-matched healthy subjects	Regional pulmonary function monitoring, identification of exacerbation and response to therapy and reversibility testing	(35) n=7 patients and n=7 healthy subjects

Clinical issue	Method of analysis / EIT measure	Brief description / EIT findings	Maneuvers / interventions besides tidal ventilation	Normal vs. pathological results (if applicable)	Suggested impact on clinical decisions	References / assessment of evidence
Cystic fibrosis	Spatial distribution of EIT-derived maximum expiratory flows ratio MEF_{25}/MEF_{75}, GI indices of inhaled volumes at 25%, 50%, 75% and 100% of IVC (36) Fraction of ventilation and filling index in the right lung region (99)	Pixel MEF_{25}/MEF75 are heterogeneously distributed, GI indices of inhaled volumes fall significantly in the course of full inspiration in patients with CF	Forced full inspiration and expiration (36), lateral posture and breathing aids (99)	Normal: Narrow distribution peaks of MEF_{25}/MEF_{75}, stable GI during deep inspiration Pathological: Broad MEF_{25}/MEF_{75} distribution, high GI indices at low inhaled volumes Temporal ventilation distribution is affected by breathing aids in healthy subjects but not in patients with CF	Regional pulmonary function monitoring, identification of exacerbation and response to drug and physical therapy	(36) n=14 patients and n=14 healthy subjects (99) n=9 patients and n=11 healthy subjects
Tracheo-broncho-malacia	Percentage of collapse and overdistension during PEEP titration (100), R/L ventilation distribution (101)	EIT identified the PEEP level where airway collapse was be prevented	Decremental PEEP trial	n.a.	Adjustment of ventilator settings	(100) n=1 patient (101) n=1 patient
Lung transplant	Ventilation distribution	Dissimilar functional status of the native and the transplanted lungs	Spontaneous breathing or mechanical ventilation	Symmetric ventilation distribution in healthy subjects	Adjustment of ventilator settings depending on the R/L ventilation distribution	(102) n=1 patient

Table E7.3. EIT use in adult patients with specific pulmonary diagnoses.

CF: cystic fibrosis; ΔEELZ: change in end-expiratory lung impedance; FEF_{25-75}: mean forced expiratory flow between 25% and 75% of FVC; FEV_1: forced expiratory volume in one second; FVC: forced expiratory vital capacity; GI: global inhomogeneity; IVC: inspiratory vital capacity; MEF_{25}: maximum expiratory flow at 25% of FVC; MEF_{75}: maximum expiratory flow at 75% of FVC; PEEP: positive end-expiratory pressure, PEF: peak expiratory flow; R/L: right-to-left; V_T: tidal volume

Recommendations for future direction

As documented by the findings of a large number of EIT studies summarized in the Tables E7.1-E7.3, EIT can generate information on regional lung ventilation and lung function that is in part unique or not easily accessible by other medical technology and from which the examined patients might benefit. This multitude of EIT results, however, does not yet allow the conclusion that EIT is already fully ready for the routine clinical use.

The current degree of knowledge implies that the routine use of EIT is most probable in the personalized bedside guidance of ventilator therapy. Prospective clinical trials are urgently needed to confirm the ability of EIT to reliably guide mechanical ventilation in comparison with the current standard clinical practice. Based on these studies, consensus algorithms for adjustment of ventilator settings should be developed based on selected EIT measures in combination with the findings of other medical diagnostic and monitoring methods. An automated generation of relevant EIT findings with easy accessibility for immediate use by the clinical staff with alerts in the case of potentially adverse situations is essential. Large multicenter outcome EIT studies should then follow. An implementation of EIT monitoring into the standard ICU monitoring would be desirable.

The use of chest EIT in cardiovascular monitoring and regional pulmonary function testing is less advanced. It still requires validation studies, for instance regarding the aspired long-term monitoring of patients with chronic lung diseases where the proof of the correlation between the disease severity and EIT findings is lacking. Methodological advances are also needed, for instance allowing reliable EIT data acquisitions and analysis under the more challenging conditions of spontaneous breathing in typically upright and partially moving patients. The subsequent steps necessary for establishing EIT in these additional clinical fields (i.e. the prospective mono- and multicenter studies mentioned above) resemble the proposed steps needed in establishing EIT for optimization of ventilator therapy.

The clinical use and acceptance of EIT would certainly benefit from further technological advances. Wearable EIT would largely increase its applicability and potentially allow home monitoring especially in pulmonology patients. EIT image reconstruction taking individual a priori anatomical information (which often is available in patients) into account might improve not only the EIT image quality but also increase the information content of EIT chest examinations. The research in these areas is ongoing and it could foster the clinical use of EIT even in not yet identified new application fields.

Document preparation

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