Article	Abstract
Wrigge H, Zinserling J, Muders T, et al: Electrical impedance tomography compared with thoracic computed tomography during a slow inflation maneuver in experimental models of lung injury. Crit Care Med 2008; 36:903-909	Objective: To determine the validity of functional electric impedance tomography to monitor regional ventilation distribution in experimental acute lung injury, and to develop a simple electric impedance tomography index detecting alveolar recruitment. Design: Randomized prospective experimental study. Setting: Academic research laboratory. Subjects: Sixteen anesthetized, tracheotomized, and mechanically ventilated pigs. Interventions: Acute lung injury was induced either by acid aspiration (direct acute lung injury) or by abdominal hypertension plus oleic acid injection (indirect acute lung injury) in ten pigs. Six pigs with normal lungs were studied as a control group and with endotracheal suction-related atelectasis. After 4 hrs of mechanical ventilation, a slow inflation was performed. Measurements and Main Results: During slow inflation, simultaneous measurements of regional ventilation by electric impedance tomography and dynamic computed tomography were highly correlated in quadrants of a transversal thoracic plane ($r^2 = 0.63 – 0.88$, $p < .0001$, bias <5%) in both direct and indirect acute lung injury. Variability between methods was lower in direct than indirect acute lung injury (11 ± 2% vs. 18 ± 3%, respectively, $p < .05$). Electric impedance tomography indexes to detect alveolar recruitment were determined by mathematical curve analysis of regional impedance time curves. Empirical tests of different methods revealed that regional ventilation delay, that is, time delay of regional impedance time curve to reach a threshold, correlated well with recruited volume as measured by CT ($r^2 = 0.63$). Correlation coefficients in subgroups were $r^2 = 0.71$ and $r^2 = 0.48$ in pigs with normal lungs with and without closed suction related atelectasis and $r^2 = 0.79$ in pigs subject to indirect acute lung injury, respectively, whereas no significant correlation was found in pigs undergoing direct acute lung injury. Conclusions: Electric impedance tomography allows assessment of regional ventilation distribution and recruitment in experimental models of direct and indirect acute lung injury as well as normal lungs. Except for pigs with direct acute lung injury, regional ventilation delay determined during a slow inflation from impedance time curves appears to be a simple index for clinical monitoring of alveolar recruitment. (Crit Care Med 2008; 36:903–909) KEY WORDS: acute lung injury; acute respiratory distress syndrome; lung imaging; lung mechanics; mechanical ventilation; monitoring.
Meier T, Luepschen H, Karsten J, et al: Assessment of regional lung recruitment and derecruitment during a PEEP trial based on electrical impedance tomography. Intensive Care Med 2008 34:543-550	Objective: To investigate whether electrical impedance tomography (EIT) is capable of monitoring regional lung recruitment and lung collapse during a positive end-expiratory pressure (PEEP) trial. Design: Experimental animal study of acute lung injury. Subject: Six pigs with saline-lavage-induced acute lung injury. Interventions: An incremental and Decremental PEEP trial at ten pressure levels was performed. Ventilatory, gas exchange, and hemodynamic parameters were automatically recorded. EIT and computed tomography (CT) scans of the same slice were simultaneously taken at each PEEP level. Measurements and results: A significant correlation between EIT and CT analyses of end-expiratory gas volumes ($r = 0.98$ up to 0.99) and tidal volumes ($r = 0.55$ up to $r = 0.88$) could be demonstrated. Changes in global and regional tidal volumes and arterial oxygenation (PaO_2/FiO_2) demonstrated recruitment/ derecruitment during the trial, but at different onsets. During the decremental trial, derecruitment first occurred in dependent lung areas. This was indicated by lowered regional tidal volumes measured in this area and by a decrease of PaO_2/FiO_2. At the same time, the global tidal volume still continued to increase, because the increase of ventilation of the non-dependent areas was higher than the loss in the dependent areas. This indicates that opposing regional changes might cancel each other out when combined in a global parameter. Conclusions: EIT is suitable for monitoring the dynamic effects of PEEP variations on the regional change of tidal volume. It is superior to global ventilation parameters in assessing the beginning of alveolar recruitment and lung collapse.
Steinmann D, Stahl C, Minner J, et al: Electrical impedance tomography to confirm correct placement of double-lumen tube: a feasibility study. Br J Anaesth 2008 101(3):411-418	Background. Double-lumen tubes (DLTs) are frequently used to establish one-lung ventilation (OLV). Their correct placement is crucial. We hypothesized that electrical impedance tomography (EIT) reliably displays distribution of ventilation between left and right lung and may thus be used to verify correct DLT placement online. Methods. Regional ventilation was studied by EIT in 40 patients requiring insertion of left sided DLTs for OLV during thoracic surgery. EIT was recorded during two-lung ventilation before induction of anesthesia and after DLT placement, and during OLV in the supine and subsequently in the lateral position. EIT measurements were made before and after verification of correct DLT placement by fiber optic bronchoscopy (FOB). Results. EIT accurately displayed distribution of ventilation between left and right lung online. All cases (n=5) of initially misplaced DLTs in the contra-lateral right main

bronchus were detected by EIT. However, EIT did not allow prediction of FOB-detected endo-bronchial cuff misplacement requiring DLT repositioning. Furthermore, after DLT repositioning, distribution of ventilation, as assessed by EIT, did not change significantly (all P.0.5).

Conclusions. This study demonstrates that EIT enables accurate display of left and right lung ventilation and, thus, non-invasive online recognition of misplacement of left-sided DLTs in the contra-lateral main bronchus. However, as distribution of ventilation did not correlate with endo-bronchial cuff placement, EIT cannot replace FOB in the routine control of DLT position.

Odenstedt H, Lindgren S, Olegard C, et al:

Slow moderate pressure recruitment maneuver minimizes negative circulatory and lung mechanic side effects: evaluation of recruitment maneuvers using electrical impedance tomography.

Intensive Care Med 2005 31:1706-1714

Objective: To evaluate the efficacy of different lung recruitment maneuvers using electric impedance tomography. Design and setting: Experimental study in animal model of acute lung injury in an animal research laboratory. Subjects: Fourteen pigs with saline lavage induced lung injury. Interventions: Lung volume, regional ventilation distribution, gas exchange, and hemodynamics were monitored during three different recruitment procedures: (a) vital capacity maneuver to an inspiratory pressure of 40 cmH_2O (ViCM), (b) pressure-controlled recruitment maneuver with peak pressure 40 and PEEP 20 cmH_2O, both maneuvers repeated three times for 30 s (PCRM), and (c) a slow recruitment with PEEP elevation to 15 cmH_2O with end inspiratory pauses for 7 s twice per minute over 15 min (SLRM). Measurements and results: Improvement in lung volume, compliance, and gas exchange were similar in all three procedures 15 min after recruitment. Ventilation in dorsal regions of the lungs increased by 60% as a result of increased regional compliance. During PCRM compliance decreased by 50% in the ventral region. Cardiac output decreased by 63 ±4% during ViCM, 44 ±2% during PCRM, and 21 ±3% during SLRM.

Conclusions: In a lavage model of acute lung injury alveolar recruitment can be achieved with a slow lower pressure recruitment maneuver with less circulatory depression and negative lung mechanic side effects than with higher pressure recruitment maneuvers. With electric impedance tomography it was possible to monitor lung volume changes continuously.

Lindgren S, Odenstedt H, Olegard C, et al:

Regional lung derecruitment after endotracheal suction during volume– or pressure-controlled ventilation: a study using electrical impedance tomography.

Intensive Care Med 2007 33:172-180

Objective: To assess lung volume and compliance changes during open- and closed-system suctioning using electric impedance tomography (EIT) during volume or pressure-controlled ventilation. Design and setting: Experimental study in a university research laboratory. Subjects: Nine bronchoalveolar saline-lavaged pigs. Interventions: Open and closed suctioning using a 14-F catheter in volume- or pressure-controlled ventilation at tidal volume 10 ml/kg, respiratory rate 20 breaths/min, and positive end-expiratory pressure 10 cmH_2O. Measurements and results: Lung volume was monitored by EIT and a modified N2 washout/-in technique. Airway pressure was measured via a pressure line in the endotracheal tube. In four ventral-to-dorsal regions of interest regional ventilation and compliance were calculated at baseline and 30 s and 1, 2, and 10 min after suctioning. Blood gases were followed. At disconnection functional residual capacity (FRC) decreased by 58 ± 24% of baseline and by a further 22 ± 10% during open suctioning. Arterial oxygen tension decreased to 59 ± 14% of baseline value 1 min after open suctioning. Regional compliance deteriorated most in the dorsal parts of the lung. Restitution of lung volume and compliance was significantly slower during pressure-controlled than volume-controlled ventilation.

Conclusions: EIT can be used to monitor rapid lung volume changes. The two dorsal regions of the lavaged lungs are most affected by disconnection and suctioning with marked decreases in compliance. Volume-controlled ventilation can be used to rapidly restitute lung aeration and oxygenation after lung collapse induced by open suctioning.

Erlandsson K, Odenstedt H, Lundin S, et al:

Positive end-expiratory pressure optimization using electrical impedance tomography in morbidly obese patients during laparoscopic gastric bypass surgery.

Acta Anaesthesiol Scand 2006 50:833-839

Background: Morbidly obese patients have an increased risk for peri-operative lung complications and develop a decrease in functional residual capacity (FRC). Electric impedance tomography (EIT) can be used for continuous, fast-response measurement of lung volume changes. This method was used to optimize positive end-expiratory pressure (PEEP) to maintain FRC. Methods: Fifteen patients with a body mass index of 49 ±8 kg/m^2 were studied during anesthesia for laparoscopic gastric bypass surgery. Before induction, 16 electrodes were placed around the thorax to monitor ventilation-induced impedance changes. Calibration of the electric impedance tomograph against lung volume changes was made by increasing the tidal volume in steps of 200 ml. PEEP was titrated stepwise to maintain a horizontal baseline of the EIT curve, corresponding to a stable FRC. Absolute FRC was measured with a nitrogen wash-out/wash-in technique. Cardiac output was measured with an esophageal Doppler method. Volume expanders, 1 ±0.5 l, were given to prevent PEEP-induced hemodynamic impairment. Results: Impedance changes closely followed tidal volume changes ($r^2 > 0.95$). The optimal PEEP level was 15 ±1 cmH_2O, and FRC at this PEEP level was 1706 ±447 ml before and 2210 ±540 ml after surgery ($P < 0.01$). The cardiac index increased significantly from 2.6 ±0.5 before to 3.1 ±0.8 $l/min/m^2$ after surgery, and the alveolar dead space decreased. PaO_2/FiO_2, shunt and compliance remained unchanged.

Conclusion: EIT enables rapid assessment of lung volume changes in morbidly obese patients, and optimization of PEEP. High PEEP levels need to be used to maintain a normal FRC and to minimize shunt. Volume loading prevents circulatory depression in spite of a high PEEP level.

Frerichs I, Dargaville P, Dudykevych T, et al:

Electrical impedance tomography: a method for monitoring regional lung aeration and tidal volume distribution?

Intensive Care Med 2003 29:2312-2316

Objective: To demonstrate the monitoring capacity of modern electrical impedance tomography (EIT) as an indicator of regional lung aeration and tidal volume distribution. Design and setting: Short-term ventilation experiment in an animal research laboratory. Patients and participants: One newborn piglet (body weight: 2 kg). Interventions: Surfactant depletion by repeated bronchoalveolar lavage, surfactant administration. Measurements and results: EIT scanning was performed at an acquisition rate of 13 images/s during two ventilatory maneuvers performed before and after surfactant administration. During the scanning periods of 120 s the piglet was ventilated with a tidal volume of 10 ml/kg at positive end-expiratory pressures (PEEP) in the range of 0 – 30 cmH_2O, increasing and decreasing in 5 cmH_2O steps. Local changes in aeration and ventilation with PEEP were visualized by EIT scans showing the regional shifts in end-expiratory lung volume and distribution of tidal volume, respectively. In selected regions of interest EIT clearly identified the changes in local aeration and tidal volume distribution over time and after surfactant treatment as well as the differences between stepwise inflation and deflation.

Conclusions: Our data indicate that modern EIT devices provide an assessment of regional lung aeration and tidal volume and allow evaluation of immediate effects of a change in ventilation or other therapeutic intervention. Future use of EIT in a clinical setting is expected to optimize the selection of appropriate ventilation strategies.

Frerichs I, Hahn G, Schröder T, et al:

Electrical impedance tomography in monitoring experimental lung injury.

Intensive Care Med 1998 24:829-836

Objective: To apply electrical impedance tomography (EIT) and the new evaluation approach (the functional EIT) in monitoring the development of artificial lung injury. Design: Acute experimental trial. Setting: Operating room for animal experimental studies at a university hospital. Subjects: Five pigs (41.3 ± 4.1 kg, mean body weight ± SD). Interventions: The animals were anaesthetized and mechanically ventilated. Sixteen electrodes were attached on the thoracic circumference and used for electrical current injection and surface voltage measurement. Oleic acid was applied sequentially (total dose 0.05 ml/kg body weight) into the left pulmonary artery to produce selective unilateral lung injury. Measurements and results: The presence of lung injury was documented by significant changes of $PaCO_2$ (40.1 mmHg vs control 37.1 mmHg), PaO_2 (112.3 mmHg vs 187.5 mmHg), pH (7.35 vs 7.42), mean pulmonary arterial pressure (29.2 mmHg vs 20.8 mmHg) and chest radiography. EIT detected 1) a regional decrease in mean impedance variation over the affected left lung (-41.4% vs control) and an increase over the intact right lung (+20.4% vs control) indicating reduced ventilation of the affected, and a compensatory augmented ventilation of the unaffected lung and 2) a pronounced fall in local baseline electrical impedance over the injured lung (-20.6%vs control) with a moderate fall over the intact lung (-10.0% vs control) indicating the development of lung edema in the injured lung with a probable atelectasis formation in the contra-lateral one.

Conclusion: The development of the local impairment of pulmonary ventilation and the formation of lung edema could be followed by EIT in an experimental model of lung injury. This technique may become a useful tool for monitoring local pulmonary ventilation in intensive care patients suffering from pulmonary disorders associated with regionally reduced ventilation, fluid accumulation and/or cell membrane changes.

Hinz J, Moerer O, Neumann P, et al:

Effect of positive end-expiratory-pressure on regional ventilation in patients with acute lung injury evaluated by electrical impedance tomography.

For the treatment of patients with adult respiratory distress syndrome and acute lung injury bedside measurements of regional lung ventilation should be considered for optimizing ventilatory settings. The aim was to investigate the effect of positive end-expiratory pressure (PEEP) on regional ventilation in mechanically ventilated patients at the bedside by electrical impedance tomography. Methods: Eight mechanically ventilated patients were included in the study. PEEP levels were increased from 0 to 5, 10, 15 mbar and back to 0 mbar. Regional

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ventilation in 912 regions of the thorax was investigated at each PEEP by electrical impedance tomography. The obtained regions were divided in four groups: none (none and poorly ventilated regions including chest wall and mediastinum), bad, moderate and well-ventilated regions. Results: Increasing the PEEP stepwise from 0 to 15 mbar decreased the non-ventilated regions (none: 540 regions at PEEP 0 and 406 regions at PEEP 15). In contrast, the other regions increased (bad: 316 regions at PEEP 0 and 380 regions at PEEP 15; moderate: 40 regions at PEEP 0 and 100 regions at PEEP 15; well: 0 region at PEEP 0 and 34 regions at PEEP 15 (median values)) indicating an improvement of regional ventilation.

Conclusions: Increasing PEEP in mechanically ventilated patients reduces none ventilated regions (atelectasis). Furthermore, it leads to a shift from none and bad ventilated regions to moderately and well-ventilated regions. Electrical impedance tomography is a bedside technique and might be an alternative to computed tomography scan to assess aerated lung regions.

Hinz J, Hahn G, Neumann P, et al:

End-expiratory lung impedance change enables bedside monitoring of end-expiratory lung volume change.

Intensive Care Med 2003 29:37-43

Objective: The aim of the study was to investigate the effect of lung volume changes on end-expiratory lung impedance change (ELIC) in mechanically ventilated patients, since we hypothesized that ELIC may be a suitable parameter to monitor lung volume change at the bedside. Design: Clinical trial on patients requiring mechanical ventilation. Settings: Intensive care units of a university hospital. Patients: Ten mechanically ventilated patients were included in the study. Intervention Patients were ventilated in volume-controlled mode with constant flow and respiratory rate. In order to induce changes in the end-expiratory lung volume (EELV), PEEP levels were increased from 0 mbar to 5 mbar, 10 mbar, and 15 mbar. At each PEEP level EELV was measured by an open-circuit nitrogen washout maneuver and ELIC was measured simultaneously using Electrical Impedance Tomography (EIT) with sixteen electrodes placed on the circumference of the thorax and connected with an EIT device. Cross-sectional electro-tomographic measurements of the thorax were performed at each PEEP level, and a modified Sheffield back projection was used to reconstruct images of the lung impedance. ELIC was calculated as the average of the end-expiratory lung impedance change. Results: Increasing PEEP stepwise from 0 mbar to 15 mbar resulted in an linear increase of EELV and ELIC according to the equation: $y = 0.98 \times -0.68$, $r^2 = 0.95$.

Conclusion: EIT is a simple bedside technique which enables monitor lung volume changes during ventilatory maneuvers such as PEEP changes.

Hinz j, Neumann, Didykevych T, et al:

Regional Ventilation by Electrical Impedance Tomography: A Comparison With Ventilation Scintigraphy in Pigs.

Chest 2003 124:314-322

Study objective: The validation of electrical impedance tomography (EIT) for measuring regional ventilation distribution by comparing it with single photon emission CT (SPECT) scanning. Design: Randomized, prospective animal study. Settings: Animal laboratories and nuclear medicine laboratories at a university hospital. Participants: Twelve anesthetized and mechanically ventilated pigs. Interventions: Lung injury was induced by central venous injection of oleic acid. Then pigs were randomized to pressure-controlled mechanical ventilation, airway pressure-release ventilation, or spontaneous breathing. Measurements and results: Ventilation distribution was assessed by EIT using cross-sectional electrotomographic measurements of the thorax, and simultaneously by single SPECT scanning with the inhalation of 99mTc-labeled carbon particles. For both methods, the evaluation of ventilation distribution was performed in the same transverse slice that was approximately 4 cm in thickness. The transverse slice then was divided into 20 coronal segments (going from the sternum to the spine). We compared the percentage of ventilation in each segment, normalized to the entire ventilation in the observed slice. Our data showed an excellent linear correlation between the ventilation distribution measured by SPECT scanning and EIT according to the following equation: $y = 0{,}82x + 0{,}7$ ($r^2 = 0.92$; range, 0.86 to 0.97).

Conclusion: Based on these data, EIT seems to allow, at least in comparable states of lung injury, real-time monitoring of regional ventilation distribution at the bedside.

Meier T, Leibecke T, Eckmann C, et al:

Electrical impedance tomography: changes in distribution of pulmonary ventilation during laparoscopic surgery in a porcine model.

Langenbecks Arch Surg 2006 391:383-389

Background: Because of the creation of a pneumoperitoneum, impairment of ventilation is a common side-effect during laparoscopic surgery. Electrical impedance tomography (EIT) is a method with the potential for becoming a tool to quantify these alterations during surgery. We have studied the change of regional ventilation during and after laparoscopic surgery with EIT and compared the diagnostic findings with computed tomography (CT) scans in a porcine study. Materials and methods: After approval by the local animal ethics committee, six pigs were included in the study. Two laparoscopic operations were performed [colon resection (n=3) and fundoplication (n=3)]. The EIT measurements (6th parasternal intercostal space) were continuously recorded by an EIT prototype (EIT Evaluation Kit, Dräger Medical, Lübeck, Germany). To verify ventilatory alterations detected by EIT, a CT scan was performed postoperatively. Results: Ventilation with defined tidal volumes was significantly correlated to EIT measurements ($r^2 = 0.99$). After creation of the pneumoperitoneum, lung compliance typically decreased, which agreed well with an alteration of the distribution of pulmonary ventilation measured by EIT. Elevation of positive end-inspiratory pressure reopened non-aerated lung areas and showed a recovery of the regional ventilation measured by EIT. Additionally, we could detect pulmonary complications by EIT monitoring as verified by CT scans postoperatively.

Conclusion: EIT monitoring can be used as a continuous non-invasive intra-operative monitor of ventilation to detect regional changes of ventilation and pulmonary complications during laparoscopic surgery. These EIT findings indicate that surgeons and anesthetists may eventually be able to optimize ventilation directly in the operating theatre.

Victorino J, Borges J, Okamoto V, et al:

Imbalances in Regional Lung Ventilation:
A Validation Study on Electrical Impedance Tomography.

AMJRCCM 2004 169:791-800

Imbalances in regional lung ventilation, with gravity dependent collapse and overdistention of nondependent zones, are likely associated to ventilator induced lung injury. Electric impedance tomography is a new imaging technique potentially capable of monitoring those imbalances. The aim of this study was to validate EIT measurements of ventilation distribution, by comparison with dynamic computerized tomography in a heterogeneous population of critically ill patients under mechanical ventilation. Multiple scans with both devices were collected during slow-inflation breaths. Six repeated breaths were monitored by impedance tomography, showing acceptable reproducibility. We observed acceptable agreement between both technologies in detecting right-left ventilation imbalances (bias = 0% and limits of agreement = -10 to 10%). Relative distribution of ventilation into regions or layers representing one fourth of the thoracic section could also be assessed with good precision. Depending on electrode positioning, impedance tomography slightly overestimated ventilation imbalances along gravitational axis. Ventilation was gravitationally dependent in all patients, with some transient blockages in dependent regions synchronously detected by both scanning techniques. Among variables derived from computerized tomography, changes in absolute air-content best explained the integral of impedance changes inside regions of interest ($r^2 = 0.92$).

Conclusion: impedance tomography can reliably assess ventilation distribution during mechanical ventilation.