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APPLICATION AND RESEARCH PROGRESS OF INTRAOPERATIVE ELEC-TRICAL IMPEDANCE TOMOGRAPHY IN LAPAROSCOPIC SURGERY

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Abstract: Laparoscopic surgery is a surgical technique performed through small incisions in the abdomen and widely used across various surgical fields. Despite challenges such as de-creased oxygen saturation, significant bleeding, and acid-base imbalance during surgery, effective perioperative management is crucial. In recent years, lung protective ventilation strategies have shown potential advantages in preventing perioperative pulmonary com-plications. Electrical impedance tomography, a non-invasive monitoring technology, has found wide application in anesthesia perioperative and critical care management, particu-larly in real-time diagnosis of pulmonary complications and lung ventilation monitoring. This review aims to summarize the diverse applications of EIT during the perioperative period of laparoscopic surgery, providing insights to broaden clinical understanding of its advantages and disadvantages, thereby promoting its wider adoption.

Keywords: Laparoscopic Surgery, Perioperative lung protection, Electrical impedance tomography

1. MAIN TEXT

Electrical impedance tomography (EIT), a noninvasive and radiation-free monitoring technique deployable bedside, has been widely used in anesthesia care during the perioperative period and in intensive care units for the real-time diagnosis of pulmonary complications, PEEP optimization, and perioperative lung ventilation monitoring. Furthermore, the increasing utilization of EIT pulmonary perfusion imaging enhanced by hypertonic saline contrast, based on impedance changes, is gaining considerable traction in clinical practice. The expanding scope of EIT applications, including cerebral perfusion monitoring, tissue perfusion assessment, and pathologic tissue differentiation, is advancing towards clinical incorporation[1]. Despite being a relatively new and rapidly evolving technology, EIT is becoming increasingly accepted and applied in clinical settings, although it remains the focus of various controversies.

Laparoscopic surgery, also known as minimally invasive surgery, is a surgical procedure conducted through small abdominal incisions and widely applied in various surgical specialties, including gastrointestinal, gynecological, and urological fields. Despite numerous studies reporting decreased postoperative complications, challenges such as persistent oxygen saturation decline, substantial intraoperative bleeding, and disturbances in acid-base balance may still manifest during surgery, presenting new obstacles for preoperative evaluation and postoperative recovery strategies. Thus, effective perioperative management plays a vital role in the promotion and advancement of laparoscopic surgery.

In recent years, a multitude of enhanced treatment modalities and innovative instruments have been integrated into clinical practices for perioperative care, significantly improving perioperative care and accelerating surgical rehabilitation. Lung-protective ventilation strategies (LPVS) are designed to prevent alveolar overdistension and collapse, reducing the occurrence of ventilator-induced lung injury (VILI). These strategies involve specialized respiratory interventions such as manual recruitment maneuvers, controlled ventilation, and adjustment of Positive End-Expiratory Pressure (PEEP) to proactively address

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pulmonary complications in laparoscopic surgery. Several studies have validated the effectiveness of these strategies in improving intraoperative ventilation, expediting postoperative recovery, reducing complication rates, and lowering mortality, especially in at-risk populations undergoing extensive and prolonged general anesthesia[2, 3].

The main aim of this review is to consolidate the multiple applications of EIT during the perioperative phase of laparoscopic surgery and provide insights to deepen the understanding of future healthcare professionals regarding the benefits and drawbacks of EIT deployment, thereby facilitating the generation of additional applications.

2. EIT TECHNOLOGY INTRODUCTION

2.1 The Improvement of EIT Devices

In the early 1980s, Benabid first applied EIT for intracranial lesion diagnosis in the field of medicine. Subsequently, EIT began to be tested in various organ tissues. After 30 years of development, EIT-related technologies have continuously evolved, breaking through many bottlenecks[4]. Dr. Frerichs conducted extensive research in pulmonary EIT, greatly advancing the development and application of pulmonary EIT. Currently, EIT hardware systems typically employ single-source or multi-source architectures. The single-source architecture offers advantages such as small size, low power consumption, and low cost. However, the multi-source architecture, by eliminating the need for multiplexers for channel switching, can reduce the impact of stray capacitance and significantly shorten measurement time through parallel measurements. In general, the basic architecture of EIT data acquisition hardware systems includes embedded controllers, current injection modules, data acquisition modules, and remote computing devices.

With the gradual accumulation of theoretical knowledge and continuous advancements in hardware technology, several comprehensive clinical EIT devices have been introduced[5], such as Dräger's PulmoVista 500, Swisstom's BB2, and Timpel's Enlight 1800 showcased in Figure 1. These devices boast measurement accuracy exceeding 5‰ and imaging speeds of 50 frames per second. They have been effectively utilized in clinical practice, enabling functional lung ventilation imaging and continuous bedside monitoring. Demonstrating effectiveness in clinical setups, these devices enable bedside lung ventilation evaluation, characterized by non-intrusiveness, radiation-free operation, reproducibility, and real-time monitoring. In recent years, the Second Military Medical University of China and Nanjing University of Aeronautics and Astronautics have integrated deep learning methods with AI information processing in EIT. The integration of new technologies has also led to a reduction in the cost of EIT, demonstrating a better development and application prospect for pulmonary EIT.

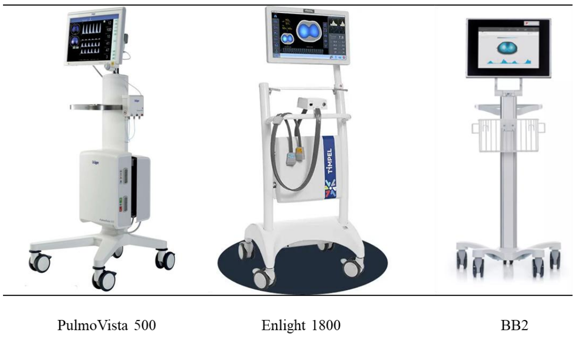

Fig. 1 Clinical EIT Devices

However, devices relying on contact electrode arrays for surface potential measurements are limited by information acquisition capacity, thereby restricting their spatial resolution. Moreover, these devices may resort to traditional medical imaging techniques like CT for locating lung lesion regions, impacting measurement accuracy due to various interference factors affecting electrical readings on the skin surface, such as humidity, roughness, and applied pressure.

Additionally, selected research groups have developed tailored portable EIT systems to meet specific needs. In 2008, Yue et al. designed the wireless EIT system OXBACT-5 based on Field Programmable Gate Array (FPGA) for impedance measurements[5]. Nevertheless, the system's bulky size and high power consumption hindered practical implementation. In 2015, Huang et al. introduced the compact EIT system DAQ for non-destructive testing of carbon nanotube films. Within the same year, Hong et al. proposed the low-power, portable

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EIT system SoC for lung ventilation monitoring. However, its wired transmission method limited its utility in intensive care units[6]. In 2016, Huang et al. developed a wearable, wireless EIT system, achieving early lung imaging[7]. In 2019, Singh et al. designed the cost-effective WMFEIT system to enhance time resolution[8]. In 2020, Jiang et al. integrated machine learning for gesture recognition into a three-dimensional EIT system based on FPGA[7]. Finally, in 2021, Fu et al. compared their wireless, low-power, compact EIT system with commercial devices for lung ventilation function monitoring[4].

In conclusion, despite significant advancements in existing EIT data acquisition hardware systems, challenges persist in achieving efficient bedside lung ventilation monitoring and assessment, encompassing stability, accuracy, power consumption, and transmission methods. Future research endeavors should prioritize addressing these challenges to establish a more dependable, portable, and compact lung ventilation monitoring impedance imaging system.

2.2 EIT Imaging Algorithm

The limitations of Electrical Impedance Tomography (EIT) technology stem from the nonlinearity and ill-posed nature of the inverse problem. Nonlinearity arises due to the 'soft field' characteristics of the current, while ill-posedness is a result of the significantly higher number of unknowns in the EIT inverse problem compared to the number of observations. A common approach involves utilizing the least squares method to linearly approximate and solve the nonlinear problem, introducing regularization terms in the equations such as L1 norm, Tikhonov, and total variation to constrain the solution. Furthermore, various techniques like the linear back-projection method[9], sensitivity matrix method[10], and singular value decomposition[11], in addition to iterative methods including the Newton-Raphson method[12], Landweber iteration[13], and conjugate gradient method[14], are employed to address these challenges.

In 2018, Liu et al. proposed a Parametric Level Set (PLS) reconstruction method based on shape-driven approaches, reframing the image reconstruction problem into a graphics recovery paradigm. This method successfully reduced the dimensionality of unknowns, facilitated flexible evolution of boundary shapes, and restored sharp lung contour features[15, 16, 17]. Subsequently, in 2020, they introduced various implicit or explicit shape reconstruction techniques, including methodologies like moving deformation components[18, 19], B-spline curves[20, 21], Boolean operations[22, 23] and super-shapes[24, 25].

Diverse network architectures are applied in Electrical Impedance Tomography (EIT) imaging, such as convolutional neural networks, adversarial neural networks, variational autoencoders, and deep neural networks. Deep learning-based EIT reconstruction methods offer significant benefits in accurately reconstructing the geometric shapes of target objects. Incorporating prior information during the learning process enhances training efficiency and image resolution, with strategies like structure-aware sparse Bayesian learning[26], supervised descent learning[27], and error-constrained networks[28] being employed. Integration of biomechanical and electrical characteristics information of the lungs in training with a 3D digital dual-lung model enables more precise reconstruction of lung conductivity changes during respiration[29]. Unlike traditional deep learning that necessitates extensive numerical or experimental simulations to construct datasets, the DeepEIT framework optimizes the conductivity distribution in the parameter space of neural networks, thereby eliminating the dataset requirement[30]. An innovative approach considers EIT image reconstruction as an equation-constrained issue by establishing the relationship between images generated from a deep generative model and conductivity change images, employing an extended alternating multiplier method to solve the augmented Lagrangian function effectively, especially in 3D time-difference chest EIT imaging[31].

In conclusion, the research on EIT image reconstruction methods is crucial for achieving accurate and stable imaging outcomes. The integration of regularization terms, deep learning, and prior information presents promising avenues for EIT image reconstruction in medical and industrial domains. However, further research is necessary to enhance the applicability and reliability of these methods before widespread adoption in clinical settings.

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2.3 EIT Clinical Observation Indicators

The efficacy and replicability of Electrical Impedance Tomography (EIT) have been substantiated through numerous experiments and clinical investigations involving comparisons with various imaging modalities such as CT scanning[32, 33, 34, 35, 36], single-photon emission CT[37], positron emission CT[35, 38, 39], lung sound vibration imaging[40], gas washout techniques[41] and lung function tests[42].These comparative studies have validated the reliability of data acquisition. Subsequently, collaborative efforts among healthcare professionals have been undertaken to develop algorithms for data processing. This facilitates swift and intuitive assessments by healthcare providers and aids in the management of lung ventilation distribution. This dataset is commonly referred to as Functional Electrical Impedance Tomography (fEIT).

2.3.1 Spatial distribution parameters.

①tidal impedance variation(TVi):

$$TV_i = \frac{1}{N}\sum_{n=1}^{N}\left(\Delta Z_{i,Ins,n} - \Delta Z_{i,\mathrm{Exp},n}\right),$$

In the context of the respiratory cycle, ΔZ signifies the impedance alteration resulting from air fluctuations within the lung, computed as the discrepancy between the peak and trough values. TVi represents the mean value aggregated from all pixels, illustrating a correlation with tidal volume.

The regional TV, derived from TVi, is commonly recognized as the region of interest (ROI):

$$TV_{ROI} = \sum_{j=256 or 513 or 769}^{1024} TV_i \Big/ \sum_{i=1}^{1024} TV_i \times 100\%,$$

ROI can reflect the ventilation characteristics of the selected target area, allowing for the retrieval of relevant data for any area and position within lung EIT imaging as required.

②End-Expiratory Lung Impedance (EELI) demonstrates a linear relationship with the air content in the lung at the conclusion of expiration, acting as a proxy indicator for End-Expiratory Lung Volume (EELV). There is a linear correlation between EELI and End-Expiratory Lung Volume (EELV).

③impedance ratio(IR): reflecting lung distension and deflation status.

④center of ventilation (COV): COV represents the relative positional coordinates of the area with the maximum impedance change measured within the lung. A higher COV indicates a posterior shift of ventilation.

$$CoV = \sum(y_i \times TV_i) / \sum TV_i \times 100\%,$$

⑤global inhomogeneity(GI): GI represents the ratio of impedance change in a
single lung region to the median impedance change across the entire lung. A higher GI value indicates a more uneven distribution of gas within the lung.

$$GI = \sum_{l\in lung}\left|TV_l - \mathrm{median}(TV_{lung})\right| \Big/ \sum_{l\in lung} TV_l,$$

⑥regional respiratory system compliance(Cdyn):Cdyn enables the localization and quantification of collapsed and overinflated regions within the lung.

$$C\mathrm{dyn} = TV\mathrm{i} / P\mathrm{plat} - P\mathrm{eep}$$

⑦"Silent spaces" involve quantifying regions of poor ventilation without distinguishing between excessive collapse or overdistension. Dependent silent spaces (DSS) indicate lung atelectasis, while non-dependent silent spaces (NSS) suggest overventilation.

2.3.2 Time distribution parameters

①regional ventilation delay inhomogeneity (RVDI): RVDI quantifies the temporal
heterogeneity of regional ventilation.

$$RVDI = \frac{t_{i,40\%}}{\sqrt{T_{inspiration,global}} \times 100\%},$$

②Local expiratory time constant(τ): quantifying the regional heterogeneity during the exhalation process.

The commonly used parameters in clinical practice are mainly ROI and EELI, which can intuitively and quickly reflect the changes in lung ventilation caused by anesthesia drugs and endotracheal intubation during the perioperative period. Parameters such as GI and RVDI are more often used in studies optimizing ventilator settings, such as oxygen concentration, respiratory rate, and titration of positive end-expiratory pressure.

3. COMMON APPLICATIONS OF EIT IN THE PERIOPERATIVE PERIOD OF LAPAROSCOPIC SURGERY

3.1 Laparoscopic and Pulmonary Monitoring.

Recent developments in medical technology, particularly the progressive integration of minimally invasive approaches in the surgical field, have led to the

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widespread acceptance and rapid advancement of laparoscopic technology among the public. Following the successful laparoscopic cholecystectomy performed by Dr. Mūhe in 1985, laparoscopic techniques have become widely utilized across various surgical disciplines[43, 44, 45]. Laparoscopy offers benefits such as minimal trauma, reduced intraoperative blood loss, swift postoperative recovery of gastrointestinal function, lower perioperative complications, decreased pain levels, and shorter hospital stays. Additionally, the enhancement of image magnification provides clear visualization of the pelvic surgical field, enhances surgical precision, and promotes effective clinical teaching and technical knowledge exchange. The promotion of the "scarless" approach has led to the increasing implementation of laparoendoscopic single-site surgery (LESS) in clinical settings. LESS, in comparison to traditional multi-port laparoscopy, presents advantages including reduced trauma, enhanced postoperative recovery speed, and improved cosmetic results[46, 47].

During laparoscopic surgery, due to general anesthesia and the need of laparoscopic surgery itself, carbon dioxide pneumoperitoneum (PnP) causes a sharp increase in intraabdominal pressure (ITP), pushing the diaphragm upwards, further exacerbating lung collapse, ventilation/perfusion mismatch, decreased oxygenation, which can lead to perioperative complications and prolonged hospital length of stay. Current laparoscopic surgery lung protection mainly focuses on reducing the impact of artificial pneumoperitoneum, primarily focusing on hypercapnia, pulmonary compliance, airway pressure, and diaphragmatic movement. Carbon dioxide (CO2) has high solubility and diffusion, making it a commonly used gas for creating artificial pneumoperitoneum. CO2 is absorbed into the blood through the peritoneum but is easily eliminated from the body due to its good water solubility and diffusion in healthy individuals. However, when there is ventilation suppression or concurrent cardiopulmonary dysfunction, CO2 accumulation can lead to hypercapnia and acidosis, the latter of which can have inhibitory effects on the cardiovascular system. To eliminate CO2, minute ventilation must be increased, which in turn increases airway pressure, increasing the risk of barotrauma. Patients with normal respiratory function under general anesthesia require a 12% to 16% increase in minute ventilation to maintain normal levels of carbon dioxide partial pressure (PaCO2). However, in patients with respiratory insufficiency, even with an increased minute ventilation, it is difficult to avoid hypercapnia[48]. The establishment of artificial pneumoperitoneum increases intraabdominal pressure, which can lead to a 50% increase in peak airway pressure, an 81% increase in plateau pressure, a 47% decrease in lung compliance, increased work of breathing, and an increased risk of barotrauma. After stopping insufflation, lung compliance is only 86% of the preoperative level. Patients with respiratory insufficiency receiving mechanical ventilation may require positive end-expiratory pressure (PEEP) to improve ventilation and oxygenation[49]. Increased intraabdominal content and specific body positions (Trendelenberg) can reduce diaphragmatic movement. Reduced or intermittent diaphragmatic movement can reduce tidal volume, increase intercostal muscle movement, and decrease functional residual capacity. In addition to the effects on respiratory function, laparoscopic surgery can have other pathophysiological effects on patients, such as the impact of hypercapnia on the cardiovascular system, and high intraabdominal pressure can also affect renal blood flow and kidney function.

Common lung imaging monitoring instruments during the perioperative period include X-ray imaging, computed tomography (CT), and ultrasound imaging. However, these instruments are mainly used for preoperative or postoperative examinations. Due to site limitations and radiation pollution issues, real-time monitoring during surgery is difficult. Radiological examinations are rarely performed before symptoms appear during preoperative and postoperative examinations, and each lung ultrasound examination relies on the operator's skills, thus requiring thorough training. The learning curve for lung ultrasound examination is steep, and even with relatively short training, a high level of consistency can be achieved between expert and non-expert operators. Automation technology may further increase accuracy. Postoperative ultrasound cannot penetrate the pleura because of obstacles such as chest drainage tubes, dressings, air, subcutaneous emphysema, and wounds or burns, which

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affect direct skin contact. Therefore, whether in terms of diagnostic time or time for further examinations, existing imaging examination methods still cannot meet the growing medical needs.

Electrical Impedance Tomography (EIT) technology offers valuable insights for anesthesiologists at any stage during the perioperative period. Frerichs et al.[50], pioneers in the field, after comparing EIT and CT, were the first to explore the application of functional EIT (fEIT) for monitoring purposes within operating theaters, surgical wards, and intensive care units. Subsequently, clinicians have increasingly harnessed the potential of EIT for preoperative assessment of lung function, monitoring cardiac activity and pulmonary perfusion during the perioperative period, as well as referencing literature reports on brain function and perfusion. Recent studies indicate that evaluating the overall lung condition of patients before surgery can equip anesthesiologists with additional insights into lung function, consequently impacting airway management during induction and mechanical ventilation. The most established application of EIT undoubtedly resides in intraoperative lung ventilation monitoring. Furthermore, the customization of ventilation parameters (such as PEEP and Vt) and the heightened diagnostic capacity for identifying intraoperative pulmonary complications underscore the efficacy of EIT. In select critically ill cases, the emerging role of EIT in monitoring organ perfusion is becoming apparent. Postoperatively, the utilization of EIT is infrequent, primarily serving to monitor lung re-expansion post-extubation and evaluate postoperative pulmonary complications. Regarding long-term postoperative recovery, the use of EIT parallels other chest imaging diagnostic modalities like X-rays and CT scans; however, as a non-invasive and swift diagnostic tool, it holds promise for promoting patients' extended recovery. Noteworthy is the ongoing research on histological and cytological tests, including the detection of tumor benignancy and malignancy, which remain at the experimental stage.

3.2 Preoperative Assessment

The preoperative evaluation of lung function predominantly relies on lung function testing, chest X-rays, and lung CT scans. Partial experiments of lung Electrical Impedance Tomography (EIT) in hospital settings suggest its promising role in future preoperative assessments. Researchers utilized lung EIT imaging on patients with chronic obstructive pulmonary disease (COPD) post lung function assessments, identifying significant spatial and temporal ventilation inhomogeneity comparable to traditional lung function test results[51]. This capability aids anesthesiologists in comprehending COPD patients' lung function, determining optimal timing for bronchodilator aerosolization, and potentially refining treatment and management during mechanical ventilation[52]. Additionally, similar experiments conducted on asthma patients and smokers using lung EIT have detected variations in ventilation function compared to healthy subjects, with treatment effects discernible by machines[53, 54, 55]. Currently, the efficacy of preoperative lung function assessment via EIT awaits confirmation through large-scale clinical studies. EIT's swift and radiation-free attributes may position it as a pivotal tool for preoperative lung function assessment, potentially supplanting chest imaging modalities like X-rays and CT scans. Moreover, the utility of preoperative EIT for identifying lesion tissue could assist perioperative healthcare providers in future delineation of surgical margins, notwithstanding the yet inconclusive confirmation of its clinical utility and stability[56, 57].

3.3 Intraoperative Management

Intraoperative airway management is a pivotal aspect of perioperative care and stands out as one of the most extensively applied realms of EIT. Particularly in conjunction with lung protective ventilation strategies (LPVS), EIT has been extensively researched in various populations undergoing laparoscopic surgeries involving the gallbladder, inguinal hernia, prostate, uterus, and associated appendages, shedding light on ventilation dynamics. Notably, obese patients, a high-risk group for perioperative pulmonary complications, further underscore the distinctive role of EIT in intraoperative monitoring[50, 58, 59, 60]. Firstly, the discovery of alterations in ventilation function is crucial. Pre- and post-mechanical ventilation, non-spontaneous breathing induces ventilation redistribution, leading to the transfer of gas from the dorsal to the ventral lung regions. Dual-handed face mask oxygen administration results in a higher tidal volume compared to single-handed delivery,

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yet ventilation heterogeneity remains unaltered[61]. As the duration of mechanical ventilation lengthens and intraoperative pneumoperitoneum forms, alterations in ventilation distribution become more distinct[62, 63]. In most cases, ventilation redistribution gradually resolves within 5 minutes after the restoration of spontaneous breathing and extubation, returning to preoperative lung ventilation conditions within 2 hours, or even sooner. However, EIT findings indicate that obese individuals demonstrate more prominent changes in intraoperative ventilation distribution compared to their normal-weight counterparts, manifesting in increased alterations in GI and EELV values, leading to a heightened likelihood and prolonged duration of perioperative dorsal lung collapse[62, 64]. Secondly, the elevation of the diaphragm post general anesthesia is notably more pronounced during laparoscopic surgeries. EIT can recognize modifications in ventilation distribution attributed to unilateral diaphragm paralysis following brachial plexus anesthesia, explained as an outcome of phrenic nerve blockade. Furthermore, EIT reveals that ultrasound-guided supraclavicular nerve block can ameliorate this undesirable effect [65, 66]. Optimizing intra-abdominal pressure via EIT monitoring during pneumoperitoneum may mitigate future complications. Additionally, EIT's role in lung protective strategies encompasses primary methods such as low tidal volume, personalized PEEP, intermittent lung recruitment, and reduced inspiratory oxygen concentration[67, 68]. Historical research suggests a direct correlation between tidal volume during mechanical ventilation and impedance variations in diverse lung regions, indicating no alterations in lung ventilation distribution. Similarly, there is no identifiable trend in impedance changes among areas with varying PEEP values [69]. Therefore, studies focused on enhancing ventilation distribution often center on individualized adjustments of intraoperative PEEP, with diverse EIT-based PEEP setting methods emerging post clinical trials on acute respiratory distress syndrome patients in the early intensive care unit setting. The utilization of fixed PEEP versus no PEEP during surgery reveals improved oxygenation and respiratory compliance, coupled with reduced ventilation redistribution [70]. EIT-guided personalized PEEP, as opposed to empirically determined values, can enhance intraoperative tidal volume distribution in mechanically ventilated patients [71]. Notably, PEEP values determined using EIT are higher than those from esophageal pressure monitoring[72], suggesting that for obese patients, integrating PEEP with lung recruitment tactics and low tidal volume ventilation remarkably refines intraoperative lung ventilation without heightening the risk of pulmonary or cardiovascular complications[64]. Postoperative findings illustrate no substantial variances in long-term lung recruitment status post-application of a lung protective strategy. Moreover, monitoring cardiovascular, pulmonary, and cerebral perfusion is imperative. Numerous studies affirm EIT's capability to detect pulmonary vascular constriction and dilation [73, 74, 75, 76]. Lung blood flow signals, often considered noise in ventilation monitoring, are eliminated using algorithms to diminish their interference. Clinical practice currently enhances lung blood flow signals by injecting hypertonic saline to monitor pulmonary perfusion[34, 77], with ongoing exploration of the EIT ventilation-perfusion ratio in critical care contexts [77, 78, 79]. Although advances have been made in cerebral perfusion imaging during surgery, emphasizing feasibility in localizing and monitoring epilepsy, stroke, and brain edema, additional evidence is required to underpin its intraoperative application[80, 81, 82]. A study on 42 patients undergoing total aortic arch replacement surgery showed that EIT, by tracking changes in brain electrical impedance, partially reflects the process of cerebral tissue hypoxia. Additionally, the difference in electrical impedance between both hemispheres could be an independent predictor of postoperative neurologic dysfunction[83]. Changes in intracranial impedance after skull drilling drainage procedures have also been successfully identified[84]. EIT presents promising prospects for future brain imaging monitoring, warranting further validation of its reliability and stability.

In summary of this part, the use of EIT in surgery is the most mature and widely used. The changes in lung ventilation function caused by laparoscopic surgery also pose higher requirements for lung ventilation monitoring devices. EIT lung ventilation images can first intuitively reflect lung ventilation status through real-time lung

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ventilation images. Secondly, functional EIT can accurately quantify changes in lung ventilation function and assist anesthesiologists in setting individualized breathing parameters, thereby achieving precise intraoperative lung protection. During the COVID-19 pandemic, the application of EIT has highlighted the measurement of lung ventilation-perfusion ratio in the intensive care unit. However, further research and verification are needed for its use in the perioperative period, especially in determining ventilation-perfusion ratios during laparoscopic surgery.

3.4 Postoperative Management

In the post-anesthesia care unit (PACU) and anesthesia intensive care unit (AICU), lung atelectasis following extubation from mechanical ventilation is a frequent occurrence. Current clinical practice includes utilizing finger pulse oximetry to aid oxygen delivery and ensuring continuous observation for a minimum of 30 minutes as a preventive measure. However, Electrical Impedance Tomography (EIT) can provide visual assessment of lung ventilation distribution pre- and post-extubation to detect atelectasis, offering valuable insights to postoperative caregivers. Park et al. [85] utilized EIT to monitor postoperative lung ventilation and determined that changes in oxygen concentration during mask-free oxygen delivery did not impact postoperative atelectasis development. In a subsequent study, Yuan et al. examined two oxygen therapy methods and patient positioning following abdominal surgery in a normal population using EIT. They noted short-term benefits of head-up positioning and High-Flow Nasal Cannula, leading to a quicker recovery of spontaneous lung ventilation[86]. In obese patients, postoperative EIT revealed more severe lung atelectasis. However, over time post-awakening, lung contour and respiratory muscle function gradually improved, as indicated by an increasing lung impedance, suggesting a gradual resolution of atelectasis, albeit slower than in individuals with normal weight[87]. Longhini et al. monitored obese patients postoperatively with EIT and found that High-Flow Nasal Cannula significantly improved end-expiratory lung impedance, with a more pronounced increase in end-expiratory capacity with higher BMI[88]. This implies that the combination of EIT monitoring and postoperative High-Flow Nasal Cannula therapy may be a critical strategy to expedite recovery in the PACU. Despite standardized extubation criteria postoperatively, adverse events post-extubation in laparoscopic surgery patients still exceed 2%. Current research does not yet demonstrate the ability of EIT to predict successful extubation, and the use of EIT for evaluating extubation criteria remains a topic of debate[89, 90]. Studies employing EIT monitoring have highlighted that high-frequency chest wall oscillations, a technique for airway clearance, notably enhanced dorsal lung ventilation in patients undergoing laparoscopic surgery, thus accelerating patient recovery[91]. Additionally, the extensive utilization of EIT in the intensive care unit has provided valuable insights into the organization of anesthesia-intensive care units in recent years. Through postoperative EIT monitoring of a pediatric liver transplant recipient, researchers explored challenges related to difficult extubation due to postoperative hypoxemia. Utilizing EIT ventilation-perfusion (V/Q) matching, they assessed and considered Hepatopulmonary Syndrome (HPS), ultimately resulting in the child's improvement and discharge based on dynamic liver function assessment rather than excessive respiratory interventions [92]. While previous studies primarily incorporated lung EIT as a continuation of intraoperative monitoring, there is a rising trend in recent literature focusing on postoperative management utilizing EIT, leading to a more accurate and efficient perioperative and postoperative care process.

3.5 Rehabilitation Treatment

To date, there is a lack of medical reports on the use of Electrical Impedance Tomography (EIT) for long-term monitoring of postoperative patients. While the application of EIT extends beyond pulmonary ventilation monitoring, its utilization remains restricted. Nevertheless, promising feasibility has been demonstrated in successful case studies. Notably, in critical care contexts, Zhou et al. [93] monitored a postoperative patient with sudden hypoxemia and prolonged pneumothorax using EIT. They achieved ventilation-perfusion matching through saline bolus injection, aiding in the identification of atelectasis-induced hypoxemia, later confirmed by CT imaging, enabling prompt and accurate intervention. Zouari et al.[94, 95] conducted EIT monitoring on patients with

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COVID-19 pneumonia, delving into remote post-treatment medical care. They also assessed lung function in both healthy individuals and those with pulmonary disorders, indicating EIT's capability in evaluating lung volume, delineation, and distinguishing between healthy and pathological states. The aforementioned online remote medical monitoring and assessment can partially address the difficulties in follow-up for surgical patients after discharge. It provides an efficient and convenient means of evaluating lung function for anesthesiologists and offers a new approach to patient follow-up. The case studies in this paragraph provide valuable experiences that can be borrowed from for long-term recovery using EIT after laparoscopic surgery.

4. LIMITATIONS OF CLINICAL APPLICATION OF LAPAROSCOPIC EIT

Firstly, comfort is a concern as the integrated electrode belt or adhesive electrode placement required for Electrical Impedance Tomography (EIT) testing can cause discomfort by exerting pressure on the skin surface of the participants. This discomfort may be intolerable for awake obese patients wearing the EIT belt for over 3 hours[88]. Secondly, the stability of the signal needs improvement. While wearable electrode belts have markedly enhanced the electrical signals of EIT, their widespread adoption is limited due to constraints related to wearer body size and high cost. Consequently, disposable electrode patches have become a more affordable and widely used alternative, but their effectiveness relies on strict skin cleansing and application of conductive gel, making the practical use of EIT cumbersome. Finally, customization standards pose a challenge. With EIT being a novel medical technology that has not yet been extensively adopted in clinical practice, there is currently no universally recognized standard to promptly assess and manage perioperative incidents. Even the selection of electrode placement is contentious. Although the recent development of 3D-EIT appears promising in addressing these issues to some extent, further refinement is still necessary.

5. CONCLUSIONS

General anesthesia mechanical ventilation and laparoscopic surgery have always been significant challenges for patients, bringing many difficulties to perioperative medical staff. The continuous improvement in medical technology and equipment has greatly increased the safety of surgery, while societal progress has placed higher demands on doctors. EIT, as a convenient, non-invasive, and non-radiation monitoring technology, was proposed as early as the 1980s. In recent years, with the emergence of deep learning methods and artificial intelligence, combined with extensive medical clinical data and experiments, the accuracy of lung monitoring with EIT is comparable to CT and ultrasound monitoring. Since the 1990s, clinical experiments with EIT have gradually been conducted in hospitals; however, in terms of frequency of use, research on the application of EIT in operating rooms is far less than in the intensive care unit. In order for EIT to become an emerging means of regulating anesthesia machine parameters and gradually participate in the perioperative resuscitation process, playing an important role in preventing and monitoring postoperative lung complications, expanding to preoperative assessment and long-term post-discharge monitoring, more perioperative medical workers should explore the use of EIT as a monitoring tool in research. In the future, with advances in computer technology and materials science, more comprehensive clinical trials will prove the effectiveness and safety of EIT, leading to the development of a systematic, accurate, and practical laparoscopic surgery EIT usage guideline, for better application in perioperative practice.

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XU Tiecheng was responsible for the overall conception and paper writing. TIAN He and XIE Qian revised the paper. LI Zhiwei and WU Yang was responsible for non-medical field. WANG Hao were responsible for the

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supervision and guidance of the paper and the overall responsibility of the paper. LU Hao provided financial support. All authors read and approved the final manuscript submitted.

DECLARATION OF CONFLICTING INTERESTS

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