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REVIEW

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Electrical impedance tomography in critical care: Advancing bedside respiratory monitoring and ventilation management

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ABSTRACT:

Electrical impedance tomography (EIT) is a transformative, non-invasive imaging tool in critical care, providing real-time, continuous monitoring of lung function. Originally applied to assess ventilation distribution in mechanically ventilated patients. EIT's scope has expanded significantly. It now encompasses a wide range of applications, including positive end-expiratory pressure (PEEP) titration, spontaneous breathing assessment, air trapping detection, alveolar recruitment guidance, and ventilation-perfusion (V/Q) matching. EIT supports personalized respiratory management across a range of therapies, including mechanical ventilation, high-flow nasal cannula (HFNC), and non-invasive ventilation (NIV), by identifying ventilation heterogeneity and preventing ventilator-induced lung injury (VILI). The ability of EIT to quantify regional lung mechanics, detect changes due to therapeutic interventions like suctioning and bronchodilation, and visualize complex phenomena such as pendelluft underscores its role in optimizing ventilation strategies and enhancing patient outcomes in critical care. Despite some technical challenges, EIT's integration into respiratory monitoring protocols is advancing, supporting data-driven, individualized management approaches that improve safety and outcomes for critically ill patients.

Keywords: Electrical impedance tomography; Critical care; Acute respiratory failure; Mechanical ventilation; Ventilator-induced lung injury

INTRODUCTION

Acute respiratory failure (ARF) represents a critical condition characterized by the lungs' inability to perform effective gas exchange, leading to severe hypoxemia (low oxygen levels), hypercapnia (elevated carbon dioxide levels), or a combination of both[1]. This condition poses a significant challenge in critical care settings, often necessitating mechanical ventilation to support oxygenation and maintain adequate gas exchange. However, the management of ventilation in these patients is complex, as inappropriate ventilator settings can contribute to ventilator-induced lung injury (VILI) and precipitate further complications such as barotrauma, volutrauma, atelectrauma, and biotrauma[2]. In the intensive care unit (ICU), effective respiratory monitoring is essential for optimizing ventilation settings and reducing the risks associated with mechanical ventilation. Electrical impedance tomography (EIT) has emerged as a valuable, non-invasive imaging technique in this context, offering continuous, real-time monitoring of lung function at the bedside[3, 4]. EIT provides a unique perspective on regional ventilation patterns, enabling clinicians to fine-tune ventilator settings based on precise, individualized insights into lung mechanics and physiology. Initially developed for assessing ventilation distribution, EIT's applications have rapidly expanded to encompass a broad range of uses [5-7]. It now serves as a vital tool for various assessments, including positive end-expiratory pressure (PEEP) titration[8], air trapping detection[9], alveolar recruitment evaluation[10, 11], and spontaneous breathing monitoring[11, 12]. Additionally, EIT supports non-invasive respiratory strategies, such as high-flow nasal cannula (HFNC) and non-invasive ventilation (NIV)[13, 14], demonstrating its adaptability across different respiratory support methods. Moreover, EIT has shown potential in assessing ventilation-perfusion matching and detecting conditions such as pneumothorax and pulmonary embolism, expanding its utility in critical care diagnostics. This review aims to provide a comprehensive overview of EIT, elucidating its fundamental principles and outlining its diverse applications in critical care medicine.

KEY MESSAGES:

- EIT provides continuous, real-time insights into regional lung ventilation, enabling personalized ventilator adjustments and reducing the risk of ventilator-induced lung injury (VILI).
- Beyond ventilation monitoring, EIT assists in PEEP titration, air trapping detection, alveolar recruitment, spontaneous breathing assessment, and ventilation-perfusion matching, making it a versatile tool in critical care.
- Despite its advantages, proper interpretation and awareness of EIT's limitations are crucial for its effective clinical application in critically ill patients.

PRINCIPLES AND PHYSIOLOGY OF EIT

Fundamental principles of EIT [15-18]

EIT is a non-invasive, radiation-free imaging technology that provides real-time, continuous monitoring of lung function at the bedside in critical care settings. This innovative approach offers unique insights into pulmonary function through sophisticated principles and processes[4].

EIT technology relies on strategic electrode placement. EIT systems utilize a flexible band or adhesive patches with 16 or 32 embedded electrodes, designed to fit various patient sizes and typically positioned between the fourth and fifth intercostal spaces (Figure 1). This placement is critical for accurate measurements, as positioning below the sixth intercostal space may introduce diaphragmatic interference. Placing the belt too high can lead to inaccurate assessments of dorsal ventilation, while incorrect orientation or rotation can distort the reconstructed image. An angled placement, with the dorsal section higher than the ventral, may underestimate dorsal lung ventilation, potentially misrepresenting dorsal hypoventilation or collapse. A transverse plane alignment is recommended to ensure optimal results in standard EIT monitoring [19, 20]. A reference electrode, usually placed on the abdomen, standardizes potential measurements across all electrode pairs. Once positioned, the system begins data collection by sending small, high-frequency alter-

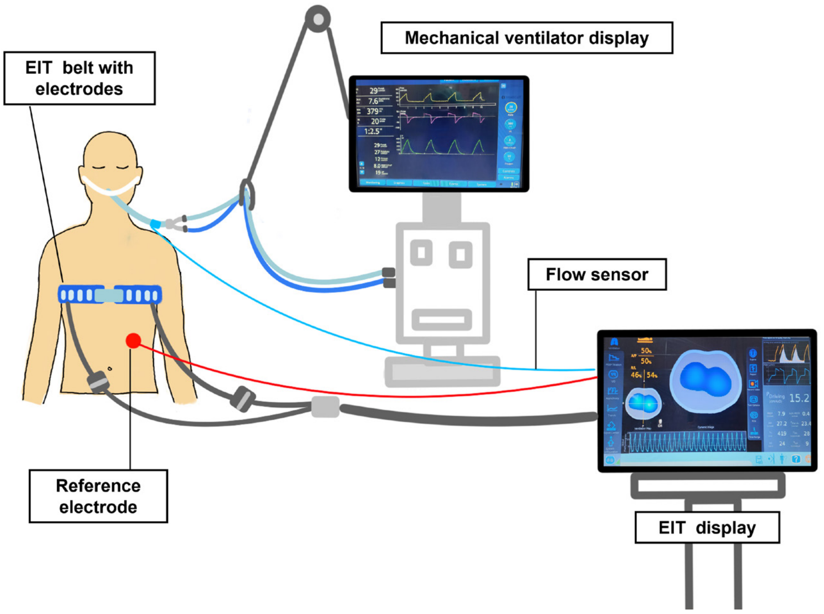


Figure 1. The image depicts a setup integrating EIT and a mechanical ventilator for real-time monitoring of lung function.An EIT belt is placed around the thorax at the fourth to fifth intercostal spaces, ensuring optimal positioning to capture accurate regional ventilation data while avoiding interference from the diaphragm. The belt contains multiple electrodes, which are connected to the EIT device via cables. The EIT system is shown as a dedicated monitor displaying dynamic lung images and ventilation distribution in real time. This monitor visualizes changes in impedance across different regions of the lung, represented by color-coded images that indicate variations in ventilation. The data collected by the EIT belt is processed by advanced algorithms to generate these detailed images. This combined setup allows clinicians to continuously monitor regional lung ventilation while adjusting ventilator parameters based on individualized patient needs.

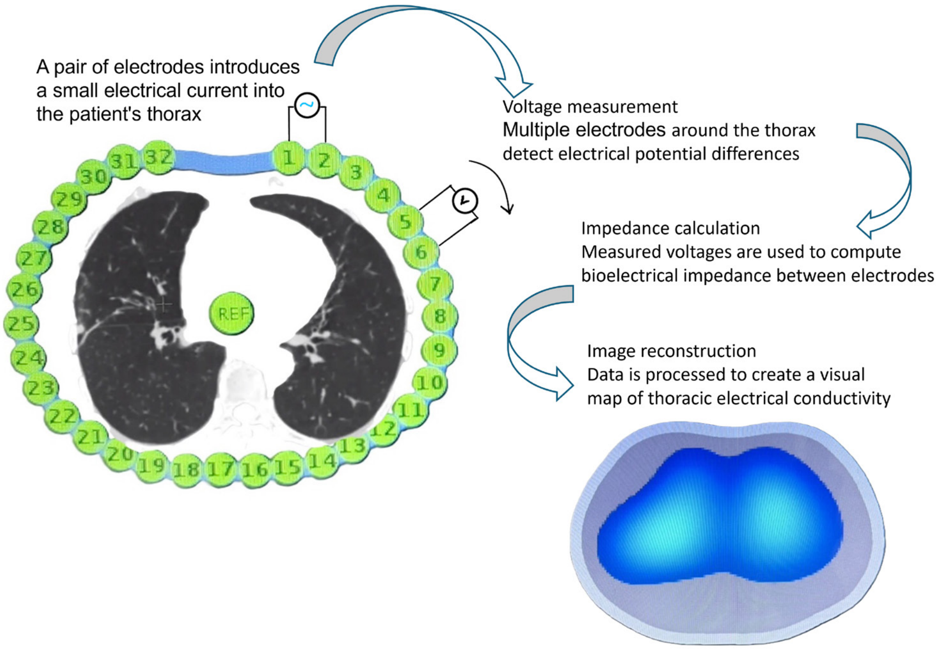


Figure 2. The image provides a detailed view of the EIT electrode configuration and its functionality. The circular arrangement of electrodes around the thorax enables the system to apply electrical currents through one electrode pair while measuring voltage differences across others. This process generates data points used to reconstruct cross-sectional images of lung conductivity. The central blue area in the image represents regions of higher impedance (e.g., air-filled lungs), while surrounding areas reflect lower impedance values (e.g., blood-filled tissues). Each electrode is labeled, illustrating its role in data acquisition and processing.

nating electrical currents (approximately 5 mA at 50-80 kHz) through electrode pairs. The remaining electrodes function as sensors, measuring voltage differences across the thoracic cavity (Figure 2). EIT operates on the principle that different tissues have distinct electrical properties. The resistance to electric currents, known as impedance, varies among tissue types such as lung, blood, and air[19]. These impedance differences throughout the thorax enable EIT to distinguish between various anatomical structures. For instance, air-filled lungs exhibit higher impedance compared to blood-filled tissues. During respiration, lung expansion causes impedance to increase during inhalation and decrease during exhalation. This dynamic change allows EIT to visualize and quantify regional ventilation patterns with remarkable precision. The process of creating an EIT image involves a sophisticated sequence of data acquisition and processing. Current is applied sequentially through each electrode pair encircling the thorax while voltage measurements are simultaneously recorded from all other electrodes. This rotation approach generates a multitude of data points or frames that are processed to construct a cross-sectional image of lung conductivity. This image captures regional changes in ventilation across the thoracic plane with remarkable detail. Modern EIT systems boast impressive temporal resolution, capable of acquiring approximately 50 frames per second. This high acquisition rate provides near real-time feedback on lung function, allowing for immediate detection of changes in ventilation patterns. The conversion of raw voltage data into meaningful images relies on advanced reconstruction algorithms. These include methods such as Sheffield back-projection, finite element model (FEM)-based approaches, and the Graz consensus reconstruction algorithm for EIT technique (GREIT) [21]. These algorithms interpret raw data, filter noise, and adjust for individual thoracic geometry variations to deliver high-resolution images. In the resulting EIT images, each pixel corresponds to a specific region of the lung, with colors indicating changes in impedance relative to a baseline frame, thereby visualizing ventilation distribution. EIT images display lung mechanics dynamically, using color coding to differentiate between regions with varying ventilation.

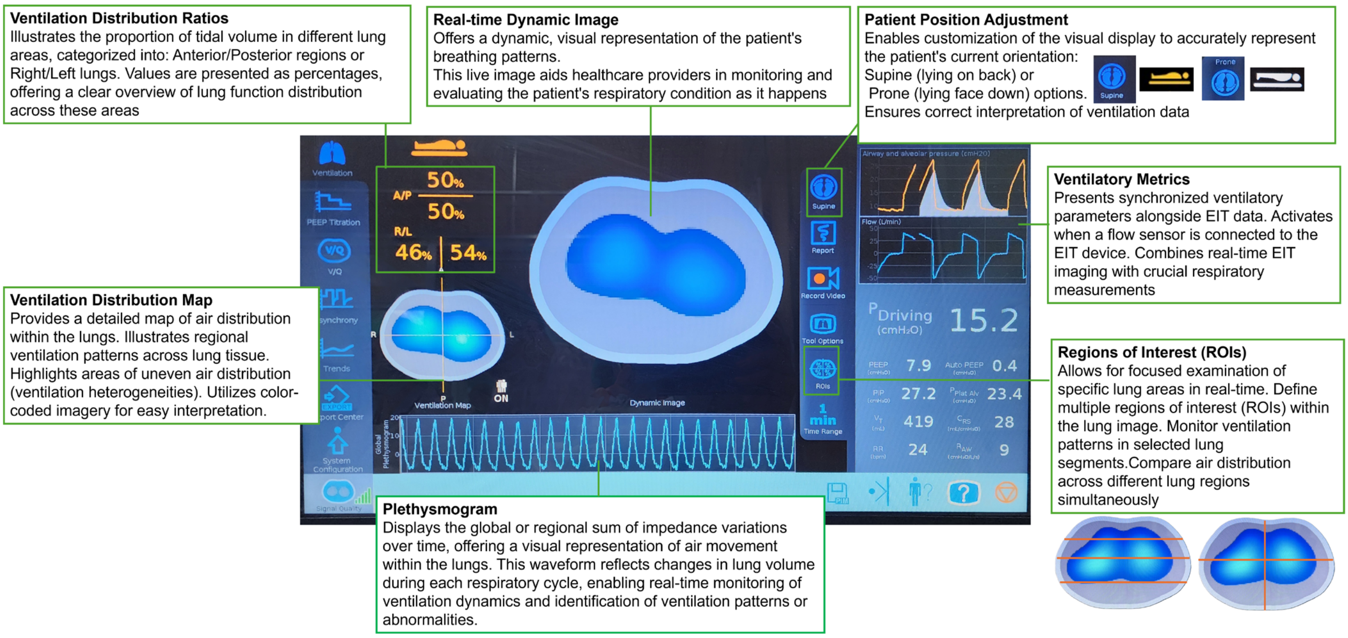
Functional EIT and quantitative measurement

Functional EIT represents a significant advancement in respiratory monitoring, integrating static EIT images with respiratory cycle waveforms, known as EIT plethysmograms, to provide detailed global and regional ventilation data. A key feature of functional EIT is its ability to segment the lungs into specific regions of interest (ROIs), such as dorsal and ventral sections or left and right lung regions. This segmentation enables clinicians to independently assess ventilation patterns in different areas of the lung, offering critical insights into regional lung function that may not be evident from global measurements alone (Figure 3). The integration of EIT plethysmograms with static images allows for the calculation of various quantitative metrics that provide valuable information about lung mechanics. These metrics include regional compliance, tidal volume, and end-expiratory lung impedance (EELI). Such measurements offer a comprehensive view of lung function, enabling clinicians to detect subtle changes in respiratory status that might otherwise go unnoticed. Functional EIT excels in assessing ventilation heterogeneity, which is crucial for managing patients with complex respiratory conditions. By providing detailed information on the distribution of ventilation across different lung regions, EIT supports the development of individualized ventilator strategies tailored to patient-specific needs. This capability is particularly valuable in optimizing ventilator settings for patients with conditions such as acute respiratory distress syndrome (ARDS), where maintaining appropriate regional ventilation is essential to prevent further lung injury. For instance, ARDS often presents with heterogeneous lung involvement, making it challenging to balance alveolar recruitment and overdistension. Functional EIT helps clinicians identify these regional differences, ensuring ventilator settings are adjusted to minimize injury while maximizing oxygenation.

Several quantitative EIT metrics have been developed to enhance data interpretation (Table 1). These include the global inhomogeneity (GI) index, which measures overall ventilation distribution; the anterior-posterior ventilation ratio, which evaluates the balance of ventilation between the front and back of the lungs; regional compliance measurements; and tidal variation analysis. Each metric provides unique insights into both global and local lung ventilation characteristics, allowing for a more nuanced evaluation of respiratory function. The combination of these quantitative metrics with the visual representation provided by EIT images creates a powerful tool for respiratory monitoring and management. Clinicians can use this information to make informed decisions about ventilation strategies, assess the effectiveness of interventions, and monitor disease progression or recovery overtime.

Factors affecting EIT readings

EIT has emerged as a valuable tool for ventilation monitoring in critical care settings. However, the accuracy and reliability of EIT readings can be influenced by various physiological and technical factors, which clinicians must consider for optimal interpretation and application of this technology. One of the primary considerations in EIT measurements is the impact of cardiac motion and changes in thoracic blood or fluid volume. These physiological processes can introduce impedance variations that are not directly related to ventilation. While primarily used for respiratory monitoring, EIT is sensitive enough to detect these cardiac-induced fluctuations. Advanced EIT systems have addressed this issue by implementing digital filtering techniques to minimize these cardiac-related artifacts, thereby improving the focus on ventilation-related data. Patient movement presents another significant challenge in EIT data acquisition. Any shift in position can alter the spatial relationship between the electrodes and the thoracic structures, potentially leading to misinterpretation of the impedance changes. Similarly, issues with electrode contact, such as poor adhesion or displacement, can compromise the quality of the electrical signals. Furthermore, electrical interference from nearby medical devices in the intensive care unit environment may introduce noise into the EIT measurements. The precise positioning of the EIT belt is crucial for accurate data collection. Incorrect placement, particularly if the belt is positioned too low on the thorax, can result in artifacts from diaphragm movement. These artifacts can significantly distort the ventilation image and lead to erroneous conclusions about regional lung function.



Ventilation Distribution Ratios
Illustrates the proportion of tidal volume in different lung areas, categorized into: Anterior/Posterior regions or Right/Left lungs. Values are presented as percentages, offering a clear overview of lung function distribution across these areas

Real-time Dynamic Image
Offers a dynamic, visual representation of the patient's breathing patterns.
This live image aids healthcare providers in monitoring and evaluating the patient's respiratory condition as it happens

Patient Position Adjustment
Enables customization of the visual display to accurately represent the patient's current orientation:
Supine (lying on back) or
Prone (lying face down) options.
Ensures correct interpretation of ventilation data

Ventilatory Metrics
Presents synchronized ventilatory parameters alongside EIT data. Activates when a flow sensor is connected to the EIT device. Combines real-time EIT imaging with crucial respiratory measurements

Ventilation Distribution Map
Provides a detailed map of air distribution within the lungs. Illustrates regional ventilation patterns across lung tissue. Highlights areas of uneven air distribution (ventilation heterogeneities). Utilizes color-coded imagery for easy interpretation.

Regions of Interest (ROIs)
Allows for focused examination of specific lung areas in real-time. Define multiple regions of interest (ROIs) within the lung image. Monitor ventilation patterns in selected lung segments.Compare air distribution across different lung regions simultaneously

Plethysmogram
Displays the global or regional sum of impedance variations over time, offering a visual representation of air movement within the lungs. This waveform reflects changes in lung volume during each respiratory cycle, enabling real-time monitoring of ventilation dynamics and identification of ventilation patterns or abnormalities.

Figure 3. EIT display showcasing key features such as ventilation distribution ratios, dynamic lung imaging, ventilation distribution maps, plethysmograms, ventilatory metrics, patient position adjustment, and ROIs for real-time respiratory monitoring and analysis.

Table 1. Quantitative metrics and clinical significance of EIT parameters.

Measure	Description	Clinical Significance	Availability
Global Inhomogeneity (GI) Index	Measures the degree of ventilation distribution inhomogeneity, often compared at different PEEP levels or conditions.	High GI values indicate uneven ventilation distribution, suggesting conditions like regional lung injury or ARDS. Useful for PEEP titration, assessing spontaneous breathing, and intraoperative lung monitoring. [22, 23]	Offline
End-Expiratory Lung Impedance (EELI)	Indicator of end-expiratory lung volume, calculated as the average minimum of the plethysmography curve across respiratory cycles.	Correlates with lung aeration at end-exhalation, helping guide PEEP titration and assess lung recruitment potential, especially in patients with derecruitment risk.[13]	Bedside and offline
Regional Ventilation Delay (RVD) Index	Identifies regions of delayed impedance change in response to inspiratory airflow, indicating regional tidal recruitment.	Regions with high RVD are more dependent on PEEP; minimizing RVD improves synchronized ventilation, reducing repetitive opening and closing of lung areas.[24]	Bedside and offline
Center of Ventilation (CoV)	Represents the vertical distribution of ventilation along the gravitational axis, with a balanced CoV at 50%.	Monitors shifts in ventilation distribution, particularly useful for assessing ventilation symmetry during positioning changes like prone positioning and detecting atelectasis. [25]	Bedside and offline
Tidal Impedance Variation (TIV)	Reflects the change in impedance between inspiration and expiration, indicating tidal volume distribution.	Helps identify overdistension or collapse, supporting optimal PEEP and tidal volume settings. Useful for assessing ventilation patterns in lung regions.[16]	Bedside and offline
Regional compliance	Compliance is calculated by dividing regional TIV by the change in driving pressure. Measure the change in impedance per unit of pressure in specific lung regions.	Monitors regional lung compliance, crucial for respiratory failure management, and supports personalized PEEP and driving pressure adjustments. Useful for detecting overdistention or recruitment.[23]	Bedside and offline
Overdistension and Collapse (ODCL)	Identifies PEEP level where compliance loss due to overdistention equals that due to collapse.	Guides optimal PEEP setting to balance recruitment and overdistension.	Bedside and offline
Pendelluft	Air movement between different lung regions without external volume change.	Indicates pressure of time-constant inequalities or diaphragm dysfunction.	Bedside and offline
Silent spaces	Area of the lung with minimal or no ventilation.	Helps identify atelectasis or severe airflow limitation.	Bedside and offline

Therefore, stable patient positioning and meticulous attention to electrode placement are essential for obtaining reliable EIT measurements. Certain patient-specific factors can also complicate the use of EIT. The presence of chest tubes, bandages, wounds, or skin burns may hinder correct belt placement, potentially affecting the quality and reliability of the data. In such cases, alternative electrode configurations or placement strategies may need to be considered. It is important to note that EIT is generally contraindicated in patients with active pacemakers or implantable cardioverter-defibrillators (ICDs) due to potential interference risks. The electrical currents used in EIT, although small, could theoretically interact with these devices, posing a safety concern.

Comparative analysis with other imaging modalities

EIT has emerged as a valuable tool in critical care, complementing established imaging modalities such as Computed Tomography (CT) and lung ultrasound. Several studies have validated EIT against CT for assessing lung ventilation and recruitment. Costa et al. demonstrated a strong correlation between EIT and CT in detecting alveolar collapse during lung recruitment maneuvers and PEEP titration in an animal model[18]. Similarly, Frerichs et al. validated EIT against electron beam CT for detecting local lung air content[6], while Victorino et al. showed that EIT could accurately assess regional lung ventilation when compared to CT[5]. Comparisons between EIT and lung ultrasound are less extensive, but emerging research shows promise. A recent study comparing quantitative lung ultrasound (Q-LUS) with EIT for detecting dynamic changes in lung aeration in preterm lambs found good correlation between the two techniques[26]. EIT excels in providing continuous, real-time monitoring, which is particularly valuable in critical care settings. CT is limited to intermittent scans, while ultrasound offers real-time imaging but is typically used intermittently. Regarding spatial resolution, CT provides excellent, sub-millimeter resolution, surpassing both EIT (moderate resolution of 3-5 cm in the cross-sectional plane) and ultrasound (good for superficial structures but limited for deep lung tissue).

In terms of diagnostic precision, each modality has its strengths. EIT is particularly good for regional ventilation assessment but has limitations in identifying specific pathologies. CT remains the gold standard for detailed anatomical imaging and specific diagnoses. Ultrasound is excellent for assessing pleural and some parenchymal conditions but is limited by air artifacts in lung tissue. While EIT offers unique advantages in bedside monitoring, it's important to contextualize its role alongside other imaging modalities (Table 2).

CLINICAL APPLICATIONS OF EIT IN CRITICAL CARE

Clinical applications of EIT in ARDS

ARDS, common in ICU patients, is characterized by diffuse alveolar damage due to increased alveolar and capillary permeability. This leads to interstitial and alveolar edema, inflammatory responses, and potential fibrosis. The resulting increased lung weight causes alveolar collapse in dependent regions, potentially contributing to multiorgan failure[27, 28]. In ARDS management, optimizing alveolar recruitment while preventing overdistension is crucial. PEEP plays a key role in stabilizing alveoli and minimizing atelectrauma. However, determining optimal PEEP levels requires balancing alveolar collapse prevention with overdistension risk [29-32]. Various methods have been proposed to determine the optimal PEEP in ARDS, each with its own advantages and limitations (Table 3).

Optimal PEEP titration with EIT

EIT has emerged as a valuable tool for optimizing PEEP in patients with ARDS. Two primary EIT-based strategies have shown promise in clinical research: Costa's algorithm and the changes in end-expiratory lung impedance (ΔEELI) - guided approach. Costa et al. developed an EIT-based algorithm to balance overdistension and alveolar collapse[18]. This method evaluates regional lung compliance variations during a decremental PEEP trial following maximal recruitment. It identifies compliance loss at high PEEP levels as overdistension and at low levels as alveolar collapse. The optimal PEEP is determined at the intersection of overdistension and collapse compliance-loss curves (ODCL), aiming to minimize both phenomena simultaneously (Figure 4). This approach has demonstrated significant benefits in ARDS patients across multiple studies[41, 43]. An alternative strategy utilizes ΔEELI measured via EIT. Eronia et al.[44] conducted a study where PEEP was adjusted in 2 cmH_2O increments if EELI decreased by more than 10% after a recruitment maneuver. This method showed improvements in PaO_2/FiO_2 ratio and driving pressure compared to the ARDS Network's lower PEEP/FiO_2 table. While both methods show promise, the Costa algorithm has been more widely adopted in clinical research. The ΔEELI-guided approach, despite its potential, has seen less frequent use in studies. Recent advancements in EIT-guided PEEP titration have further expanded its potential. These include integration with mechanical power calculations to minimize ventilator-induced lung injury[45], combination with esophageal pressure measurements for a more comprehensive assessment of lung mechanics, and the use of machine learning algorithms to predict optimal PEEP settings based on EIT data.

EIT in patients with ARDS receiving veno-venous extracorporeal membrane oxygenation (VV ECMO).

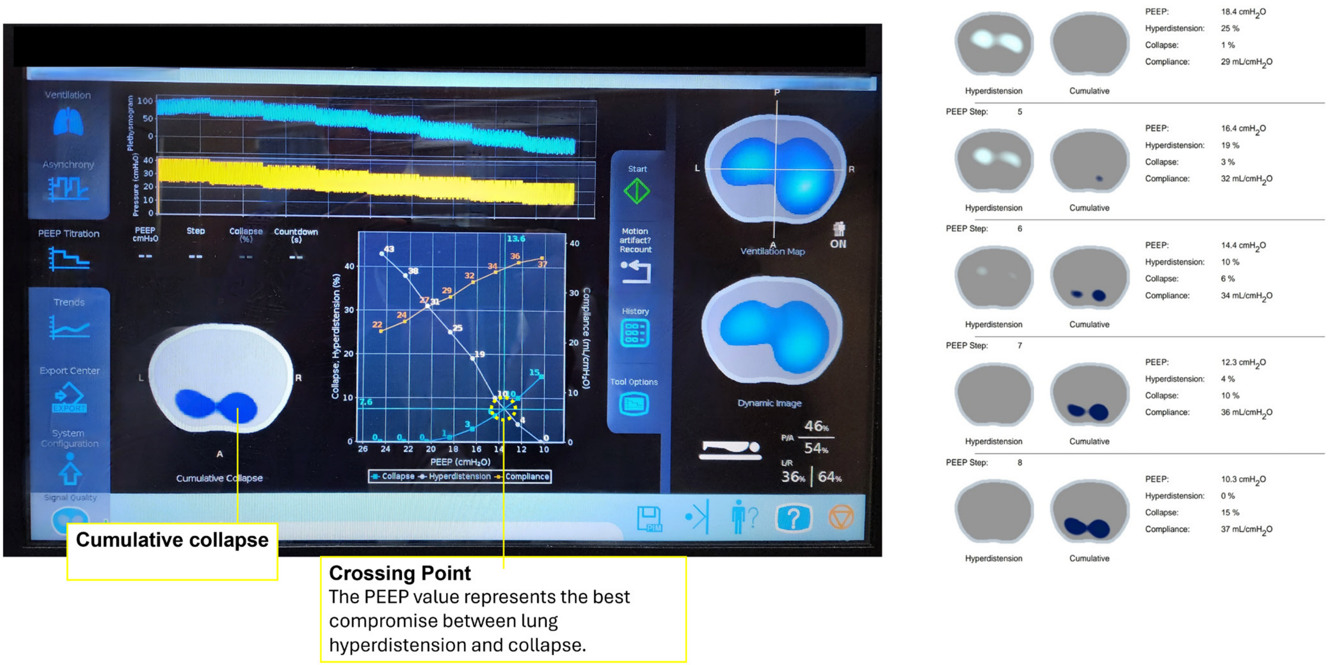
EIT has emerged as a promising tool for optimizing ventilation strategies in patients with ARDS receiving VV ECMO. Current evidence suggests that EIT enables clinicians to fine-tune PEEP settings and balance lung recruitment. Franchineau et al. demonstrated the viability of using EIT in VV-ECMO patients under ultraprotective ventilation with minimal tidal volumes[46]. Their study revealed a wide range of optimal PEEP levels across severe ARDS patients, emphasizing the need for personalized ventilation strategies based on individual ARDS lesion distribution. A case report has demonstrated the use of an EIT-guided whole-process respiratory management strategy[47]. EIT offers real-time visualization of regional ventilation during veno-venous extracorporeal membrane oxygenation (VV ECMO) therapy, enabling clinicians to evaluate the effects of ventilator settings and patient positioning on lung recruitment and ventilation heterogeneity. For instance, EIT can assist in guiding prone positioning by illustrating the redistribution of ventilation from ventral to dorsal regions. Additionally, EIT may aid in transitioning from full ECMO support to conventional ventilation by providing feedback on regional lung recruitment as ECMO flow is gradually reduced. This capability can help optimize ventilator settings throughout the weaning process.

Table 2. Comparison between different imaging modalities.

Feature	EIT	CT	Ultrasound
Principle	Impedance	X-rays	High frequency sound
Radiation exposure	None	High	None
Real-time monitoring	Continuous	Limited	Real-time, Intermittent
Spatial resolution	Moderate	Excellent	Moderate
Bedside availability	High	Low	High
Cost	Moderate	High	low
Diagnostic precision	Good for regional ventilation	Excellent for detailed anatomy	Good

Table 3. Summary table of PEEP optimization strategies in ARDS according to current evidence.

Strategy	Description	Advantages	Limitation	Evidence
PEEP/FiO_2 tables	Standardized tables based on oxygenation requirements	Simple, reproducible, widely used	Doesn't account for individual lung mechanics	Established in large RCTs (ARMA, ALVEOLI trials) [33, 34]
Decremental PEEP titration	Incrementally increase then reduce PEEP to find optimal compliance/oxygenation	Individualized approach	Potential for increased barotrauma; mixed mortality outcomes in large trials	ART trial showed increased mortality[35]; PHARLAP trial showed no benefit[36]
Esophageal pressure-guided	Uses esophageal manometry to estimate transpulmonary pressure	Accounts for chest wall mechanics	Requires specialized equipment and expertise	EPVent-2 trial showed no mortality benefit[37]
Stress index	Analyzes pressure-time curve during constant flow. straight line (SI = 1) reflects optimal PEEP	May reduce inflammatory markers and lung injury	Requires deep sedation; limited large-scale validation	Small studies show promise, but lacks large RCTs[30]
Pressure-volume curve analysis	Targets recruitment/derecruitment points on PV curve	May improve compliance and oxygenation	Complex to implement at bedside	Physiologically sound, but practical challenges limit use[38, 39]
Driving pressure minimization	Adjusts PEEP to minimize driving pressure	Associated with improved survival; easy to implement	May not address regional heterogeneity	Strong observational data, but lacks large RCT validation[40]
CT-guided	Precise assessment of recruitment/derecruitment	High-resolution imaging of lung tissue	Radiation exposure; not for continuous monitoring	Valuable research tool, impractical for routine use
EIT	Real-time regional ventilation assessment	Enables personalized PEEP titration; may reduce VILI	Requires specific equipment and expertise	Growing evidence of benefits in small studies[41, 42]



Cumulative collapse

Crossing Point
The PEEP value represents the best compromise between lung hyperdistension and collapse.

Figure 4. EIT guided PEEP titration The images illustrate the process of PEEP titration using EIT based on Costa et al.'s algorithm. The graph plots overdistension and collapse percentages against PEEP levels, with lung compliance shown as a separate curve. The "crossing point" on the graph represents the optimal PEEP level, where the curves for overdistension and collapse intersect. This point indicates the best compromise between minimizing alveolar overdistension and preventing collapse while maximizing lung compliance. For each PEEP step, EIT provides a visual representation of regional lung overdistension (highlighted in light blue) and alveolar collapse (highlighted in dark blue).

EIT in obstructive lung disease

Obstructive lung disease (OLD), including asthma and COPD, results in airway obstruction caused by inflammation, mucus, and structural changes, leading to increased resistance, flow limitation, and lung hyperinflation. While conventional spirometry provides global lung function assessments, it cannot capture regional variations. Advanced imaging such as computed tomography offers structural insights but is invasive, costly, and unsuitable for routine functional monitoring. EIT overcomes these limitations by providing real-time, regional assessments of lung function. It estimates flow and volume changes from impedance variations during breathing, enabling EIT-based spirometry to measure parameters like FEV1, FVC, and flow-volume loops to reveal regional flow limitations. This technique has been validated against conventional spirometry and has shown the ability to detect increased ventilation inhomogeneity in patients with COPD[48]. In ventilated OLD patients, EIT can detect air trapping and intrinsic PEEP, aiding treatment adjustments[49, 50]. EIT tracks bronchodilator effects, demonstrating improved regional ventilation distribution beyond global flow-volume changes. It benefits patients who struggle with spirometry by enabling lung function assessment without forced maneuvers[51, 52]. Additionally, EIT assists in optimizing PEEP by analyzing regional ventilation delays and expiratory time constants, enabling clinicians to select the most suitable ventilation mode or support type for patients with flow limitation and lung hyperinflation[53, 54]. Moreover, EIT has revealed that suctioning does not reduce lung volume in OLD patients and highlights the superiority of neurally adjusted ventilatory assist over pressure support ventilation for improving dorsal ventilation and reducing dead space in acute COPD exacerbations[55]. EIT also evaluates pendelluft caused by regional time constant differences or dynamic pleural pressure variations, visualizing airway obstruction improvement after treatment[56]. Recent studies have explored the potential of EIT as an early screening tool for lung function impairment, even in participants with normal spirometry results [57]. This suggests that EIT could detect subtle changes in lung function before they become apparent through conventional testing methods. EIT has proven to be a valuable tool in enhancing OLD diagnosis and management.

EIT in spontaneous breathing and weaning trials

Spontaneous breathing during mechanical ventilation has been shown to enhance lung compliance, preserve end-expiratory lung volumes, and minimize ventilation redistribution to ventral lung regions, potentially reducing atelectrauma caused by cyclic alveolar collapse and tidal recruitment[58]. EIT plays a critical role in visualizing and quantifying spatial ventilation distribution in real time, helping clinicians evaluate the benefits of partial ventilatory support and predict outcomes during spontaneous breathing trials (SBTs)[11, 59, 60]. The technology utilizes parameters such as the GI index and changes in EELI to assess weaning readiness and forecast SBT success. One of the key advantages of EIT in this context is its ability to detect subtle changes in regional lung function that may not be apparent through conventional monitoring methods. For instance, elevated ventilation heterogeneity or a rapid decline in EELI may signal muscle fatigue or inadequate respiratory drive, indicating the need for continued ventilatory support. This real-time feedback allows clinicians to make more informed decisions about the timing and progression of weaning attempts. Additionally, EIT can identify conditions such as pendelluft, an abnormal airflow between lung regions caused by asynchronous diaphragmatic activity. By detecting potential self-inflicted lung injury during spontaneous breathing, EIT enables clinicians to adjust strategies to mitigate regional stress on lung tissues. Recent studies have further expanded the application of EIT in weaning trials. For example, Li et al. found that certain EIT parameters during spontaneous breathing trials could predict weaning success with good sensitivity and specificity in patients after upper abdominal surgery[61]. Another study by Longhini et al. showed that EIT could guide the titration of pressure support levels during weaning, potentially optimizing the balance between respiratory muscle unloading and patient effort[12]. While EIT provides valuable insights, studies on its use in weaning and SBTs include diverse methodologies and patient populations, limiting the generalizability of findings. Further research is needed to determine the most effective EIT-derived metrics for predicting weaning success and optimizing outcomes across different patient groups and clinical scenarios.

EIT with HFNC and NIV support

EIT has demonstrated significant potential in non-invasive respiratory support settings, such as in patients receiving HFNC or NIV for hypoxemic respiratory failure. HFNC therapy is known to increase end-expiratory lung volume and improve functional residual capacity. EIT can visualize these effects in real-time, allowing clinicians to track HFNC's impact on lung aeration across different regions, independent of patient positioning[62]. This capability enables the customization of oxygen delivery settings based on specific patient needs. Riera et al. used EIT to demonstrate that HFNC therapy increased EELI and tidal variation of impedance, indicating improved lung volume and ventilation[62]. Similarly, Mauri et al. utilized EIT to show that HFNC reduced inspiratory effort and improved ventilation distribution in patients with acute hypoxemic respiratory failure[63]. For patients on NIV, EIT assists in assessing regional ventilation and tidal volume distribution, providing critical information on how different NIV settings affect ventilation uniformity. EIT-derived data on the ventilation heterogeneity index or anterior-posterior ventilation distribution help clinicians tailor NIV settings and avoid exacerbating regional lung injury, supporting safer and more effective respiratory support[64].

EIT in prone positioning and other positions

Prone positioning is a recognized strategy in ARDS management for enhancing oxygenation by redistributing ventilation to dependent lung regions. EIT enhances this approach by providing real-time monitoring of ventilation distribution, allowing for precise adjustments to ventilator settings to optimize gas exchange. A recent study demonstrated that prolonged prone ventilation increased dorsal ventilation and perfusion, resulting in improved ventilation-perfusion matching and oxygenation[65]. EIT is also valuable in evaluating other positions, such as lateral decubitus and semi-recumbent. In the lateral decubitus position, EIT reveals ventilation redistribution influenced by gravity, typically favoring the non-dependent lung. This insight is particularly useful for managing patients with unilateral lung disease or those requiring selective lung ventilation. Sequential lateral positioning has been shown to increase EELI in COVID-19 pneumonia, indicating recruitment and providing an alternative for patients unable to tolerate prone positioning[66]. In semi-recumbent positioning, EIT demonstrates improved functional residual capacity and a reduced risk of aspiration compared to supine positioning, offering valuable guidance for safely positioning mechanically ventilated patients. By monitoring ventilation distribution in various positions, EIT supports personalized respiratory management, enhancing lung mechanics and oxygenation in critically ill patients.

ADVANCED APPLICATIONS

Detection of pendelluft

Pendelluft is the bidirectional movement of gas between lung regions due to inhomogeneities in regional resistances and compliances. This asynchronous filling and emptying of different areas may not contribute to effective gas exchange and has implications for lung injury and ventilation strategies[67]. EIT is a unique tool for real-time pendelluft detection. Its high temporal resolution allows continuous monitoring of rapid changes in air distribution during respiration, providing a dynamic view of lung behavior previously unattainable. This capability is crucial in critical care settings where quick adjustments to ventilation strategies may be necessary. EIT has revealed correlations between pendelluft and regional lung inflammation, both modulated by PEEP, suggesting potential for optimizing ventilation strategies[68]. While negative associations with clinical outcomes have been reported[69], the direct causal impact of pendelluft on patient prognosis remains under investigation. Researchers have used EIT to study how different ventilatory settings affect regional lung mechanics during spontaneous breathing. It has enabled detailed analysis of air movement between dependent and non-dependent lung regions, enhancing our understanding of ventilation distribution in healthy and diseased lungs [56, 70]. Various EIT-based methods have been developed to quantify pendelluft, tailored to different clinical scenarios. These include measuring bidirectional gas flow magnitude and analyzing the timing and duration of pendelluft events. EIT shows promise in guiding personalized ventilation strategies by providing real-time feedback on regional lung mechanics and pendelluft occurrence. This could help minimize ventilator-induced lung injury and improve outcomes in critically ill patients. Despite these advancements, challenges remain in standardizing measurement techniques, interpreting criteria, and validating EIT findings against other imaging modalities. Further research is needed to establish the clinical significance of different pendelluft degrees and determine optimal intervention thresholds.

Ventilation-perfusion (V/Q) matching and pulmonary perfusion

Ventilation-perfusion (V/Q) matching is a crucial aspect of lung function, determining the efficiency of gas exchange in the lungs. Accurate assessment of V/Q matching is essential for understanding and managing various respiratory conditions. EIT has emerged as a promising tool for evaluating V/Q matching and pulmonary perfusion in real-time, offering significant advantages over traditional imaging methods. EIT extends its functionality beyond ventilation monitoring to assess pulmonary perfusion, facilitating real-time evaluation of V/Q matching. By measuring the impedance of fluids, EIT can visualize perfusion distribution across the thorax. The perfusion component of EIT imaging is typically achieved through two main methods: the conductivity-contrasting bolus injection technique and the pulsatility technique. The bolus technique involves the rapid injection of a contrast agent, usually hypertonic saline, during a brief apnea period. In contrast, the pulsatility technique filters the pulsatile heartbeat component from the EIT signals to derive perfusion information. While both methods have their merits, the bolus technique has shown better agreement with established imaging modalities such as Single-Photon Emission Computed Tomography (SPECT) and Positron Emission Tomography (PET), making it the current reference standard for EIT-based V/Q assessment[71, 72]. The procedure for the bolus technique is relatively straightforward. Using a central line catheter, approximately 10 mL of hypertonic saline (typically 5-10% NaCl) is rapidly injected within 1-2 seconds[72] during a breath-hold of 8-15 seconds[73]. EIT images of perfusion (Q) are then calculated by subtracting the heart pixels from the data. The ventilation (V) component is derived by filtering the pre-apnea ventilation signal to remove heart rate-related components. This allows for pixel-by-pixel V/Q matching to be determined[74]. A potential concern regarding the bolus technique is the electrolyte load of the saline injection. However, the salt load is relatively small (10 mL of 5% saline corresponds to 0.5 g or 8.5 mEq of NaCl), and no adverse effects of electrolyte disturbances have been reported to date after rapid or repeated bolus administration. Nevertheless, it remains unclear how the 10 mL requirement scales with patient mass, blood volume, and cardiac output. Advanced software is required to automatically process these EIT data and calculate V/Q images at the bedside. If independent measures of minute ventilation and cardiac output are available, a calibrated V/Q image can be produced. In the absence of these measurements, the EIT-V/Q image remains unitless, providing a relative V/Q image. Recent studies have demonstrated EIT's potential in various clinical applications. For instance, a case report by Prins et al. demonstrated EIT's capability to detect pulmonary embolism (PE) by visualizing the improvement in pulmonary circulation following thrombolytic therapy[75]. He et al. developed a saline bolus-based EIT method for rapid bedside assessment of regional lung perfusion during ECMO therapy[76], highlighting EIT's versatility in complex critical care scenarios. EIT-based V/Q assessment has proven particularly valuable in improving our understanding of gas exchange abnormalities and evaluating the effects of various interventions on regional V/Q matching. Pavlovsky et al. utilized EIT to study the effects of PEEP on regional ventilation-perfusion mismatch in ARDS patients[77], while Scaramuzzo et al. employed EIT to investigate the influence of PEEP titration on the effects of prone positioning in ARDS. Despite its many advantages and promising results, it's important to note that EIT-based V/Q assessment is still a relatively new technique in the clinical context. Ongoing research is focused on standardizing protocols, improving image resolution, and validating EIT findings against established imaging modalities. Further studies are needed to validate its use across different patient populations and clinical scenarios.

Detection of pneumothorax and pleural effusion

EIT’s sensitivity to impedance changes makes it an effective tool for pneumothorax detection in high-risk patients, such as those with chest trauma or undergoing central line placement. The rapid detection of changes in impedance associated with air leakage can alert clinicians to pneumothorax development before clinical signs become apparent. Studies have shown that EIT-based algorithms can detect pneumothoraces as small as 20 mL with high sensitivity and specificity[78], and can identify the location of the pneumothorax correctly within just three respiratory cycles. In experimental models, EIT has proven capable of identifying even smaller pneumothoraces (as little as 10 mL) before changes in physiological parameters like SpO_2 and heart rate become apparent[79]. One of the key advantages of EIT in pneumothorax management is its ability to provide real-time feedback on interventions. For instance, studies have shown that EIT can visualize the resolution of a pneumothorax after treatment. Additionally, EIT can differentiate pneumothorax from pleural effusion by recognizing the contrasting impedance characteristics of air and fluid. This capability makes it valuable for diagnosing and managing complications at the bedside. In the realm of pleural effusion detection, research has demonstrated a high correlation between lung resistivity measured by EIT and the volume of pleural fluid removed from patients[80]. The technique has shown sensitivity to small changes in pleural fluid volume, making it a potentially valuable tool for monitoring patients with known or suspected pleural effusions. However, despite these promising results, EIT-based detection of pneumothorax and pleural effusion is still in its developmental stages and faces some limitations. Current algorithms often rely on comparisons to baseline measurements, which may not always be available in acute clinical settings. Additionally, while EIT has shown good correlation with traditional imaging methods, further validation against gold standard techniques is needed to establish its reliability across various clinical scenarios.

Limitation of EIT

Although EIT is a valuable tool for real-time lung monitoring, it has limitations. Accurate measurements require proper belt placement, which can be challenging in cases of spinal injuries or damaged skin. EIT is contraindicated in patients with pacemakers due to interference risks, and defibrillation should not coincide with EIT use. Measurements are sensitive to movement artifacts from body repositioning, electrode pressure, or rapid fluid shifts, although regional ventilation and compliance data are unaffected. Image quality may be poor in morbidly obese patients, and EIT's cross-sectional view (5–10 cm) assumes uniform behavior across the lung, which may not always be accurate. Furthermore, EIT provides relative, not absolute, impedance values, requiring baseline references for interpretation. While EIT effectively analyzes ventral-to-dorsal ventilation distribution, it lacks cranial-to-caudal coverage, limiting its scope in some cases. Proper belt positioning and careful interpretation remain key to maximizing EIT’s clinical utility.

Future directions

The future of EIT in critical care is on the cusp of significant breakthroughs, with several promising avenues of research emerging. As this innovative technology continues to evolve, researchers and clinicians are exploring novel approaches to enhance its capabilities and expand its applications in intensive care environments. A particularly promising direction focuses on the development of advanced EIT algorithms capable of simultaneously assessing ventilation and perfusion in real-time. This approach holds the potential to transform the management of complex respiratory conditions such as ARDS and pulmonary embolism. However, the journey towards clinical implementation is not without challenges. Ongoing efforts are required to standardize measurement techniques and interpretation criteria, while further validation against established imaging modalities is essential to confirm EIT's accuracy and reliability across diverse clinical scenarios. Additionally, the development of algorithms that do not rely on baseline measurements would significantly enhance EIT's applicability in acute settings. The integration of artificial intelligence and machine learning with EIT presents a paradigm-shifting opportunity. These cutting-edge technologies could revolutionize image reconstruction, automate lung contour detection, refine signal filtering, and correct artifacts. Furthermore, they have the potential to unveil subtle patterns in ventilation-perfusion relationships that may elude human observation, potentially enabling earlier detection of patient deterioration or treatment response. Three-dimensional EIT represents another frontier of innovation. By employing multiple electrode belts and sophisticated reconstruction algorithms, 3D-EIT could dramatically improve spatial resolution and image quality. This advancement promises more precise ventilation-perfusion assessments and a reduction in artifacts caused by organ movement, offering a more comprehensive and accurate view of lung function.

CONCLUSION

EIT has revolutionized critical care by offering real-time, non-invasive insights into regional lung function. Its ability to optimize ventilation strategies, guide interventions, and assess ventilation-perfusion matching has transformed patient management in intensive care units. While challenges remain, such as artifact sensitivity and application in specific patient populations, EIT's potential to personalize respiratory care is undeniable. The future of EIT is promising, with ongoing advancements in image reconstruction, artificial intelligence integration, and three-dimensional imaging set to expand its capabilities. These innovations will likely enhance diagnostic precision and enable more targeted interventions, further improving patient outcomes. As EIT technology matures, its role in critical care will undoubtedly grow. Through continued research, validation, and standardization efforts, EIT is poised to become an indispensable tool in intensive care medicine. By providing a window into the complex dynamics of lung function, EIT empowers clinicians to make informed decisions and deliver tailored care. In essence, EIT represents a paradigm shift in critical care monitoring. Its evolution from a novel technology to a cornerstone of respiratory management exemplifies the power of innovation in medicine. As we look to the future, EIT stands as a beacon of progress, promising a new era of personalized, precise, and effective critical care.

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REFERENCES

1. Greene KE, Peters JI. PATHOPHYSIOLOGY OF ACUTE RESPIRATORY FAILURE. Clinics in Chest Medicine. 1994;15(1):1-12.
2. Slutsky AS, Ranieri VM. Ventilator-induced lung injury. N Engl J Med. 2013;369(22):2126-36.
3. Costa EL, Lima RG, Amato MB. Electrical impedance tomography. Curr Opin Crit Care. 2009;15(1):18-24.
4. Frerichs I, Hahn G, Schiffmann H, Berger C, Hellige G. Monitoring regional lung ventilation by functional electrical impedance tomography during assisted ventilation. Ann N Y Acad Sci. 1999;873:493-505.
5. Victorino JA, Borges JB, Okamoto VN, Matos GF, Tucci MR, Caramez MP, et al. Imbalances in regional lung ventilation: a validation study on electrical impedance tomography. Am J Respir Crit Care Med. 2004;169(7):791-800.
6. Frerichs I, Hinz J, Herrmann P, Weisser G, Hahn G, Dudykevych T, et al. Detection of local lung air content by electrical impedance tomography compared with electron beam CT. J Appl Physiol (1985). 2002;93(2):660-6.
7. Wolf GK, Arnold JH. Noninvasive assessment of lung volume: respiratory inductance plethysmography and electrical impedance tomography. Crit Care Med. 2005;33(3 Suppl):S163-9.
8. Meier T, Luepschen H, Karsten J, Leibecke T, Grossherr M, Gehring H, et al. Assessment of regional lung recruitment and derecruitment during a PEEP trial based on electrical impedance tomography. Intensive Care Med. 2008;34(3):543-50.
9. Sang L, Zhao Z, Lin Z, Liu X, Zhong N, Li Y. A narrative review of electrical impedance tomography in lung diseases with flow limitation and hyperinflation: methodologies and applications. Annals of Translational Medicine. 2020;8(24):1688.
10. Jonkman AH, Alcala GC, Pavlovsky B, Roca O, Spadaro S, Scaramuzzo G, et al. Lung Recruitment Assessed by Electrical Impedance Tomography (RECRUIT): A Multicenter Study of COVID-19 Acute Respiratory Distress Syndrome. Am J Respir Crit Care Med. 2023;208(1):25-38.
11. Lima JNG, Fontes MS, Szmuszkowicz T, Isola AM, Maciel AT. Electrical impedance tomography monitoring during spontaneous breathing trial: Physiological description and potential clinical utility. Acta Anaesthesiol Scand. 2019;63(8):1019-27.
12. Longhini F, Maugeri J, Andreoni C, Ronco C, Bruni A, Garofalo E, et al. Electrical impedance tomography during spontaneous breathing trials and after extubation in critically ill patients at high risk for extubation failure: a multicenter observational study. Ann Intensive Care. 2019;9(1):88.
13. Li Z, Zhang Z, Xia Q, Xu D, Qin S, Dai M, et al. First Attempt at Using Electrical Impedance Tomography to Predict High Flow Nasal Cannula Therapy Outcomes at an Early Phase. Front Med (Lausanne). 2021;8:737810.
14. Artaud-Macari E, Bubenheim M, Le Bouar G, Carpentier D, Grangé S, Boyer D, et al. High-flow oxygen therapy versus noninvasive ventilation: a randomised physiological crossover study of alveolar recruitment in acute respiratory failure. ERJ Open Res. 2021;7(4).
15. Lobo B, Hermosa C, Abella A, Gordo F. Electrical impedance tomography. Ann Transl Med. 2018;6(2):26.
16. Piraino T. An Introduction to the Clinical Application and Interpretation of Electrical Impedance Tomography. Respir Care. 2022;67(6):721-9.
17. Bodenstein M, David M, Markstaller K. Principles of electrical impedance tomography and its clinical application. Crit Care Med. 2009;37(2):713-24.
18. Costa EL, Borges JB, Melo A, Suarez-Sipmann F, Toufen C, Jr., Bohm SH, et al. Bedside estimation of recruitable alveolar collapse and hyperdistension by electrical impedance tomography. Intensive Care Med. 2009;35(6):1132-7.
19. Frerichs I, Amato MB, Van Kaam AH, Tingay DG, Zhao Z, Grychtol B, et al. Chest electrical impedance tomography examination, data analysis, terminology, clinical use and recommendations: consensus statement of the TRanslational EIT developmeNt stuDy group. Thorax. 2017;72(1):83-93.
20. Karsten J, Stueber T, Voigt N, Teschner E, Heinze H. Influence of different electrode belt positions on electrical impedance tomography imaging of regional ventilation: a prospective observational study. Crit Care. 2016;20:3.
21. Mansouri S, Alharbi Y, Haddad F, Chabcoub S, Alshrouf A, Abd-Elghany AA. Electrical Impedance Tomography - Recent Applications and Developments. J Electr Bioimpedance. 2021;12(1):50-62.
22. Battaglini D, Robba C, Caiffa S, Ball L, Brunetti I, Loconte M, et al. Chest physiotherapy: An important adjuvant in critically ill mechanically ventilated patients with COVID-19. Respiratory Physiology & Neurobiology. 2020;282:103529.
23. Quintana ARG, Atallah ÁN, Saconato H, Wale JL, Melnik T. Respiratory therapy for removing bronchial secretions in mechanically ventilated adult patients. The Cochrane Database of Systematic Reviews. 2018;2018(2).
24. Muders T, Luepschen H, Zinserling J, Greschus S, Fimmers R, Guenther U, et al. Tidal recruitment assessed by electrical impedance tomography and computed tomography in a porcine model of lung injury*. Critical Care Medicine. 2012;40(3):903-11.
25. Frerichs I, Dargaville PA, Van Genderingen H, Morel DR, Rimensberger PC. Lung volume recruitment after surfactant administration modifies spatial distribution of ventilation. American Journal of Respiratory and Critical Care Medicine. 2006;174(7):772-9.
26. He LLH, Foo G, Kenna KR, Douglas E, Fatmous M, Sutton RJ, et al. Lung ultrasound detects regional aeration inhomogeneity in ventilated preterm lambs. Pediatric Research. 2024;95(1):129-34.
27. Bellani G, Laffey JG, Pham T, Fan E, Brochard L, Esteban A, et al. Epidemiology, Patterns of Care, and Mortality for Patients With Acute Respiratory Distress Syndrome in Intensive Care Units in 50 Countries. Jama. 2016;315(8):788-800.
28. Ranieri VM, Suter PM, Tortorella C, De Tullio R, Dayer JM, Brienza A, et al. Effect of mechanical ventilation on inflammatory mediators in patients with acute respiratory distress syndrome: a randomized controlled trial. Jama. 1999;282(1):54-61.
29. Talmor D, Sarge T, Malhotra A, O'Donnell CR, Ritz R, Lisbon A, et al. Mechanical ventilation guided by esophageal pressure in acute lung injury. N Engl J Med. 2008;359(20):2095-104.

30. Grasso S, Terragni P, Mascia L, Fanelli V, Quintel M, Herrmann P, et al. Airway pressure-time curve profile (stress index) detects tidal recruitment/hyperinflation in experimental acute lung injury. Crit Care Med. 2004;32(4):1018-27.
31. Jonkman AH, Alcala GC, Pavlovsky B, Roca O, Spadaro S, Scaramuzzo G, et al. Lung recruitment assessed by electrical impedance tomography (RECRUIT): a multicenter study of COVID-19 acute respiratory distress syndrome. American Journal of Respiratory and Critical Care Medicine. 2023;208(1):25-38.
32. Zhao Z, Lee LC, Chang MY, Frerichs I, Chang HT, Gow CH, et al. The incidence and interpretation of large differences in EIT-based measures for PEEP titration in ARDS patients. J Clin Monit Comput. 2020;34(5):1005-13.
33. Brower RG, Matthay MA, Morris A, Schoenfeld D, Thompson BT, Wheeler A. Ventilation with lower tidal volumes as compared with traditional tidal volumes for acute lung injury and the acute respiratory distress syndrome. N Engl J Med. 2000;342(18):1301-8.
34. Brower RG, Lanken PN, MacIntyre N, Matthay MA, Morris A, Ancukiewicz M, et al. Higher versus lower positive end-expiratory pressures in patients with the acute respiratory distress syndrome. N Engl J Med. 2004;351(4):327-36.
35. Cavalcanti AB, Suzumura É A, Laranjeira LN, Paisani DM, Damiani LP, Guimarães HP, et al. Effect of Lung Recruitment and Titrated Positive End-Expiratory Pressure (PEEP) vs Low PEEP on Mortality in Patients With Acute Respiratory Distress Syndrome: A Randomized Clinical Trial. Jama. 2017;318(14):1335-45.
36. Hodgson CL, Cooper DJ, Arabi Y, King V, Bersten A, Bihari S, et al. Maximal Recruitment Open Lung Ventilation in Acute Respiratory Distress Syndrome (PHARLAP). A Phase II, Multicenter Randomized Controlled Clinical Trial. Am J Respir Crit Care Med. 2019;200(11):1363-72.
37. Beitler JR, Sarge T, Banner-Goodspeed VM, Gong MN, Cook D, Novack V, et al. Effect of Titrating Positive End-Expiratory Pressure (PEEP) With an Esophageal Pressure-Guided Strategy vs an Empirical High PEEP-Fio2 Strategy on Death and Days Free From Mechanical Ventilation Among Patients With Acute Respiratory Distress Syndrome: A Randomized Clinical Trial. Jama. 2019;321(9):846-57.
38. Pintado MC, de Pablo R, Trascasa M, Milicua JM, Rogero S, Daguerre M, et al. Individualized PEEP setting in subjects with ARDS: a randomized controlled pilot study. Respir Care. 2013;58(9):1416-23.
39. Albaiceta GM, Taboada F, Parra D, Luyando LH, Calvo J, Menendez R, et al. Tomographic study of the inflection points of the pressure-volume curve in acute lung injury. Am J Respir Crit Care Med. 2004;170(10):1066-72.
40. Amato MB, Meade MO, Slutsky AS, Brochard L, Costa EL, Schoenfeld DA, et al. Driving pressure and survival in the acute respiratory distress syndrome. N Engl J Med. 2015;372(8):747-55.
41. Songsangvorn N, Xu Y, Lu C, Rotstein O, Brochard L, Slutsky AS, et al. Electrical impedance tomography-guided positive end-expiratory pressure titration in ARDS: a systematic review and meta-analysis. Intensive Care Med. 2024;50(5):617-31.
42. V. C. Veiga ISM, C. Zandonai, et. al. Comparison of 4 Methods of Positive End Expiratory Pressure (PEEP) Titration in Acute Respiratory Distress Syndrome (ARDS): PEEP/FiO2 Table, Best Compliance, Esophageal Catheter and Electric Impedance Tomography (EIT): A Randomized Controlled Trial. Am J Respir Crit Care Med. 2020;201(A1138).
43. Gao Y, He H, Chi Y, Frerichs I, Long Y, Zhao Z. Electrical impedance tomography guided positive end-expiratory pressure titration in critically ill and surgical adult patients: a systematic review and meta-analysis. BMC Pulmonary Medicine. 2024;24(1):582.
44. Eronia N, Mauri T, Maffezzini E, Gatti S, Bronco A, Alban L, et al. Bedside selection of positive end-expiratory pressure by electrical impedance tomography in hypoxemic patients: a feasibility study. Ann Intensive Care. 2017;7(1):76.
45. Jimenez JV, Munroe E, Weirauch AJ, Fiorino K, Culter CA, Nelson K, et al. Electric impedance tomography-guided PEEP titration reduces mechanical power in ARDS: a randomized crossover pilot trial. Crit Care. 2023;27(1):21.
46. Franchineau G, Bréchot N, Lebreton G, Hekimian G, Nieszkowska A, Trouillet JL, et al. Bedside Contribution of Electrical Impedance Tomography to Setting Positive End-Expiratory Pressure for Extracorporeal Membrane Oxygenation-treated Patients with Severe Acute Respiratory Distress Syndrome. Am J Respir Crit Care Med. 2017;196(4):447-57.
47. Zhao Y, Su L, He H, Liu D, Long Y. Whole-process respiratory management strategies based on electrical impedance tomography in a pregnant woman with diffuse alveolar hemorrhage induced by systemic lupus erythematosus under veno-venous extracorporeal membrane oxygenation. Pulm Circ. 2023;13(4):e12302.
48. Zhao Z, Fischer R, Frerichs I, Müller-Lisse U, Möller K. Regional ventilation in cystic fibrosis measured by electrical impedance tomography. J Cyst Fibros. 2012;11(5):412-8.
49. Zhao Z, Chang MY, Frerichs I, Zhang JH, Chang HT, Gow CH, et al. Regional air trapping in acute exacerbation of obstructive lung diseases measured with electrical impedance tomography: a feasibility study. Minerva Anestesiol. 2020;86(2):172-80.
50. Mueller JL, Muller P, Mellenthin M, Murthy R, Capps M, Alsaker M, et al. Estimating regions of air trapping from electrical impedance tomography data. Physiol Meas. 2018;39(5):05nt1.
51. Frerichs I, Zhao Z, Becher T, Zabel P, Weiler N, Vogt B. Regional lung function determined by electrical impedance tomography during bronchodilator reversibility testing in patients with asthma. Physiol Meas. 2016;37(6):698-712.
52. Vogt B, Zhao Z, Zabel P, Weiler N, Frerichs I. Regional lung response to bronchodilator reversibility testing determined by electrical impedance tomography in chronic obstructive pulmonary disease. Am J Physiol Lung Cell Mol Physiol. 2016;311(1):L8-l19.
53. Karagiannidis C, Waldmann AD, Róka PL, Schreiber T, Strassmann S, Windisch W, et al. Regional expiratory time constants in severe respiratory failure estimated by electrical impedance tomography: a feasibility study. Crit Care. 2018;22(1):221.
54. Kostakou E, Barrett N, Camporota L. Electrical impedance tomography to determine optimal positive end-expiratory pressure in severe chronic obstructive pulmonary disease. Crit Care. 2016;20(1):295.
55. Sun Q, Liu L, Pan C, Zhao Z, Xu J, Liu A, et al. Effects of neurally adjusted ventilatory assist on air distribution and dead space in patients with acute exacerbation of chronic obstructive pulmonary disease. Crit Care. 2017;21(1):126.
56. Sang L, Zhao Z, Yun PJ, Frerichs I, Möller K, Fu F, et al. Qualitative and quantitative assessment of pendelluft: a simple method based on electrical impedance tomography. Ann Transl Med. 2020;8(19):1216.
57. Qu S, Feng E, Dong D, Yang L, Dai M, Frerichs I, et al. Early screening of lung function by electrical impedance tomography in people with normal spirometry reveals unrecognized pathological features. Nature Communications. 2025;16(1):622.
58. Radke OC, Schneider T, Heller AR, Koch T. Spontaneous breathing during general anesthesia prevents the ventral redistribution of ventilation as detected by electrical impedance tomography: a randomized trial. Anesthesiology. 2012;116(6):1227-34.
59. Zhao Z, Peng SY, Chang MY, Hsu YL, Frerichs I, Chang HT, et al. Spontaneous breathing trials after prolonged mechanical ventilation monitored by electrical impedance tomography: an observational study. Acta Anaesthesiol Scand. 2017;61(9):1166-75.
60. Bickenbach J, Czaplik M, Polier M, Marx G, Marx N, Dreher M. Electrical impedance tomography for predicting failure of spontaneous breathing trials in patients with prolonged weaning. Crit Care. 2017;21(1):177.
61. Li J, Zeng F, Yang F, Luo X, Liu R, Ren Y, et al. Electrical Impedance Tomography Predicts Weaning Success in Adult Patients With Delayed Upper Abdominal Surgery: A Single-Center Retrospective Study. Front Med (Lausanne). 2021;8:748493.
62. Riera J, Pérez P, Cortés J, Roca O, Masclans JR, Rello J. Effect of high-flow nasal cannula and body position on end-expiratory lung volume: a cohort study using electrical impedance tomography. Respir Care. 2013;58(4):589-96.
63. Mauri T, Turrini C, Eronia N, Grasselli G, Volta CA, Bellani G, et al. Physiologic Effects of High-Flow Nasal Cannula in Acute Hypoxemic Respiratory Failure. Am J Respir Crit Care Med. 2017;195(9):1207-15.
64. Rauseo M, Mirabella L, Laforgia D, Lamanna A, Vetuschi P, Soriano E, et al. A Pilot Study on Electrical Impedance Tomography During CPAP Trial in Patients With Severe Acute Respiratory Syndrome Coronavirus 2 Pneumonia: The Bright Side of Non-invasive Ventilation. Front Physiol. 2021;12:728243.
65. Wang YX, Zhong M, Dong MH, Song JQ, Zheng YJ, Wu W, et al. Prone positioning improves ventilation-perfusion matching assessed by electrical impedance tomography in patients with ARDS: a prospective physiological study. Crit Care. 2022;26(1):154.
66. Bein T, Ploner F, Ritzka M, Pfeifer M, Schlitt HJ, Graf BM. No change in the regional distribution of tidal volume during lateral posture in mechanically ventilated patients assessed by electrical impedance tomography. Clin Physiol Funct Imaging. 2010;30(4):234-40.
67. Otis AB, McKerrow CB, Bartlett RA, Mead J, McIlroy MB, Selver-Stone NJ, et al. Mechanical factors in distribution of pulmonary ventilation. J Appl Physiol. 1956;8(4):427-43.
68. Yoshida T, Torsani V, Gomes S, De Santis RR, Beraldo MA, Costa EL, et al. Spontaneous effort causes occult pendelluft during mechanical ventilation. Am J Respir Crit Care Med. 2013;188(12):1420-7.
69. Chi Y, Zhao Z, Frerichs I, Long Y, He H. Prevalence and prognosis of respiratory pendelluft phenomenon in mechanically ventilated ICU patients with acute respiratory failure: a retrospective cohort study. Annals of Intensive Care. 2022;12(1):22.
70. Coppadoro A, Grassi A, Giovannoni C, Rabboni F, Eronia N, Bronco A, et al. Occurrence of pendelluft under pressure support ventilation in pa-

tients who failed a spontaneous breathing trial: an observational study. Annals of Intensive Care. 2020;10(1):39.

71. Borges JB, Suarez-Sipmann F, Bohm SH, Tusman G, Melo A, Maripuu E, et al. Regional lung perfusion estimated by electrical impedance tomography in a piglet model of lung collapse. J Appl Physiol (1985). 2012;112(1):225-36.
72. Bluth T, Kiss T, Kircher M, Braune A, Bozsak C, Huhle R, et al. Measurement of relative lung perfusion with electrical impedance and positron emission tomography: an experimental comparative study in pigs. Br J Anaesth. 2019;123(2):246-54.
73. Xu M, He H, Long Y. Lung Perfusion Assessment by Bedside Electrical Impedance Tomography in Critically Ill Patients. Front Physiol. 2021;12:748724.
74. Spinelli E, Kircher M, Stender B, Ottaviani I, Basile MC, Marongiu I, et al. Unmatched ventilation and perfusion measured by electrical impedance tomography predicts the outcome of ARDS. Crit Care. 2021;25(1):192.
75. Prins SA, Weller D, Labout JAM, den Uil CA. Electrical Impedance Tomography As a Bedside Diagnostic Tool for Pulmonary Embolism. Crit Care Explor. 2023;5(1):e0843.
76. He H, Jiang J, Xu M, Yuan S, Long Y, Chi Y, et al. Saline bolus-based electrical impedance tomography method for rapid bedside assessment of regional lung perfusion during ECMO therapy. Critical Care. 2022;26(1):266.
77. Pavlovsky B, Pesenti A, Spinelli E, Scaramuzzo G, Marongiu I, Tagliabue P, et al. Effects of PEEP on regional ventilation-perfusion mismatch in the acute respiratory distress syndrome. Crit Care. 2022;26(1):211.
78. Costa EL, Chaves CN, Gomes S, Beraldo MA, Volpe MS, Tucci MR, et al. Real-time detection of pneumothorax using electrical impedance tomography. Critical care medicine. 2008;36(4):1230-8.
79. Bhatia R, Schmolzer G, Davis PG, Tingay DG. 505 Electrical Impedance Tomography (EIT) Can Rapidly Detect Small Pneumothoraces. Pediatric Research. 2010;68(1):258-9.
80. Arad M, Zlochiver S, Davidson T, Shoenfeld Y, Adunsky A, Abboud S. The detection of pleural effusion using a parametric EIT technique. Physiol Meas. 2009;30(4):421-8.