

Application and Progress of Resistive Tomography in the Treatment of Acute Respiratory Distress Syndrome

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Abstract: Acute Respiratory Distress Syndrome (ARDS), a clinically common critical condition caused by acute lung injury, presents significant individual variations, treatment challenges, and high mortality rates, making personalized monitoring essential. Electrical Impedance Tomography (EIT), with its bedside-friendly, non-invasive, radiation-free, and dynamic functional imaging features, is increasingly being applied in ARDS patient management. With continuous advancements in technology and algorithms, EIT imaging now enables 3D real-time lung function analysis, providing comprehensive pulmonary data for ARDS patients. This study aims to provide clinical reference for the application of EIT in ARDS patients.

Keywords: Resistive Tomography; Acute Respiratory Distress Syndrome; Mechanical Ventilation; Pulmonary Ventilation.

1. Background

Acute respiratory distress syndrome (ARDS) was first described in 1967, characterized by a sudden clinical presentation of significant hypoxemia accompanied by diffuse pulmonary infiltration on imaging [1]. In 1988, the Pulmonary Injury Score was introduced as a clinical definition to more precisely quantify the severity of physiological respiratory injury [2]. Since then, the clinical definition of ARDS has undergone multiple revisions. Each update aims to improve patient identification for better clinical care, epidemiological studies, observational research, and interventional trials. The 2012 Berlin Definition, proposed by the Working Group on ARDS Definitions convened by the European Society of Intensive Care Medicine (ESICM) in Berlin [3], defines ARDS as acute, diffuse, inflammatory lung injury characterized by increased pulmonary vascular permeability, epithelial permeability, pulmonary edema, and gravity-dependent atelectasis—all leading to loss of ventilated lung tissue [3]. Although the Berlin Definition marked a significant step forward, it revealed limitations that were soon identified post-publication. Specifically, it became apparent that in resource-constrained settings—such as those lacking mechanical ventilation or unable to meet patients' needs for non-invasive or invasive ventilation—the definition's applicability faces challenges [4]. In June 2021, a global consensus meeting was convened with extensive international representation and participation from 32 ARDS experts from diverse backgrounds in the field of critical care. The meeting proposed recommendations for updating the definition of ARDS and established a new global definition [5]. Based on current evidence and clinical practice, the updated global definition of ARDS proposes improvements to the Berlin ARDS definition. It includes patients receiving high-flow nasal oxygen therapy (HFNO) at $\geq 30\text{L/min}$ in the diagnosis, and allows pulse oximetry to replace arterial blood gas oxygen partial pressure for ARDS diagnosis. Patients in resource-limited environments (small hospitals lacking blood gas analysis, CT scans, and mechanical ventilation) will no longer be excluded from ARDS definitions and may be

included in epidemiological studies and clinical trials. When chest X-rays and/or CT scans are unavailable, ultrasound images obtained by trained ultrasound operators can serve as alternatives to radiographic imaging [5].

2. Introduction and Function of EIT

Electrical Impedance Tomography (EIT) is a non-invasive, radiation-free regional lung imaging technique that can be performed at the patient's bedside. It has been proven effective in detecting physiological and pathophysiological changes in regional pulmonary ventilation [6]. EIT delivers small alternating currents through 8-32 evenly spaced electrodes arranged circumferentially along the chest wall [7], depending on the model and manufacturer. The principle of EIT involves measuring voltage changes induced by weak alternating currents applied to the skin surface to detect electrical impedance distribution. By dynamically monitoring real-time ventilation and blood flow patterns in the chest cavity, EIT guides perioperative respiratory parameter adjustments [8,9], ensuring patient safety, reducing complications, and promoting rapid recovery. Changes in pulmonary ventilation during respiration cause corresponding EIT impedance variations, enabling effective monitoring of ventilatory status [10]. With a frame rate of 20-50 images per second, EIT offers both high temporal resolution and sensitivity for pulmonary ventilation monitoring [11]. This functional monitoring device is particularly suitable for treating severe acute respiratory failure patients in intensive care units. Since examinations can be performed at the bedside without known risks, there is no need to transfer critically ill patients to the radiology departments [12].

3. EIT and ARDS

3.1. EIT Guided Individualized Titration of PEEP in ARDS Patients

Various PEEP titration methods are employed in ARDS patients, including stress index method, esophageal pressure measurement, gas exchange analysis, compliance assessment, PEEP reduction protocol, pressure-volume curve analysis,

pulmonary volume measurement, and imaging techniques [13]. Imaging modalities encompass CT scans, ultrasound, and EIT. Notably, EIT plays a pivotal role in evaluating alveolar re-expansion. Studies demonstrate that EIT-guided PEEP titration correlates with enhanced respiratory compliance and significantly elevated PaO₂/FiO₂ ratios, achieving comparable outcomes to conventional approaches. Furthermore, EIT maintains an optimal balance between safety and efficacy compared to standard protocols. The data from EIT provide clinicians with comprehensive evaluations supported by robust evidence [14]. This non-invasive bedside technique enables real-time monitoring of impedance changes associated with pulmonary states, particularly ventilatory resistance variations during PEEP titration in ARDS patients [15,16]. EIT-powered real-time pulmonary function monitoring allows personalized PEEP calibration, which substantially improves lung compliance while reducing mechanical power consumption [17]. As a non-invasive imaging modality delivering real-time regional lung information, EIT facilitates individualized PEEP optimization. This approach holds promise for improving respiratory mechanics, as precise PEEP settings are critical determinants of ventilator-induced lung injury (VILI) in ARDS patients [18]. EIT not only enables bedside evaluation for personalized PEEP selection but also helps identify pulmonary re-expansion and strike an optimal balance between regional lung re-expansion and overdistension [19]. Early individualized PEEP optimization through EIT may accelerate organ function recovery. Experimental studies showed a 6% absolute reduction in mortality rates in the EIT group—a statistically insignificant difference that remains clinically significant. This finding warrants further investigation to validate the clinical benefits of EIT-guided PEEP adjustment for ARDS patients [20]. Compared with traditional holistic respiratory mechanics parameters, EIT provides clinicians with regional pulmonary biomechanical data, theoretically enabling more precise PEEP customization that enhances lung protection [11].

3.2. EIT Guided Prone Ventilation in ARDS Patients

Prolonged prone position ventilation (PPV) can reduce mortality in patients with acute respiratory distress syndrome (ARDS), serving as a simple yet effective intervention [21]. Before intubation and during invasive ventilation, the prone position has been widely used to treat COVID-19 Acute Respiratory Distress Syndrome (C-ARDS) [22,23]. Currently recognized as a cornerstone of C-ARDS ventilatory management [24], PPV reduces ventilator-induced lung injury (VILI) through improved pulmonary homogeneity, enhanced lung re-expansion, and reduced pulmonary overdistension [25]. This positioning proves particularly effective in addressing ARDS-related atelectasis and lung collapse while improving hypoxia. In contrast, supine ventilation exhibits disproportionate gas-to-blood perfusion ratios. Within gravity-dependent regions, abundant blood flow in lung tissues leads to alveolar collapse or atelectasis [26], resulting in inadequate ventilation and decreased gas-to-blood ratio. Conversely, non-gravity dependent areas show excessive lung expansion with insufficient blood flow in alveolar walls, increasing gas-to-blood ratio. By altering back ventilation and anterior chest wall perfusion, PPV homogenizes intrapulmonary gas distribution, thereby enhancing gas-to-blood ratio [27]. Studies have demonstrated

[28] that prone positioning with mechanical ventilation demonstrates superior efficacy in improving blood gas status, reducing right ventricular load, and promoting recovery in patients with moderate-to-severe acute respiratory distress syndrome (ARDS). A prospective physiological study [29] revealed that bedside end-tidal time (EIT) monitoring supports extended prone ventilation duration, which enhances bilateral lung ventilation/perfusion and improves ventilator-perfusion coordination, thereby optimizing oxygenation. A Meta-analysis [30] found compelling evidence that VV-ECMO and prone ventilation strategies reduce ARDS mortality rates compared to low-to-moderate tidal volume (VT) approaches in critically ill patients with severe ARDS and PaO₂/FiO₂ ratios below 80 mmHg. Research [31] further indicates that EIT monitoring enables precise pulmonary ventilation partitioning (PPV) – effectively managing both gravity-dependent and non-gravity-dependent zones, reducing pleural space vertical pressure gradients, decreasing lung elastic resistance, and optimizing dead-space-to-diversion ratio [32]. In critical care medicine, EIT has become a pivotal intervention for PPV management in ARDS patients.

3.3. EIT Guided Mechanical Ventilation Withdrawal in ARDS Patients

Mechanical ventilation forms the cornerstone of ARDS treatment for critically ill patients in intensive care units. While invasive mechanical ventilation can save lives, it carries risks of pulmonary injury [33]. For patients receiving invasive ventilation, determining the optimal timing for weaning is critical. The Spontaneous Breathing Trial (SBT), a widely used clinical test, guides physicians in selecting appropriate weaning windows. During SBT, patients undergo challenges requiring maintained adequate ventilation and oxygenation while gradually reducing or discontinuing ventilator support. Post-weaning, Exhaled Inhalation Testing (EIT) helps assess individual physiological trends to identify optimal weaning intervals. EIT evaluates changes in pulmonary ventilation distribution and quantifies electrical characteristic heterogeneity during SBT, providing insights into potential physiological factors contributing to weaning failure [34].

3.4. EIT Guided Oxygen Therapy Prognosis in ARDS Patients

Currently, High-Flow Nasal Cannula (HFNC) therapy is a widely adopted measure to reduce mechanical ventilation duration [35]. Recent studies indicate that it not only improves respiratory drive and biomechanics but also enhances CO₂ clearance, reducing 90-day mortality rates [36,37]. Emerging research demonstrates that Endotracheal Intubation (EIT) can help identify lung overdistension caused by HFNC [38]. EIT monitoring shows that HFNC reduces respiratory rate and improves oxygenation through increased end-expiratory lung volume (EELV) and tidal volume [39]. Mauri et al. [40] also found that HFNC flow rates improve pulmonary ventilation in patients with acute respiratory failure. However, Piastra et al. [41] reported uncommon barotrauma in infants treated with HFNC (2 L/kg/min, FiO₂ 0.6). Therefore, pulmonary injury induced by HFNC therapy warrants attention. Lung overdistension, pulmonary pressure, and lung strain are primary factors contributing to ventilator-induced lung injury (VILI) [42]. Studies show that HFNC exhibits varying responses to local ventilation patterns (compensation, decompensation, and overdistension), with

outcomes differing among individuals. EIT-assisted identification of these ventilatory patterns may guide post-extubation HFNC management. Therefore, the development of individualized HFNC programs guided by EIT to improve the prognosis of ARDS patients is of great significance in critical care medicine.

3.5. EIT Monitoring of Pulmonary Perfusion in ARDS Patients

The clinical management of patients with impaired gas exchange may be improved through bedside measurement of local ventilation and perfusion. While the Multiple Inert Gas Elimination Technique (MIGET) can assess overall ventilation and perfusion, it remains a cumbersome technique in clinical practice [43]. EIT, a non-radiation technology, measures relative ventilation and potential perfusion based on chest electrical conductivity. Since ventilation causes proportional changes in conductivity, reliable measurements can be obtained through EIT [44-45]. Non-uniform distribution of ventilation (V') and perfusion (Q), along with areas of hyperperfusion and ventilation exceeding perfusion, serve as markers of acute respiratory distress [50] syndrome (ARDS) [46]. The V'/Q ratio ranges from 0 (shunt chamber) to infinity (dead space chamber). When V'/Q equals or exceeds 1 (ideal V'/Q match), it indicates poor gas exchange in lung units, leading to hypoxemia and/or hypercapnia – factors associated with poor prognosis in ARDS patients [47-48]. Experimental studies [49-51] also demonstrate that significant local ventilation or perfusion deficits can cause bilateral diffuse lung injury in healthy animals through multiple mechanisms. These include localized perfusion insufficiency, alveolar collapse, redistribution of ventilation in hypo-perfusion zones, alveolar hypocapnia, and inflammation. Notably, the physiological compensation of shunting and dead space plays a critical role in the development of new-onset pulmonary injury. Therefore, V/Q imbalance not only serves as a prognostic marker for ARDS severity but also represents a mechanism of lung injury. EIT not only dynamically evaluates the distribution of ventilation and perfusion regional fractions within the lungs but also precisely quantifies the relative V/Q ratio (i.e., the percentage of V' divided by the percentage of Q reaching each pixel) [52]. In the study by Leali et al. [53], two physiological compensation indicators of shunting and dead space derived from EIT's V/Q maps were analyzed. These findings elucidated the physiological interactions between these metrics and oxygenation levels, ventilation settings, and clinical outcomes. This demonstrates that bedside EIT-based V/Q imaging, as a valuable non-invasive measurement for assessing ARDS severity, may not only guide personalized treatment but also inform early-stage disease monitoring during less advanced clinical phases.

3.6. EIT-guided Veno-ven Extracorporeal Membrane Oxygenation (V-V ECMO) in ARDS Patients

Venous-venous extracorporeal membrane oxygenation (V-V ECMO) is a form of extracorporeal life support that provides blood with adequate extracorporeal oxygenation and carbon dioxide removal, serving as an alternative to cardiopulmonary function [54]. V-V ECMO can significantly reduce tidal volume, respiratory rate, plateau pressure, and drive pressure [55-56]. Studies have shown that EIT is a useful monitoring technique for individualizing PEEP levels

in V-V ECMO patients receiving low tidal volume over-protective ventilation. The significance of this technology lies in its ability to detect pulmonary collapse and hyperventilation at the bedside, as well as assess regional ventilation distribution, thereby enabling personalized ventilatory parameter adjustments [57]. Three-dimensional (3D) resistivity tomography (EIT) is a recently developed imaging technique for lung ventilation and perfusion. Traditional two-dimensional (2D) EIT only provides information on a single plane, which may overlook critical details. By offering lung information across three planes, 3D EIT can overcome these limitations [58]. Recently, the saline perfusion method of 3D EIT has been used to evaluate mismatch between local lung perfusion and ventilation/perfusion (V/Q) in animal studies [59], though relevant research remains limited. Understanding that pulmonary ventilation cannot comprehensively assess lung physiology, and that pulmonary perfusion also significantly influences V/Q , reports indicate consistent changes in local lung ventilation and perfusion measured by EIT before and after treatment [60]. This suggests EIT may hold potential for evaluating local lung perfusion and V/Q matching during V-V ECMO therapy.

4. Issues and Prospects

Electrical Impedance Tomography (EIT), as a widely used emerging imaging technique, still has several limitations: (1) EIT provides lung tomographic imaging but cannot achieve full coverage of ventilated areas; (2) The image quality is suboptimal with relatively low spatial resolution and contrast, resulting in limited monitoring effectiveness for lung tissue and susceptibility to noise interference; (3) Patient movement can induce pulmonary functional artifacts, complicating medical interpretation of EIT images and affecting subsequent treatment; (4) There is a lack of standardized clinical indicators and operational protocols, such as the selection of PEEP titration methods and mechanical ventilation modes.

Resistive Indexing Tomography (EIT) is increasingly being applied in the treatment of acute respiratory distress syndrome (ARDS) due to its multiple advantages. With continuous advancements in technology and algorithms, EIT imaging now enables 3D real-time lung function analysis, providing comprehensive pulmonary data for ARDS patients. Future developments will integrate EIT with microwave and low-frequency ultrasound technologies to optimize the extraction and visualization of both functional and structural information. Furthermore, the integration of EIT with other respiratory monitoring devices represents a key trend in medical practice, ultimately enabling personalized treatment strategies for ARDS patients.

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