Original Article

Research trends and hotspots in the field of electrical impedance tomography for mechanical ventilation: a bibliometric analysis

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Background: Electrical impedance tomography (EIT) is a relatively recent functional imaging technique that is both noninvasive and radiation free. EIT measures the associated voltage when a weak current is applied to the surface of the human body to determine the distribution of electrical resistance within tissues. We performed a bibliometrics-based review to explore the geographic hotspots of current research and future trends developing in the field of EIT for mechanical ventilation.

Methods: The Web of Science database was searched from its inception to June 25, 2023. CiteSpace software was used to visualize and analyze the relevant literature and identify the most impactful literature, trends, and hotspots.

Results: 363 articles describing EIT use in mechanical ventilation were identified. A fluctuating growth in the number of publications was observed from 1998 to 2023. Germany had the highest number of articles (n=154), followed by Italy (n=53) and China (n=52). A cluster analysis of keyword co-occurrence revealed that "titration", "ventilator-related lung injury", and "oxygenation" were the most actively researched terms associated with the use of EIT in mechanically ventilated patients.

Conclusions: Significant progress has been made in EIT research for mechanical ventilation. EIT research is limited to a small number of countries with a present research focus on the prevention and treatment of ventilator-related lung injury, oxygenation status, and prone ventilation. These topics are expected to remain research hotspots in the future.

Keywords: Electrical impedance tomography (EIT); mechanical ventilation; bibliometric analysis

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Introduction

Ventilator-induced lung injury (VILI), remains a significant concern for clinicians in the ongoing care of critically ill patients (1-3). Consequently, there is a growing interest in identifying and developing mechanisms to mitigate lung injury caused by mechanical ventilation and accelerate recovery of respiratory function and liberation from assisted mechanical ventilation (4-8).

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Electrical impedance tomography (EIT) is an emerging, noninvasive, and radiation free functional imaging technology. EIT involves detecting the distribution of electrical impedance within tissues via the application of a weak alternating current to the surface of the human body and measuring the corresponding voltage (9-13). EIT enables real-time dynamic monitoring of ventilation distribution and blood flow in the thoracic cavity, thereby guiding perioperative respiratory parameter adjustments (14,15). As a result, there is increasing interest in EIT in the fields of anesthesia and respiratory critical care (16,17).

Bibliometric analysis involves the uniform and objective analysis of influential published manuscripts in a given research area (18-20). Currently, there is a paucity of high-quality bibliometric analyses on EIT for mechanical ventilation. The aim of this study was to characterize the citation trends of published papers, identify the key areas of ongoing research and appropriate research directions for future investigations.

Highlight box

Key findings

- This bibliometric analysis summarized the developments in electrical impedance tomography (EIT) for monitoring mechanical ventilation.

What is known and what is new?

- Use of electrical EIT has been shown to optimize ventilation.
- The field of EIT for mechanical ventilation has garnered increased attention.

What is the implication, and what should change now?

- Research trends included a shifted focus to customized EIT integration in ventilation.
- Despite changing trends, the keyword "electrical impedance" has remained relevant for over 11 years.

Methods

Search strategy

All the data used in this study were retrieved from the Web of Science (WoS) Core Collection, which includes literature from most biomedical fields. We conducted a comprehensive literature search using predefined keywords of articles published from database inception to June 25, 2023. We used the following search strategy containing the search terms (TS). TS = ("electrical impedance tomography") OR TS = ("electrical impedance imaging") OR TS = ("electric impedance tomography") OR TS = ("impedance imaging") OR TS = ("conductivity imaging") AND TS = ("mechanical ventilation") OR TS = ("mechanical ventilatory") OR TS = ("mechanical ventilate") OR TS = ("mechanical ventilates")

We focused only on articles and reviews in the English language. The search yielded 450 citations. Two independent researchers (N.L. and C.J.F.) evaluated the titles and abstracts of the obtained publications. Disagreements and inconsistencies were resolved via consultation with a third reviewer (Z.M.L.). After completing the preliminary screening, the two reviewers read the entire text and evaluated all potentially eligible studies. Editorials, letters to the editor, and abstracts were excluded as were any articles not related to the application of EIT in mechanical ventilation. Three hundred and sixty-three relevant articles were identified. The flowchart of the literature screening is shown in *Figure 1*.

Statistical analysis

CiteSpace 6.2.R3 software was used to conduct bibliometric analysis. CiteSpace is applied to data collection for collation and visual analysis, including developing statistical and descriptive analysis, collaborative network analysis, co-occurrence analysis, citation bursts analysis, and co-citation analysis. We analyzed the research constituents (authors, institutions, countries, and keywords) and generated co-occurrence networks and keyword emergence diagrams. In a co-occurrence network diagram, the node size reflects the frequency of occurrence and the lines between the nodes indicate associations, with thicker lines denoting stronger relationships. The purple outer circle nodes indicate high intermediary centrality (intermediate centrality >0.1), which indicates the importance of nodes in reference relationships or co-reference relationships. Meanwhile, a keyword mutation map indicates a significant change in keyword frequencies in a certain period of time, indicating shifts in research hotspots. The dark blue bar indicates the years in which keywords showed slight increases in co-occurrence, and the red bar indicates the years in which co-occurrence rose sharply. Data are expressed as numbers and percentages.

Results

Year of publication

From database inception on January 1, 1998, to June

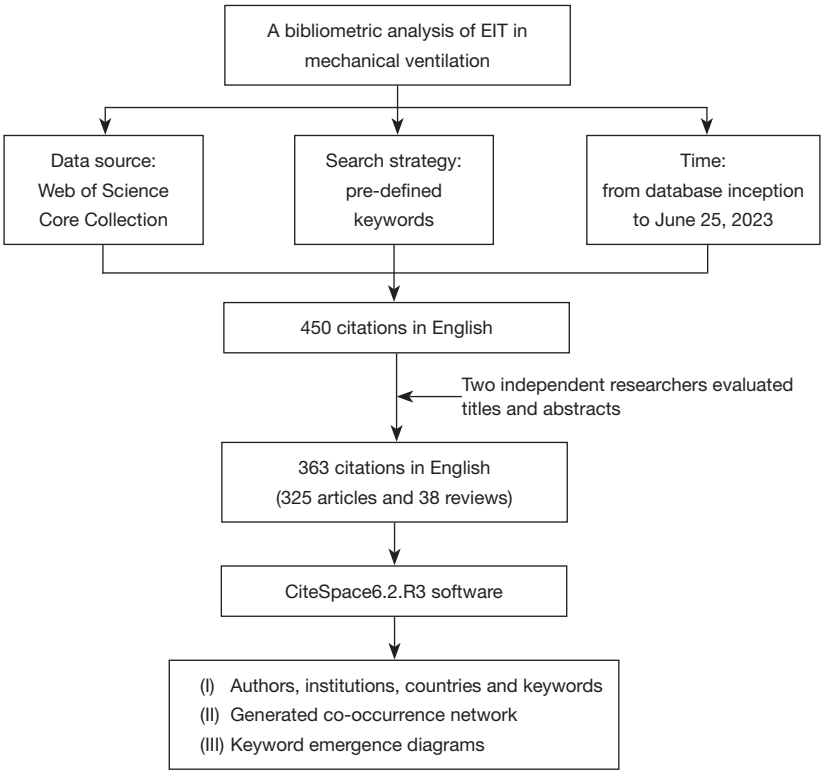

Figure 1 A flowchart of the study. EIT, electrical impedance tomography.

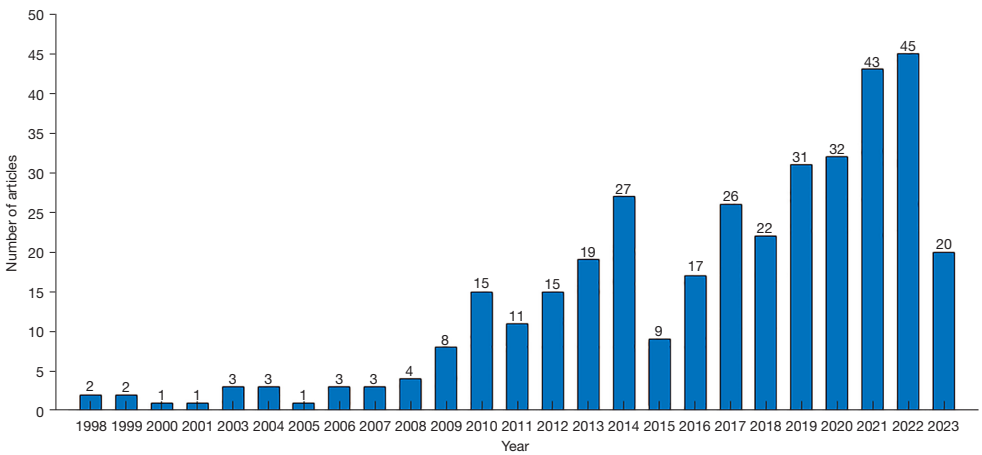

Figure 2 Number of publications by year from January 1, 1998 to June 25, 2023.

25, 2023, 363 articles on EIT for mechanical ventilation were published in English, including 325 original articles and 38 reviews. The earliest article on the subject was published in *Intensive Care Medicine* in 1998 (21). Another notable publication on the topic was published in *Acta Anaesthesiologica Scandinavica* in the same year (22). From 1998 to 2014, literature related to EIT for mechanical ventilation in English was published almost every year, showing a gradual increase in frequency (*Figure 2*). However, there was a sharp decline in publication volume in 2015, which gradually rebounded. The publication volume increased to a peak value in 2022 with 45 articles, with 20

articles published during the nearly 6 months of available data for 2023.

Country of publication

The country with the highest number of publications was Germany (n=154), followed by Italy (n=53) and China (n=52) (*Table 1*). Germany, Italy, the Netherlands, Australia, Switzerland, and Sweden exhibited higher intermediary centrality (*Figure 3*). Interestingly, although Switzerland ranked ninth in terms of publication volume (n=22), its intermediary centrality value surpassed that of Germany, which ranked first.

Table 1 Top ten countries with the highest number of publications from January 1, 1998 to June 25, 2023

Rank	Country	Number of publications	Centrality divergence
1	Germany	154	0.21
2	Italy	53	0.17
3	China	52	0
4	Brazil	51	0.08
5	USA	42	0.05
6	Canada	41	0.02
7	The Netherlands	33	0.11
8	Australia	29	0.13
9	Switzerland	22	0.3
10	Sweden	21	0.21

Institution of publication

The top three institutions ranked according to the highest number of publications were as follows: the University Medical Center Schleswig-Holstein (45 articles), the University of São Paulo (37 articles), and Furtwangen University (34 articles) (*Table 2*). University Medical Center Schleswig-Holstein, Carleton University, the University of Toronto, the University of Göttingen, Istituto di Ricovero e Cura a Carattere Scientifico, and Erasmus Medical Centre demonstrated higher intermediary centrality (*Figure 4*). Although the University of Göttingen ranked seventh (n=16) in terms of the number of articles, its intermediary centrality surpassed that of the top-ranked University Medical Center Schleswig-Holstein.

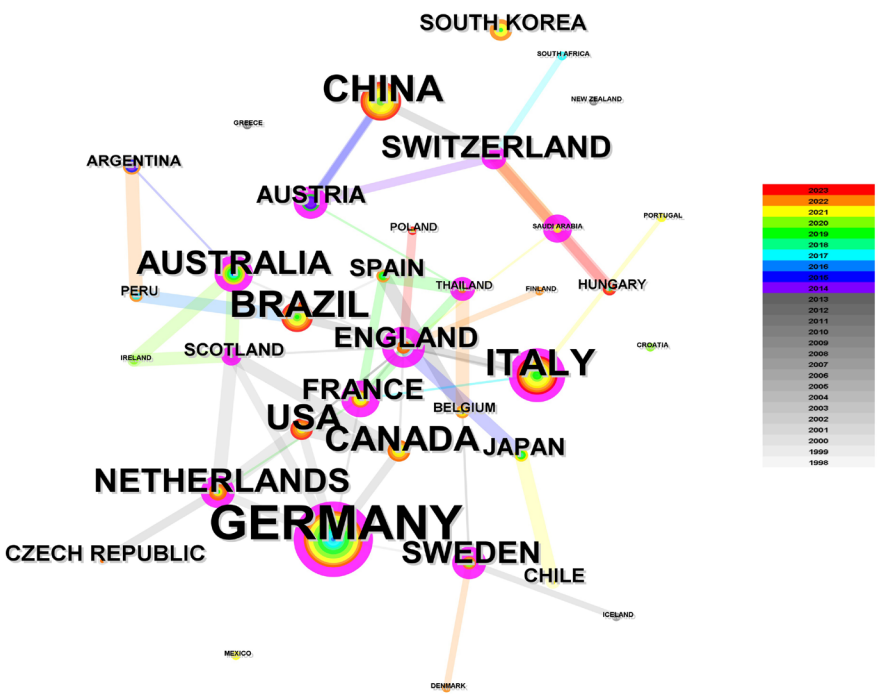

Figure 3 Map of cooperation between countries (frequency ≥1). The node size reflects the frequency of occurrence, while the purple outer ring indicates a higher centrality divergence (centrality divergence >0.1).

Table 2 Top ten institutions with the highest number of publications from January 1, 1998 to June 25, 2023

Rank	Institution	Number of publications	Centrality divergence
1	University Medical Center Schleswig-Holstein, Kiel, Germany	45	0.25
2	University of São Paulo, Sao Paulo, Brazil	37	0.06
3	Furtwangen University, Baden-Württemberg, Germany	34	0.11
4	Fourth Military Medical University, Xi'an, China	22	0
5	Carleton University, Ottawa, Canada	17	0.1
6	University of Toronto, Toronto, Canada	16	0.14
7	University of Göttingen, Gottingen, Germany	16	0.27
8	Istituto di Ricovero e Cura a Carattere Scientifico, Pavia, Italy	14	0.24
9	University of Milan, Milan, Italy	14	0
10	Erasmus Medical Centre, Rotterdam, Netherlands	10	0.11

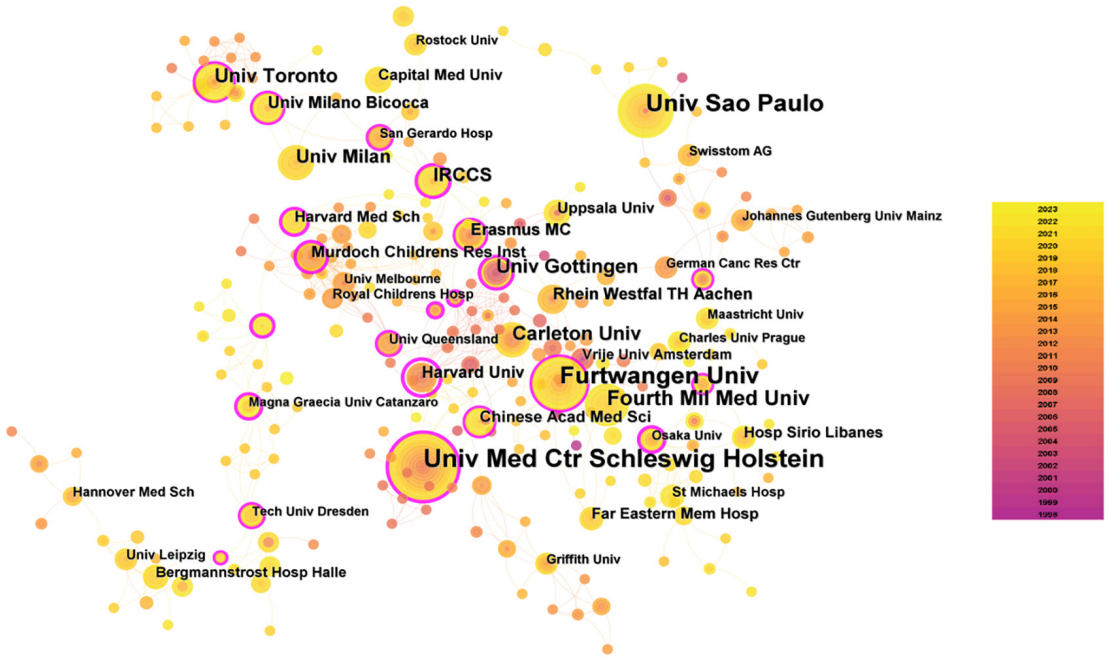

Figure 4 Map of cooperation between institutions (frequency ≥5). The node size reflects the frequency of occurrence, while the purple outer ring indicates a higher centrality divergence (centrality divergence >0.1).

Author of publication

Frerichs from the Medical Center of Schleswig-Holstein University in Germany, had the highest number of publications (n=60) (*Table 3*). Following closely behind were Amato from Brazil (n=29) and Zhao from China (n=27), ranked second and third, respectively. Additionally, Frerichs from Germany, Amato from Brazil, Bellani from Italy, and Zhao from China demonstrated high intermediate centralities (nodes with purple outer circles, values >0.1) (*Figure 5*).

Citation volume of publications

An article by Frerichs *et al.* [2017] entitled "Chest electrical impedance tomography examination, data

Table 3 Top ten authors with the highest frequency of publications from January 1, 1998 to June 25, 2023

Rank	Author	Country	Number of publications	Centrality divergence
1	Frerichs, Inez	Germany	60	0.3
2	Amato, MBP	Brazil	29	0.36
3	Zhanqi, Zhao	China	27	0.1
4	Adler, Andy	Canada	18	0.01
5	Moeller, Knut	Germany	11	0
6	Mauri, Tommaso	Italy	11	0.02
7	Elke, Gunnar	Germany	11	0
8	Bellani, Giacomo	Italy	10	0.24
9	Weiler, Norbert	Germany	10	0
10	Leonhardt, Steffen	Germany	9	0.08

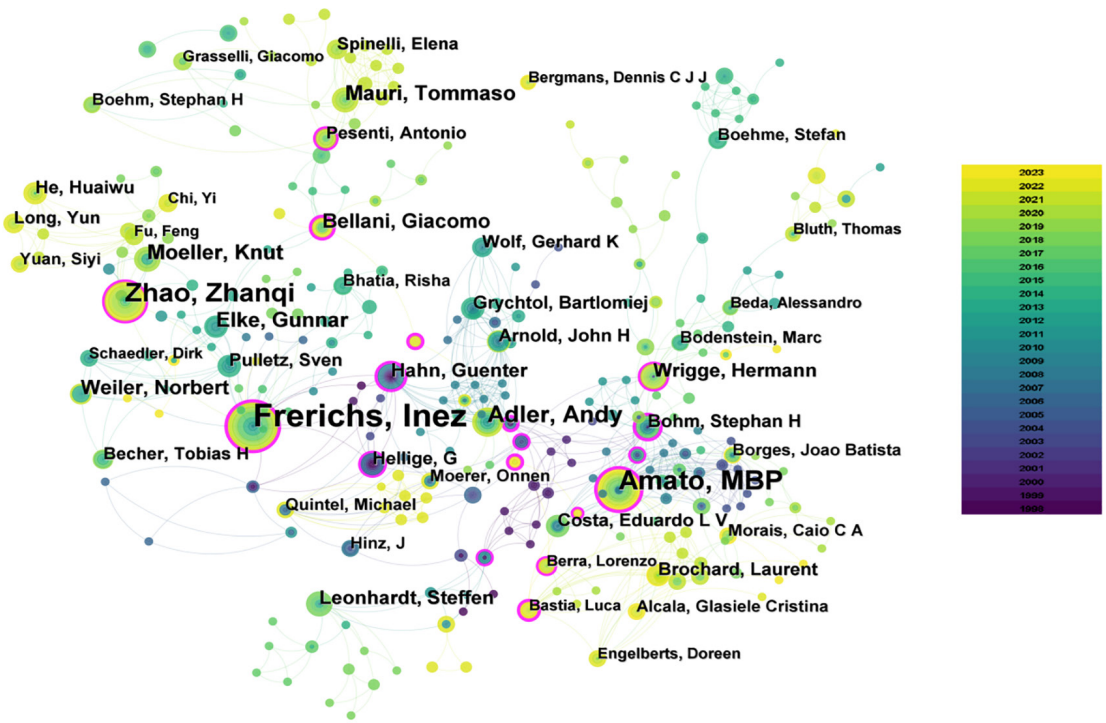

Figure 5 Map of cooperation between authors (frequency ≥5). The node size reflects the frequency of occurrence, while the purple outer ring indicates a higher centrality divergence (centrality divergence >0.1).

analysis, terminology, clinical use and recommendations: consensus statement of the translational EIT development study group" had the highest frequency of citations (n=95) (23) (*Table 4*). Following closely behind was an article entitled "Assessment of regional lung recruitment and derecruitment during a PEEP trial based on electrical impedance tomography" by Meier *et al.* [2008], which was cited 29 times (24).

Analysis of keywords and hotspots

After removal of redundant keywords, the keywords

Table 4 Top ten most-cited articles on electrical impedance tomography in mechanical ventilation from January 1, 1998 to June 25, 2023

Rank	Article reference	Number of citations
1	Frerichs I, 2017, *THORAX*, V72, P83, DOI 10.1136/thoraxjnl-2016-208357	95
2	Meier T, 2008, *INTENS* CARE *MED*, V34, P543, DOI 10.1007/s00134-007-0786-9	29
3	Franchineau G, 2017, *AM J RESP CRIT CARE*, V196, P447, DOI 10.1164/rccm.201605-1055OC	28
4	Bellani G, 2016, *JAMA-J AM MED ASSOC*, V315, P788, DOI 10.1001/jama.2016.0291	26
5	Amato MBP, 2015, *NEW ENGL J MED*, V372, P747, DOI 10.1056/NEJMsa1410639	24
6	Costa ELV, 2009, *INTENS CARE MED*, V35, P1132, DOI 10.1007/s00134-009-1447-y	24
7	Blankman P, 2014, *CRIT CARE*, V18, P0, DOI 10.1186/cc13866	22
8	Zhao ZQ, 2010, *CRIT CARE*, V14, P0, DOI 10.1186/cc8860	21
9	Zhao ZQ, 2019, *ANN INTENSIVE CARE*, V9, P0, DOI 10.1186/s13613-019-0484-0	20
10	Wolf GK, 2013, *CRIT CARE MED*, V41, P1296, DOI 10.1097/CCM.0b013e3182771516	20

Table 5 Top ten keywords with the highest number of occurrences from January 1, 1998 to June 25, 2023

Rank	Keywords	Occurrences	Centrality divergence
1	Electrical impedance tomography	247	0.06
2	Mechanical ventilation	188	0.16
3	End expiratory pressure	125	0.1
4	Respiratory distress syndrome	106	0.1
5	Recruitment	80	0.06
6	Acute lung injury	78	0.01
7	Acute respiratory distress syndrome	74	0.1
8	Positive end expiratory pressure	56	0.04
9	Computed tomography	55	0.09
10	Tidal volume	50	0.03

"mechanical ventilation", "end-expiratory pressure", "respiratory distress syndrome", and "acute respiratory distress syndrome" exhibited higher intermediate centrality, serving a bridging role in the collinear networks (*Table 5* and *Figure 6*).

Keyword burst value analysis

CiteSpace's burst value analysis identifies keywords or cited references with significant changes over time. Researchers can use keywords and cited references with burst features to explore hotspots of research (21). The top 25 keywords with the strongest burst values are summarized in *Figure* 7. Throughout the period spanning from 1998 to 2023, the keyword "titration" exhibited the highest burst strength (burst strength =3.91), followed by "ventilator-induced lung injury" (burst strength =3.7), "oxygenation" (burst strength =3.63), "strategy" (burst strength =3.25), "beam Computed Tomography (CT)" (burst strength =3.12), "derecruitment" (burst strength =3.09), and "model" (burst strength =3.06). In terms of sudden emergence intensity, the top three keywords were "titration" "ventilator-induced lung injury" and "oxygenation". Of significance is the extended duration of the emergence of the keyword "electrical impedance", which persisted over 11 years. Moreover, the keywords maintaining a high burst value to the present were "airway pressure" (burst strength =2.20), "respiratory failure" (burst strength =3.66), and "titration" (burst strength =5.46),

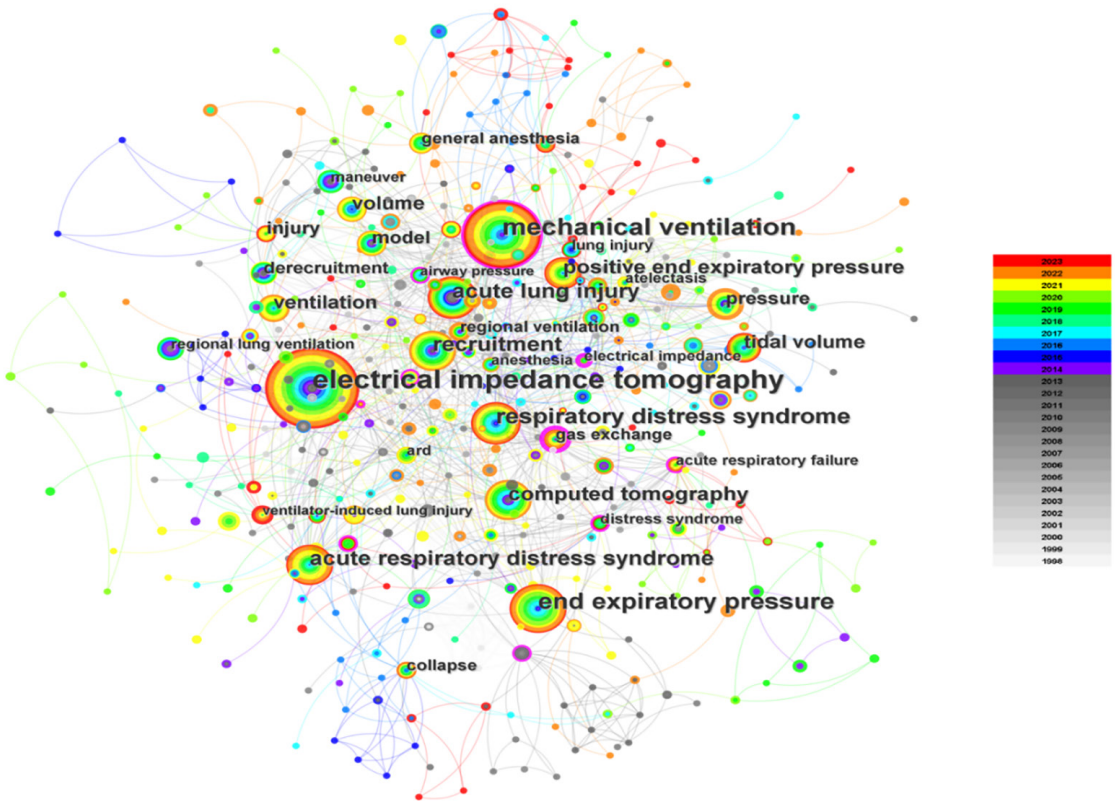

Figure 6 Map of cooperation between keywords (frequency ≥15). The node size reflects the frequency of occurrence, while the purple outer ring indicates a higher centrality divergence (centrality divergence >0.1).

suggesting that these topics remain of significant interest to researchers.

Discussion

EIT is a noninvasive, radiation free imaging modality that can quantify lung disorders and optimize mechanical ventilation (25-28). There is a growing body of literature regarding the application of EIT in mechanical ventilation. In this study, we conducted a bibliometric analysis to provide an overview of developments in the field of EIT for mechanical ventilation over the past 20 years. Analysis showed an increasing number of publications over time with a focused group of researchers leading these efforts based on country and institutional location. Keywords related to EIT research were also identified.

Overall, 363 articles written in English addressing the implementation of EIT in mechanical ventilation have been published in the past 20 years, including 325 articles and 38 reviews. Although the overall number of articles was not substantial, there was a noticeable upward trend over time (*Figure 2*). This trend indicates growing interest and attention dedicated to research on EIT for mechanical ventilation.

Germany ranked first in terms of publication volume and number of research institutions (*Tables 1,2*). Additionally, researchers in Germany appeared to have established a robust network of collaboration with research teams worldwide (intermediary centrality =0.1) (*Figure 3*). These results highlight Germany's substantial investment in resources and support for this area of research, in addition to its large number of experienced researchers. Their accumulated professional expertise enables them to produce a greater quantity of high-quality research and achieve higher citation frequency.

Although China ranked third in terms of publication volume, its intermediary centrality remained at 0, implying that the lower cooperation of Chinese groups with other groups worldwide (*Figure 3*). Moreover, this also suggests that the influence of Chinese research teams on the

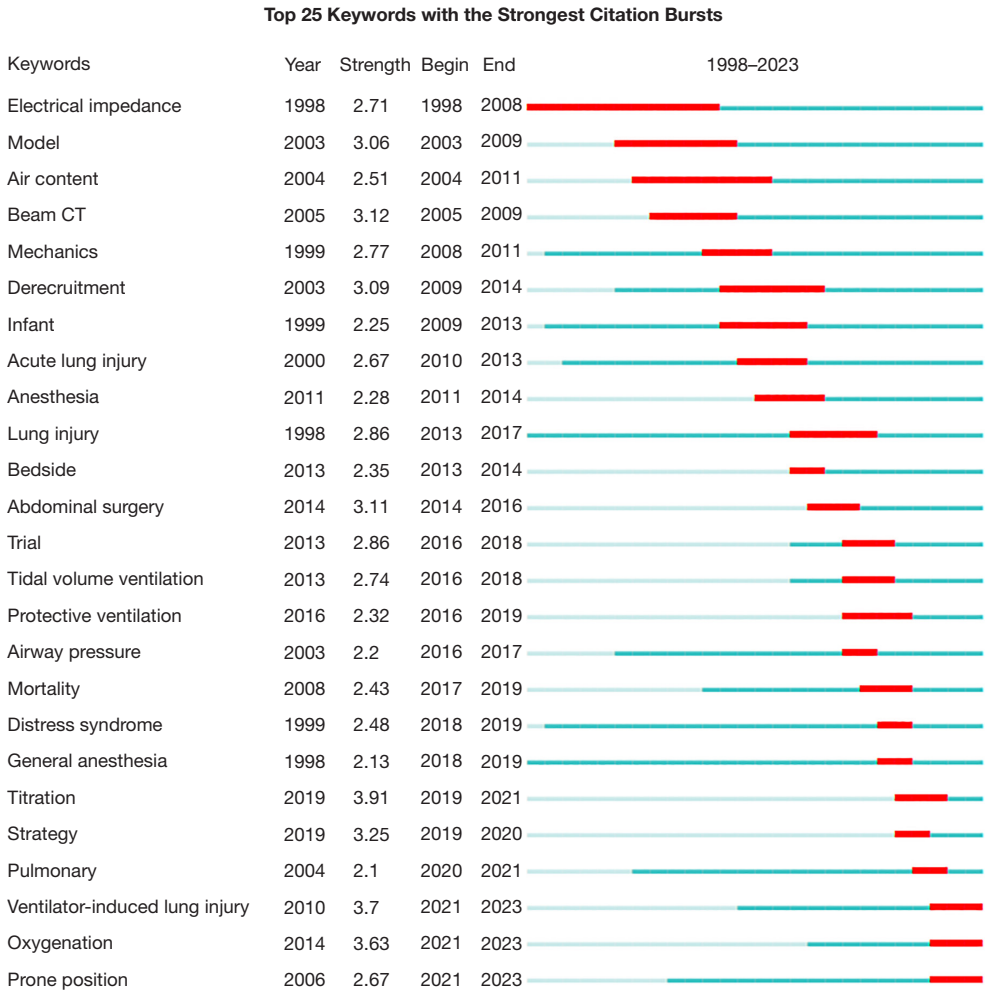

Figure 7 Top 25 keywords with the strongest burst value from January 1, 1998 to June 25, 2023. The dark blue bar indicates the years in which keywords showed slight increases in co-occurrence, and the red bar indicates the years in which co-occurrence rose sharply. CT, computed tomography.

international academic community might be relatively weak. Chinese research teams may want to consider prioritizing enhanced cooperation and communication with leading international institutions to enhance their impact on the international stage.

The German researcher Frerichs had the highest publication volume (*Table 3*). This author has the greatest scientific research output and influence in this field, and her research has garnered widespread attention and citation. Amato ranked second in terms of publication volume. His high intermediary centrality suggests that he has played a key role in coordinating and transmitting information and promoting research cooperation (*Figure 5*). Furthermore, he has had a significant impact on scientific research output in this field. Zhao from China ranks third in terms of publication volume and fourth in terms of citation frequency.

Among the top ten articles identified in terms of citation frequency (*Table 4*), the article published in *Thorax* in 2017 by Frerichs (23) described the examination methods for EIT, encompassing electrode arrangement, signal acquisition, and imaging processes. Additionally, it provides a detailed description of the analysis of the into the application of EIT in mechanical ventilation and its potential clinical applications in lung function assessment, diagnosis, and treatment of lung diseases. As a noninvasive real-time monitoring technology, EIT holds great potential for application in personalized ventilation and lung

protection strategies.

The collinear network of keywords suggests that the research over the past 20 years has primarily focused on using EIT for the following clinical interventions: mechanical ventilation optimization, adjustment of positive end-expiratory pressure and tidal volume in patients with acute respiratory distress syndrome, and acute lung injury (*Figure 6*). Compared with monitoring airway pressure and ventilation volume, EIT enables real-time and continuous monitoring of the lung, offering more comprehensive and objective data. This facilitates the optimization of ventilation strategies and reduces the occurrence of mechanical ventilation-induced pulmonary complications (29,30).

The emergence chart of keywords illustrates the development of research trends in EIT (*Figure 7*). Initially, studies primarily focused on basic concepts and technology related to EIT, such as electrical impedance measurements, model establishment, and air content. During the midterm stage, researchers progressively shifted their focus toward the application effectiveness and benefits of EIT in specific fields such as lung injury, abdominal surgery, and clinical trials. Recent studies have explored the application of EIT in the prevention and treatment of VILI, oxygenation status, and prone position during mechanical ventilation (31-33).

Regarding the keyword emergence intensity, the top three keywords ranked in order of highest to lowest were "titration", "ventilator-induced lung injury", and "oxygenation" (*Figure 7*). This indicates that considerable attention and research efforts have been directed toward regulating mechanical ventilation parameters, preventing VILI, and optimizing oxygenation status. Notably, the keyword "electrical impedance" demonstrated the longest burst time, indicating its enduring centrality and continued importance as the core concept and technology of EIT. An analysis of the keyword emergence graphs revealed that the research focus of EIT in mechanical ventilation has changed over the years. These studies are critical to improving the effectiveness of mechanical ventilation and reducing associated complications (34-38).

This study has limitations. First, the research scope was limited to articles published in the English language and available in the WoS database, potentially introducing a language bias due to the exclusion of non-English language literature. Second, the application of EIT in mechanical ventilation requires the intersection and integration of multiple disciplines, posing challenges in terms of interdisciplinary cooperation and the integration of data fusion and analysis techniques. However, our paper is strengthened by its long time period and meticulous review of all included articles to construct the presented data analysis. It represents a novel evaluation of the impact of EIT and research on this topic in the field of mechanical ventilation.

Conclusions

Substantial advancements have been made in applying EIT for mechanical ventilation, with the focus shifting from EIT as a standalone concept to its tailored implementation in mechanical ventilation. Currently, the primary international research hotspots are centered around the prevention and treatment of ventilator-related lung injuries, oxygenation status, and prone ventilation, which can be expected to dominate future research.

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Footnote

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Ethical Statement: The authors are accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

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