# Research Trends and Hotspots of Medical Electrical Impedance Tomography Algorithms: A Bibliometric Analysis From 1987 to 2021

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## Abstract

Electrical impedance tomography (EIT) is a gradually maturing medical imaging technique that relies on computational algorithms for reconstructing and visualizing internal conductivity distributions within the human body. To provide a comprehensive and objective understanding of the current state and trends in the EIT algorithm research, we conducted bibliometric analysis on a 25-year EIT algorithm research dataset sourced from Web of Science Core Collections. We visualized publication characteristics, collaboration patterns, keywords, and co-cited references. The results indicate a steady increase in annual publications over recent decades. The United States, United Kingdom, China, and South Korea contributed 60% of the articles collaboratively. Keyword analysis unveiled three distinct stages in the evolution of EIT algorithm research: the establishment of fundamental algorithm frameworks, optimization for improved imaging performance, and the development of algorithms for clinical applications. Additionally, there has been a shift in research focus from traditional theories to the incorporation of new methods, such as artificial intelligence. Co-cited references suggest that integrating EIT with other established imaging techniques may emerge as a new trend in EIT algorithm research. In summary, EIT algorithms have been a consistent research focus, with current efforts centered on optimizing algorithms to enhance imaging performance. The emerging research trend involves utilizing more diverse and intersecting algorithms.

**Categories:** Emergency Medicine, Medical Physics, Radiology
**Keywords:** hotspot, woscc, algorithm, eit, bibliometric analysis

## Introduction And Background

Electrical impedance tomography (EIT) is a bioimaging technique that relies on measuring electrical impedance through body-surface electrodes. Medical EIT has been used in various clinical and experimental settings, including pulmonary, brain, and tissue monitoring [1-3].

The EIT algorithms play a crucial role in generating EIT images used in bedside applications, making it a key focus of research within the EIT field [4]. The EIT algorithms encompass tasks such as reconstructing EIT images, analyzing electrical properties of tissues, calculating sensitivity matrices, and interpreting images [5]. Notably, recent advancements in reconstruction algorithms have received significant attention [5,6]. An objective review of the current research status on EIT algorithms would aid researchers in acknowledging the progress achieved in this field, identifying the scientific focus, promoting further interdisciplinary collaboration, and expanding clinical applications [7].

The bibliometric analysis offers a feasible approach for qualitatively and quantitatively evaluating publications on a specific topic through machine learning. The evaluation includes productivity, international cooperation, identification of hot spots, and emerging trends. Several studies have utilized bibliometric analysis to construct a research map of EIT clinical applications and hardware [3,8-10]. However, a specific bibliometric analysis of the topic of the EIT algorithm has not yet been conducted. The present study aims to investigate and visualize the knowledge map of the current status, emerging research areas, and future trends in medical EIT algorithms through bibliometric analysis to provide a comprehensive understanding.

## Review

### Materials and methods

*Objects and Retrieval Strategies*

The Web of Science Core Collection (WoSCC) database is one of the most comprehensive, systematic, and authoritative databases, encompassing over 12,000 influential journals from around the world [11]. For our research, we extracted the complete dataset from the WoSCC. The search strategy employed was as follows: TS = ("Electrical Impedance Tomography") AND (("algorithm") OR ("reconstruction")), with a time window from January 1, 1987, to December 31, 2021. We limited the publication type to include "Article," "Review," "Letter," and "Proceeding paper" and restricted the language to English. All investigators gathered the literature on January 23, 2021, to mitigate any potential bias due to database updates.

*Data Collection*

All the results were independently searched by two investigators, and there was a 98% agreement between their findings, indicating a significant level of consistency. Publications that were deemed less relevant to the algorithm or reconstruction topic were excluded based on the judgment of at least two experienced experts, such as publications in the fields of materials science and technology (such as materials science ceramics and materials science textiles), chemistry (including thermodynamics, engineering, and petroleum), physics (including mechanics and engineering aerospace), geography (including engineering geological, mining mineral processing, construction building technology, meteorology atmospheric sciences, and water resources), agriculture, forestry, animal husbandry, and environmental sciences. The data was exported in both text format and Unicode Transformation Format-8 (UTF-8) to facilitate further software analysis.

*Bibliometric Analysis by WoSCC Output*

The primary functions of the WoS core database and Microsoft Excel (Microsoft 365; Microsoft, Redmond, Washington) are to generate and present various characteristics of publications. These characteristics include the number of literature items, publication years, countries, institutions, journals, citations, etc.

*Bibliometric Analysis by VOSviewer*

We utilized VOSviewer, a bibliometric software version 1.6.16 (Leiden University, Leiden, the Netherlands, https://www.vosviewer.com/), to process the data and generate a co-authorship network map depicting the relationships between countries, authors, and institutions as well as the co-occurrence map of keywords [12]. Certain thresholds were set, including a minimum publication count of five for collaborative countries, authors, and institutions and a minimum co-occurrence count of five for the co-occurrence network of keywords. To enhance the efficiency of our analysis, we merged different keywords that had similar meanings. For example, "eit," "electrical impedance tomography (EIT)," "electrical-impedance tomography," and "impedance tomography" were consolidated into the single term "electrical impedance tomography."

*Bibliometric Analysis by CiteSpace*

CiteSpace, a bibliometric software, version 5.7R5 (Chen Meichao, Drexel University, https://citespace.podia.com/), was utilized for conducting keyword burst analysis as well as cited reference burst, cluster, and timeline view analysis.

## Results

*Publication Output of WoSCC*

According to the search strategy, a total of 2513 publications were identified. After filtering, we analyzed 2217 research articles, reviews, letters, and proceeding papers published in English and focused on the EIT algorithm (Figure *1*).

**FIGURE 1: Flow chart of included publications**

WoSCC: Web of Science Center.
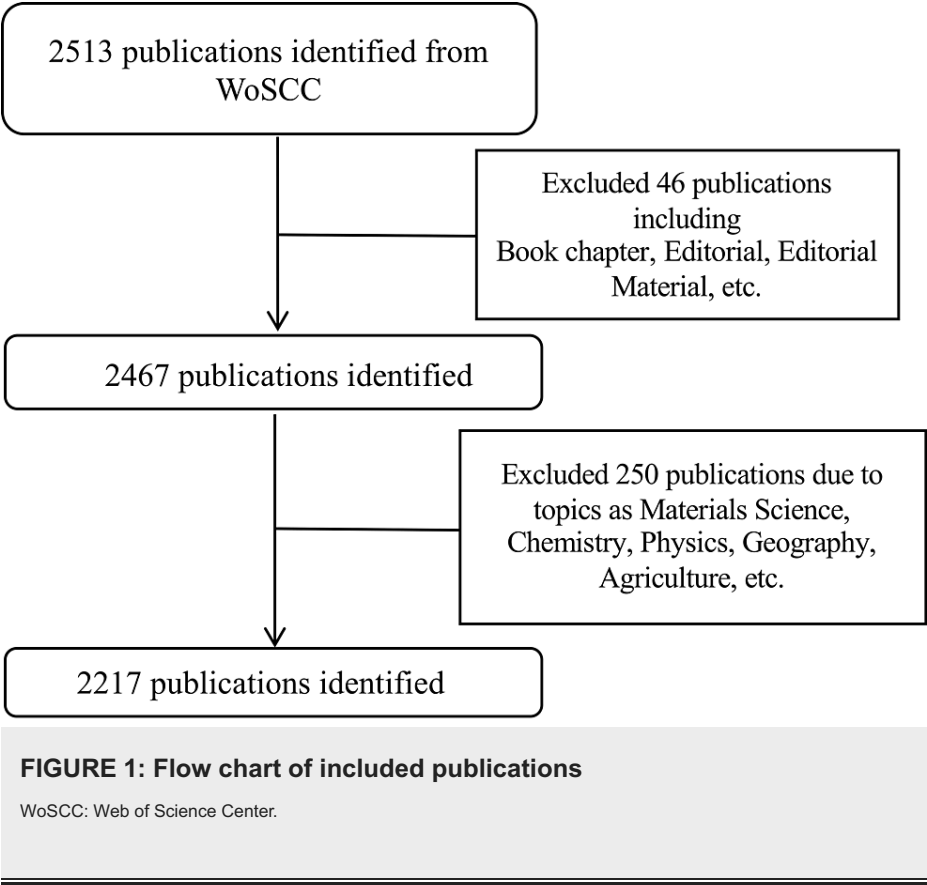
*Growth Trend and Geographical Distribution*

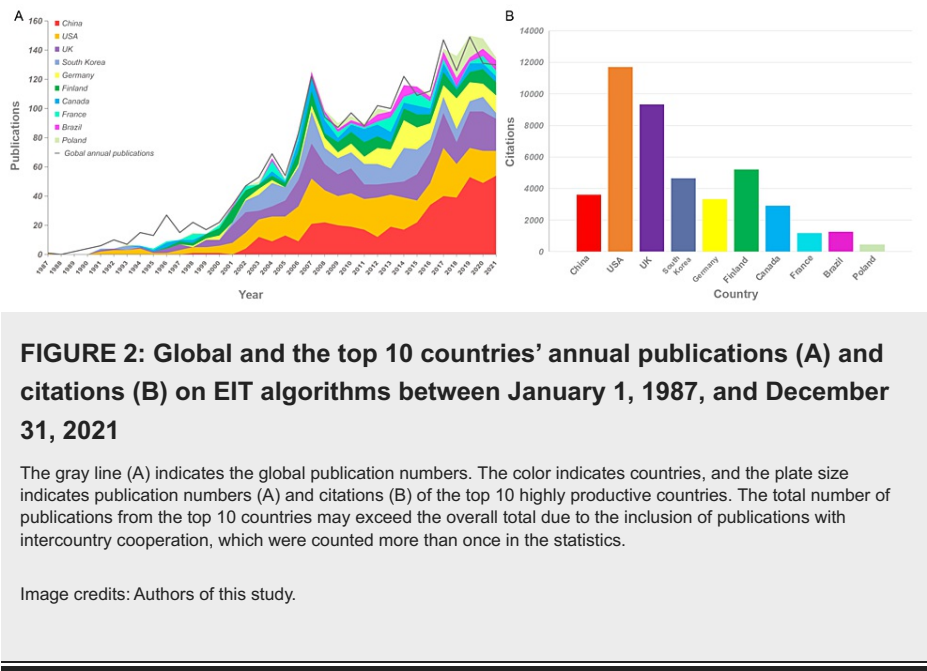Publications on the EIT algorithm from 1987 to 2021 were available in 63 countries. The annual global publications on the EIT algorithm showed a generally increasing trend and exceeded 100 for the first time in 2007 (Figure 2). The top three most prolific and cited countries were China, the United States of America (USA), and the United Kingdom (UK).



**FIGURE 2: Global and the top 10 countries' annual publications (A) and citations (B) on EIT algorithms between January 1, 1987, and December 31, 2021**

The gray line (A) indicates the global publication numbers. The color indicates countries, and the plate size indicates publication numbers (A) and citations (B) of the top 10 highly productive countries. The total number of publications from the top 10 countries may exceed the overall total due to the inclusion of publications with intercountry cooperation, which were counted more than once in the statistics.

Image credits: Authors of this study.

*Most Productive Institutions, Authors, Journals, and Highly Cited References*

The top 10 institutions, authors, and journals that published the most pieces of literature on EIT algorithms are summarized in Tables 1-3, respectively. In our study, universities (described as

univ; publication numbers; and citation numbers) are the main types of institutions. Kyung Hee University (Kyung Hee Univ; 122; 2960), Tianjin University (Tianjin Univ; 121; 938), and Yonsei University (Yonsei Univ; 89; 2844) ranked top three in the number of publications. The *Journal of Physiological Measurement (J Physiol Meas*; 269; 6,522) published the highest number of EIT publications and owned the most frequently published articles. In addition, a total of 338 authors have contributed to related articles, with Woo EJ, Seo JK, and Kwon O from South Korea emerging as the top three most prolific authors. The top 10 cited references included two reviews and eight articles (Table *4*), and the article by Cheney et al. [13] was the most cited.

| No. | Institute | Publication | Citation |
|---|---|---|---|
| 1 | Kyung Hee Univ | 122 | 2960 |
| 2 | Tianjin Univ | 121 | 938 |
| 3 | Yonsei Univ | 89 | 2844 |
| 4 | UCL | 88 | 3262 |
| 5 | Univ Manchester | 75 | 3577 |
| 6 | Konkuk Univ | 71 | 2073 |
| 7 | Carleton Univ | 55 | 1429 |
| 8 | Fourth Mil Med Univ | 51 | 346 |
| 9 | Middlesex Univ | 48 | 1611 |
| 10 | Dartmouth Coll | 47 | 1389 |

**TABLE 1: Top 10 prolific institutions of EIT algorithm research**

UCL: University College London; EIT: Electrical impedance tomography.

| No. | Author | Publication | Citation* |
|---|---|---|---|
| 1 | Woo and Seo | 120 | 3206 |
| 2 | Seo et al. | 78 | 2672 |
| 3 | Kwon et al. | 70 | 2227 |
| 4 | Adler et al. | 67 | 2376 |
| 5 | Wang et al. | 50 | 485 |
| 6 | Dong F | 45 | 308 |
| 7 | Bayford RH | 44 | 1258 |
| 8 | Vauhkonen et al. | 43 | 2282 |
| 9 | Rymarczyk T | 43 | 256 |
| 10 | Fu F | 38 | 238 |

**TABLE 2: Top 10 prolific authors of EIT algorithm research**

*Citation: The cumulative citation count for all publications by the author.

EIT: Electrical impedance tomography.

| No. | Journal* | Publication | Citation | IF# |
|---|---|---|---|---|
| 1 | Physiol Meas | 269 | 6522 | 2.83 |
| 2 | Inverse Probl | 128 | 4219 | 2.41 |
| 3 | IEEE T Med Imaging | 103 | 3799 | 10.05 |
| 4 | Meas Sci Technol | 90 | 2378 | 2.05 |
| 5 | IEEE T Bio-Med Eng | 75 | 3416 | 4.54 |
| 6 | Phys Med Biol | 59 | 2586 | 3.61 |
| 7 | IEEE Sens J | 51 | 781 | 3.30 |
| 8 | IEEE T Instrum Meas | 46 | 568 | 4.02 |
| 9 | Inverse Probl Imag | 37 | 574 | 1.64 |
| 10 | Inverse Probl Sci En | 37 | 358 | 1.95 |

**TABLE 3: Top 10 prolific journals of EIT algorithm research**

*Physiol Meas: Physiological Measurement; Inverse Probl: Inverse Problems; IEEE T Med Imaging: IEEE Transactions on Medical Imaging; Meas Sci Technol: Measurement Science and Technology; IEEE T Bio-Med Eng: IEEE Transactions on Biomedical Engineering; Phys Med Biol: Physics in Medicine and Biology; IEEE Sens J: IEEE Sensors Journal; IEEE T Instrum Meas: IEEE Transactions on Instrumentation and Measurement; Inverse Probl Imag: Inverse Problems and Imaging; Inverse Probl Sci En: Inverse Problems in Science and Engineering.

#IF: Impact factor.

EIT: Electrical impedance tomography.

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| Reference title | Publication type | Author | Year | Journal | Citations | Reference |
|---|---|---|---|---|---|---|
| Electrical impedance tomography | Article | Cheney et al. | 1999 | Siam Rev | 722 | [13] |
| Electrical impedance tomography | Review | Borcea | 2002 | Inverse Probl | 489 | [14] |
| Uses and abuses of EIDORS: an extensible software base for EIT | Article | Adler et al. | 2006 | Physiol Meas | 411 | [15] |
| Comparing reconstruction algorithms for electrical impedance tomography | Article | Yorkey et al. | 1987 | IEEE T Bio-Med Eng | 402 | [16] |
| GREIT: a unified approach to 2D linear EIT reconstruction of lung images | Article | Adler et al. | 2009 | Physiol Meas | 356 | [17] |
| Imbalances in regional lung ventilation a validation study on electrical impedance tomography | Article | Victorino et al. | 2004 | Am J Resp Crit Care | 344 | [18] |
| Tikhonov regularization and prior information in electrical impedance tomography | Article | Vauhkonen et al. | 1998 | IEEE T Med Imaging | 336 | [19] |
| Calderon's inverse conductivity problem in the plane | Article | Astala and Païvärinta | 2006 | Ann Math | 334 | [20] |
| Three-dimensional electrical impedance tomography | Article | Metherall et al. | 1996 | Nature | 309 | [21] |
| EIT reconstruction algorithms: pitfalls, challenges, and recent developments | Review | Lionheart | 2004 | Physiol Meas | 308 | [5] |

**TABLE 4: The top 10 most cited reference\* articles on EIT algorithm publications**

\*Cited reference: The reference articles of publications on the EIT algorithm involved in the analysis.

EIT: Electrical impedance tomography.

*Collaboration Between Countries, Authors, and Institutions*

The collaboration map illustrating the relationships between countries, authors, and institutions is presented in Figure 3. The visualization showcases the combined efforts, measured as total link strength, among the most prolific countries, institutions, and authors. According to our study, the USA (225), the UK (216), and China (165) emerged as the most cooperative countries in terms of the EIT algorithm. Additionally, Woo EJ (207) and Kim HJ (143) from South Korea as well as Fu F (154) and Dong XZ (132) from China were identified as the most cooperative authors worldwide, showcasing strong internal collaboration. Notably, Kyung Hee University (164), Yonsei University (136), and Konkuk University (107) were the institutions with the highest level of cooperation.
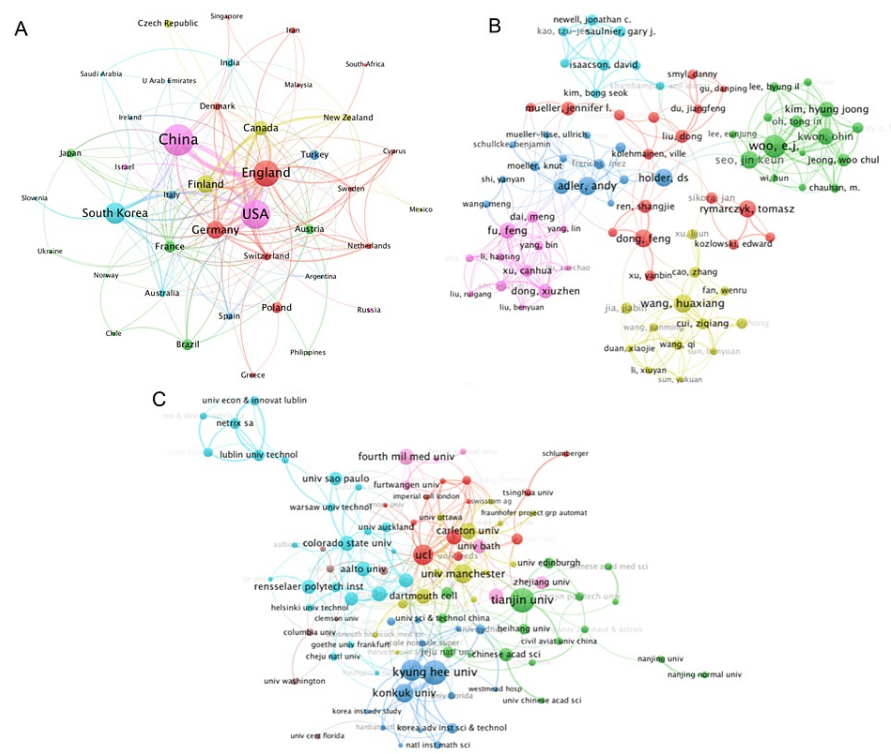
**FIGURE 3: Collaborations between countries (A), authors (B), and institutions (C) on EIT algorithm research between January 1, 1987, and December 31, 2021**

Different colors indicated different clusters of countries (A), authors (B), and institutions (C); color plate size indicated the publications number, and the boldness of lines between circles indicated the strength of linkage calculated on the frequency of collaborations.

Image credits: Authors of this study.

*Keywords Co-occurrence Network and Overlay Analysis*

Co-occurrence network mapping and overlay analysis were conducted on 447 keywords that appeared five or more times in publications on the EIT algorithm. The keywords were categorized into eight clusters, with the five largest clusters focusing successively on "algorithm," "lung-based clinical application direction," "new algorithm reconstruction methods," "key problems in reconstruction algorithm," and "algorithm optimization." The remaining clusters were related to "extrapulmonary clinical application" and "comparison of algorithms". The main keywords in each cluster are presented in Appendix Table *7*. In addition to the keywords "electrical impedance tomography," "reconstruction," and "algorithm," five other frequently co-occurring keywords were identified: "inverse problem" (316; 755), "conductivity" (273; 1882), "tomography" (195; 923), "system" (174; 1063), and "regularization" (165; 927) (Figure *4*, Panel A). The top 10 most frequent keywords are listed in Table *5*.

| Rank | Keywords | Occurrences | Link strength |
|------|----------|-------------|---------------|
| 1 | Electrical impedance tomography | 1524 | 6973 |
| 2 | Image reconstruction | 801 | 4157 |
| 3 | Algorithms | 429 | 2586 |
| 4 | Inverse problem | 316 | 1755 |
| 5 | Conductivity | 273 | 1882 |
| 6 | Tomography | 195 | 923 |
| 7 | System | 174 | 1063 |
| 8 | Regularization | 165 | 927 |
| 9 | MREIT | 135 | 968 |
| 10 | Electrode models | 180 | 619 |

**TABLE 5: Top 10 highly frequent keywords on EIT algorithm publication**

EIT: Electrical impedance tomography; MREIT: Magnetic resonance electrical impedance tomography.

To further explore the trends in these keywords, an overlay network was created (Figure 4, Panel B). The earliest and latest keywords, along with their average publication year, are summarized in Table 6. The keyword "applied potential tomography" (2003.08) was the earliest, while "deep learning" (2020.06) was the latest. Among the earliest frequent keywords, "boundary-value problem" (2007.64) had the highest co-occurrence frequency, while "machine learning" (2018.81) ranked first among the latest frequent keywords.
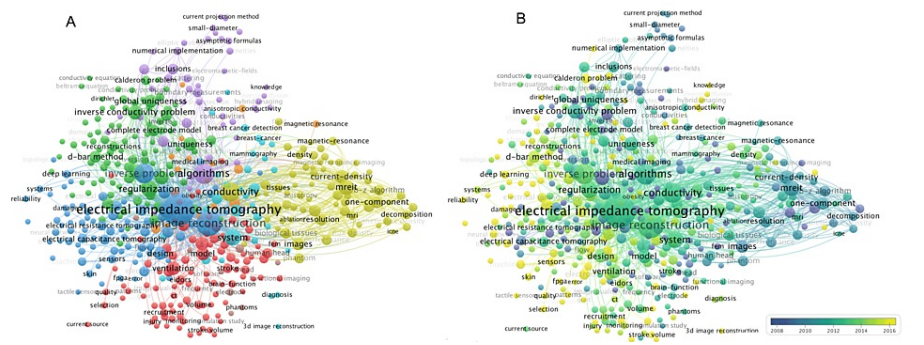


**FIGURE 4: Keywords co-occurrence network map (A) and overlay analysis (B) on EIT algorithm research between January 1, 1987, and December 31, 2021**

Circle size represents the number of occurrences, and the line boldness indicates link strengths. Different colors represent different clusters (A) and different average years of publications in which the keyword occurs (B), and the color of publications before 2008 in Panel B is the same as 2008 due to the limited number.

Image credits: Authors of this study.

*Keywords Burst Analysis*

The burst strength of keywords was another important indicator that reflected the research hotspots and emerging trends over time. Figure 5 presents the top 15 keywords with high burst values. Throughout the entire research period, "current computed tomography" (21.8) had the highest burst value, followed by "one component" (9.61), "mreit" (9.38), "regularization" (7.87), and "applied potential tomography" (7.35). In the earlier period of 1990-2013, keywords such as "current computed tomography," "one component," "mreit," "applied potential tomography," and "tomography" (7.08) were of significant concern. In contrast, "shape reconstruction" (5.31), "regularization" (7.87), and "skin" (6.05) gained strong attention after 2013 and maintained a high burst value until the present.
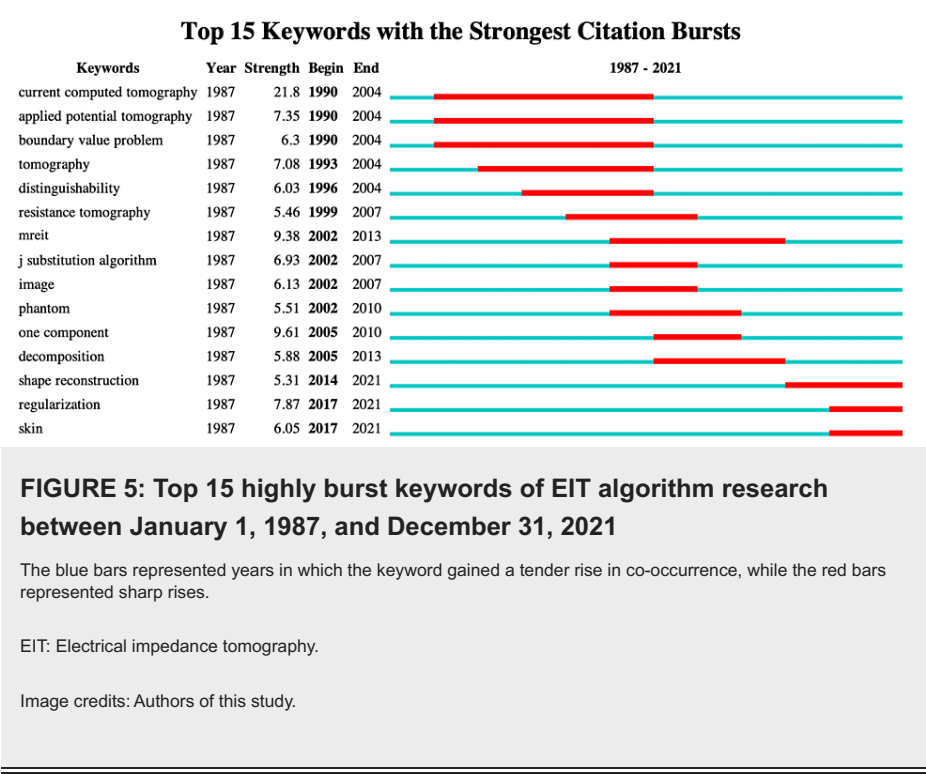
| Rank | Earliest Keyword | Occurrences | Avg. pub. year* | Latest Keyword | Occurrences | Avg. pub. year* |
|---|---|---|---|---|---|---|
| 1 | Applied potential tomography | 25 | 2003.08 | Voltage measurement | 16 | 2020.50 |
| 2 | Impedance imaging | 19 | 2004.53 | Deep learning | 17 | 2020.06 |
| 3 | Current computed tomography | 94 | 2005.38 | Convolutional neural network | 6 | 2019.67 |
| 4 | Uniqueness theorem | 15 | 2005.60 | Inclusion boundary reconstruction | 5 | 2019.60 |
| 5 | Kalman filter | 24 | 2006.92 | Acousto-electric tomography | 5 | 2019.20 |
| 6 | Boundary-value problem | 48 | 2007.64 | Skin | 14 | 2019.14 |
| 7 | J-substitution algorithm | 36 | 2007.83 | Strain | 14 | 2019.08 |
| 8 | Prior information | 25 | 2007.88 | Framework | 8 | 2018.88 |
| 9 | MREIT | 41 | 2008.32 | Spatial prior | 6 | 2018.83 |
| 10 | Conductivity image | 22 | 2008.50 | Machine learning | 21 | 2018.81 |

**TABLE 6: Top 10 frequent keywords in the earliest and latest stages of EIT algorithm publications**

*Avg. pub. year: The average publication year of the articles in which the keyword occurs (to the nearest two decimal places).

EIT: Electrical impedance tomography; MREIT: Magnetic resonance electrical impedance tomography.



**FIGURE 5: Top 15 highly burst keywords of EIT algorithm research between January 1, 1987, and December 31, 2021**

The blue bars represented years in which the keyword gained a tender rise in co-occurrence, while the red bars represented sharp rises.

EIT: Electrical impedance tomography.

Image credits: Authors of this study.

*Clustering and Time Evolution of Co-cited References*

References co-cited by publications on the EIT algorithm were divided into 22 clusters (described as cluster no, cluster size) (Figure 6), A vertical descending sequence illustrates the size of each cluster. The largest cluster, labeled as "magnetic resonance" (#0, 149), is followed by the next five largest clusters: "shape reconstruction" (#1, 137), "using Calderon's method" (#2, 121), "boundary measurement" (#3, 112), "human

brain activity" (#4, 85), and "canine brain" (#5, 84). The largest eight clusters are listed in Appendix Table *6*. Analysis of co-cited references over time revealed that references related to "boundary measurement" (#3), "human brain activity" (#4), "canine brain" (#5), and "second section" (#7) were highly cited before 2013, while "magnetic resonance" (#0) and "shape reconstruction" (#1) remained popular citation topics up to the present.
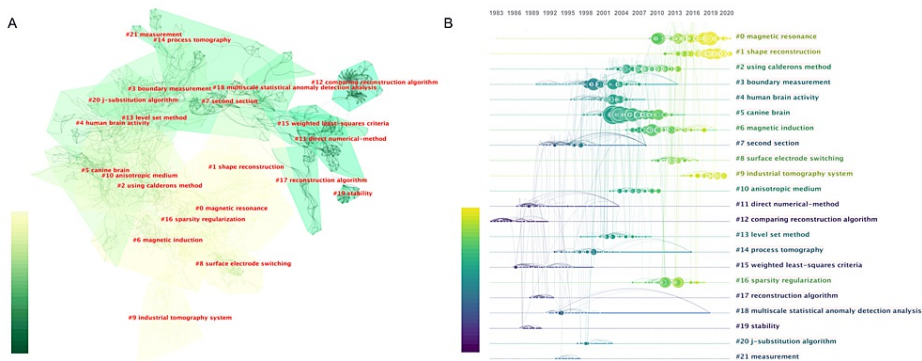


**FIGURE 6: The clustering (A) and time-evolving analysis (B) of co-cited reference on EIT algorithm research between January 1, 1987, and December 31, 2021**
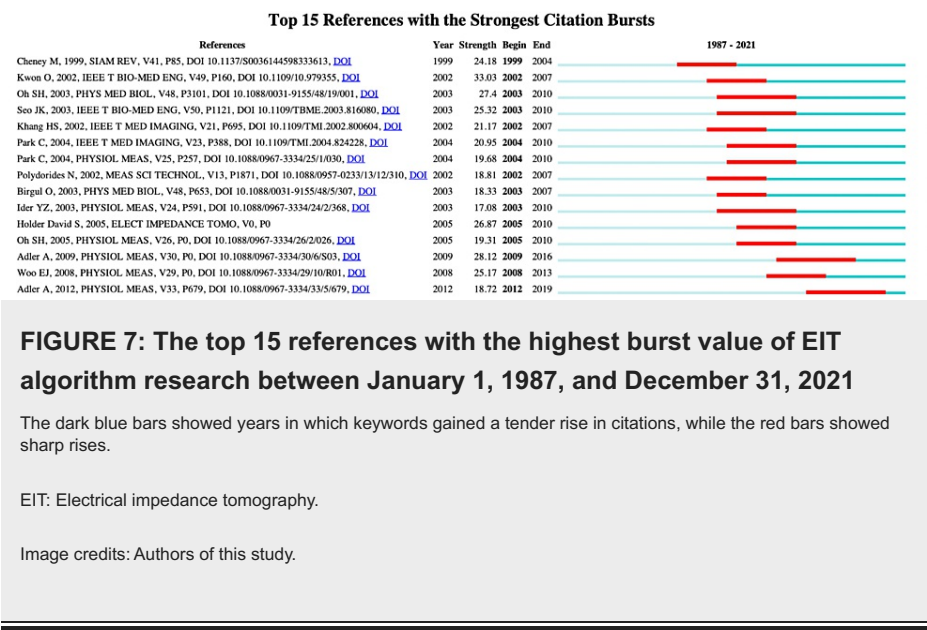
Different colors meant the decadal transition of publication year. The vertical descending sequence represented the size of the cluster. (A) The line boldness represented the linkage tightness. (B) The color curves represented co-cited links added in the corresponding color year. Large nodes represented that the articles are either highly referenced, have reference bursts, or both. The specific publication year is indicated above the map. The modularity Q score is 0.8567, the mean silhouette is 0.9363, and the harmonic mean (Q, S) is 0.8947.

EIT: Electrical impedance tomography.

Image credits: Authors of this study.

*Co-cited References Burst Analysis*

The top 15 references with strong co-cited burst values of the EIT algorithm are summarized in Figure *7*. These references started to burst in 1999, and approximately one-third of them were published in the journal *Physiol Meas*. The article "Cheney et al., 1999, SIAM Rev [13]" had the highest burst strength with a value of 33.03, followed by the article "Adler et al., 2009, *Physiol Meas* [17]" with a value of 28.12, the book "Holder, 2005, *Biomed Eng Online* [22]" with a value of 26.87, and the article "Seo, 2003, *IEEE Trans Biomed Eng* [23]" with a value of 25.32. The burst value duration ranged from four to seven years, and the most recent reference with a burst duration from 2012 to 2019 is the review by Adler et al. [24]. A summary of the top 15 co-cited references can be found in Appendix Table *7*.

**Top 15 References with the Strongest Citation Bursts**

| References | Year | Strength | Begin | End | 1987 - 2021 |
|---|---|---|---|---|---|
| Cheney M, 1999, SIAM REV, V41, P85, DOI 10.1137/S0036144598333613, DOI | 1999 | 24.18 | 1999 | 2004 | |
| Kwon O, 2002, IEEE T BIO-MED ENG, V49, P160, DOI 10.1109/10.979355, DOI | 2002 | 33.03 | 2002 | 2007 | |
| Oh SH, 2003, PHYS MED BIOL, V48, P3101, DOI 10.1088/0031-9155/48/19/001, DOI | 2003 | 27.4 | 2003 | 2010 | |
| Seo JK, 2003, IEEE T BIO-MED ENG, V50, P1121, DOI 10.1109/TBME.2003.816080, DOI | 2003 | 25.32 | 2003 | 2010 | |
| Khang HS, 2002, IEEE T MED IMAGING, V21, P695, DOI 10.1109/TMI.2002.800604, DOI | 2002 | 21.17 | 2002 | 2007 | |
| Park C, 2004, IEEE T MED IMAGING, V23, P388, DOI 10.1109/TMI.2004.824228, DOI | 2004 | 20.95 | 2004 | 2010 | |
| Park C, 2004, PHYSIOL MEAS, V25, P257, DOI 10.1088/0967-3334/25/1/030, DOI | 2004 | 19.68 | 2004 | 2010 | |
| Polydorides N, 2002, MEAS SCI TECHNOL, V13, P1871, DOI 10.1088/0957-0233/13/12/310, DOI | 2002 | 18.81 | 2002 | 2007 | |
| Birgul O, 2003, PHYS MED BIOL, V48, P653, DOI 10.1088/0031-9155/48/5/307, DOI | 2003 | 18.33 | 2003 | 2007 | |
| Ider YZ, 2003, PHYSIOL MEAS, V24, P591, DOI 10.1088/0967-3334/24/2/368, DOI | 2003 | 17.08 | 2003 | 2010 | |
| Holder David S, 2005, ELECT IMPEDANCE TOMO, V0, P0 | 2005 | 26.87 | 2005 | 2010 | |
| Oh SH, 2005, PHYSIOL MEAS, V26, P0, DOI 10.1088/0967-3334/26/2/026, DOI | 2005 | 19.31 | 2005 | 2010 | |
| Adler A, 2009, PHYSIOL MEAS, V30, P0, DOI 10.1088/0967-3334/30/6/S03, DOI | 2009 | 28.12 | 2009 | 2016 | |
| Woo EJ, 2008, PHYSIOL MEAS, V29, P0, DOI 10.1088/0967-3334/29/10/R01, DOI | 2008 | 25.17 | 2008 | 2013 | |
| Adler A, 2012, PHYSIOL MEAS, V33, P679, DOI 10.1088/0967-3334/33/5/679, DOI | 2012 | 18.72 | 2012 | 2019 | |

**FIGURE 7: The top 15 references with the highest burst value of EIT algorithm research between January 1, 1987, and December 31, 2021**

The dark blue bars showed years in which keywords gained a tender rise in citations, while the red bars showed sharp rises.

EIT: Electrical impedance tomography.

Image credits: Authors of this study.

## Discussion

The EIT image reconstruction algorithm plays a crucial role in its clinical application. Our bibliometric analysis has visualized the development process, current status, and emerging trends in EIT algorithm research. This analysis offers concise and informative references for researchers interested in the EIT algorithm, providing research directions and potential collaboration opportunities.

The number of annual articles on the EIT algorithm has steadily increased since its first publication by Rose and Cheney [25] in 1987, rising from one article to 140 articles in 2021. The USA, UK, China, and South Korea have contributed to over 60% of these articles. The significant rise in Chinese publications since 2015 may be attributed to the increasing interest from Chinese research institutes, such as Nanjing University of Aeronautics and Astronautics and Tsinghua University, inspired by the annual conference held by the EIT branch of the Chinese Society of Biomedical Engineering [26].

Notably, strong collaboration was observed among highly prolific institutions and authors (Figure 3). In contrast to the geographical distribution of cooperation projects in other academic fields, as reported by Kudu and Danış[27], researchers in the field of EIT actively collaborated across continents in the development of algorithms. For instance, the Graz Consensus Reconstruction Algorithm for EIT (GREIT), a consensus linear reconstruction algorithm for lung EIT, was developed through cooperation between Europe and America [17]. Similarly, researchers in Asia and America proposed an isotropic conductivity reconstruction algorithm in magnetic resonance electrical impedance tomography (MREIT), which is based on a single current injection to decrease scanning time [28]. *Physiol Meas* is the journal that has published the highest number of articles and received the most citations, possibly because of its long-standing association with the EIT Annual Conference and its publication of annual focus sets aimed at presenting the latest advances in EIT research. This association offers an opportunity for transnational and interest-driven cooperation on EIT algorithm research.

Several studies that pioneered classic EIT algorithm frameworks in the early stages were highly cited, which aligns with our frequently used keywords, such as "inverse problem" and "regularization." Vauhkonen et al. developed the utilization of Tikhonov regularization and prior information to enhance the stability and accuracy of EIT reconstruction [19]. Grychtol et al. proposed the use of a linear EIT reconstruction technique called GREIT for pulmonary monitoring. They achieved several important improvements, including a uniform amplitude response, minimized position error, reduced ringing artifacts, maintained uniform resolution, limited shape deformation, and provided high-resolution results [29]. These empirical EIT algorithms laid a solid foundation for medical applications. Subsequently, the primary objective of developing EIT algorithms has been to obtain the ideal solution to the inverse problem, ensuring that the measured boundary voltage maps the impedance distribution accurately. Initial studies focused on applying well-known theories for solving the inverse problem, such as the "uniqueness theorem," "Kalman filter," and "boundary-value problem." More recently, there has been an emerging trend in building EIT algorithms using artificial intelligence methods, such as "deep learning" [30], "convolutional neural networks" [31], and "machine learning" (Table 6) [32].

Bursting keywords over time illustrate the changes in the study topics. Initially, the points focused on fundamental issues of the EIT algorithm, specifically the resolution of the "boundary-value problem" and the enhancement of EIT distinguishability. Woo's research team presented a promising approach to achieve high-resolution impedance imaging by combining MRI and EIT. They incorporated the internal current

density distribution into EIT image reconstruction, known as the "J-substitution algorithm" [33]. During the same period, there was a focus on developing accurate reconstruction models that incorporate anatomical structure and impedance distribution based on CT/MRI to improve spatial resolution, shape error, and position error [34]. Additionally, there were studies on accurate phantoms being conducted concurrently to evaluate the efficacy of the new EIT algorithm. Currently, the research focus has shifted to improving custom reconstruction strategies that meet specific application requirements. For instance, Liu et al. approached the EIT reconstruction problem as a "shape reconstruction" problem, aiming to enhance the tolerance toward modeling errors and uncertainties in EIT for lung imaging [35].

The co-cited reference cluster highlights several methods related to the EIT algorithm, including weighted least-squares criteria, Calderon's method, the level set method, sparsity regularization, and the J-substitution algorithm. It also mentions that "shape reconstruction" has been the focal point of research since 2013. Novel reconstruction strategies are often proposed to meet both the advanced acknowledgment of inverse problem theories and clinical requirements. The review by Cheney et al. from the group of Rensselaer Polytechnic Institute, published in 1999, was the highest burst co-cited reference [13]. This review describes the design of the famous Rensselaer EIT system, known as the adaptive current tomography (ACT) system, and surveys typical reconstruction algorithms. The time evolution of co-cited references further shows that "MREIT" novel imaging modalities regarding magnetic resonance is a highly co-cited reference cluster. Since Woo's research group proposed MREIT in 2005 [36], articles regarding innovative MREIT algorithms and their validation were published, providing the basis for future generations to establish the basic algorithm framework of MREIT. In summary, high-quality reviews and articles from pioneering institutions over time provide a relatively complete knowledge map at that time. Integrating EIT with other imaging technologies may open up a new research branch for EIT algorithms.

## Strengths and limitations

This study aims to visualize the current situation, hot issues, and research trends in EIT algorithm research between 1987 and 2021, providing a convenient and objective reference for researchers in need. However, there are certain limitations. First, due to the interdisciplinary nature of EIT, we chose to include all citation indexes under WoSCC and subjectively excluded less relevant literature with the help of EIT experts to ensure the maximum inclusion of relevant literature. Second, the WoSCC database is constantly updated, so some new data may be missed, even if the entire database search was conducted within a single day. Third, the various ways in which authors, institutions, and keywords are expressed result in a dispersion of counts and clusters. Although these issues were addressed using the merge and normalization function of the software, they cannot be eliminated.

## Conclusions

The EIT algorithm has been the subject of research over the past three decades. The research focus on this topic has generally progressed through three stages: first, the establishment of basic algorithm frameworks; second, the optimization of algorithms to enhance imaging performance; and lastly, the improvement to facilitate clinical applications. Another emerging research trend is the exploration of more diversified algorithms and the intersection of EIT with machine learning techniques.

## Appendices

| Co-occurrence cluster | Keywords |
|---|---|
| Cluster 1: Algorithm | fidelity-embedded regularization; regularization; inverse problem; electrode models; finite element method; optimization; state estimation; Kalman filter; machine learning; level set method; approximation errors; deep learning; statistical inversion; Bayesian inversion; extended Kalman filter; sensitivity-analysis; total variation regularization; boundary element method; conformal transformation; modeling errors; Tikhonov; adaptive mesh refinement; boundary estimation; Calderon's method; iteration method; Monte-Carlo methods; nonlinear image-reconstruction; singular value decomposition; sparse representation. |
| Cluster 2: Lung and brain-based clinical application direction | ventilation; stroke; volume; perfusion; regional lung ventilation; recruitment; brain-function; end-expiratory pressure; hemorrhage; human brain-function; lung perfusion; stroke volume; current patterns; derecruitment; infants; epilepsy; GREIT; multifrequency EIT system; source localization; acute respiratory distress syndrome; blood-flow. |
| Cluster 3: New algorithm reconstruction methods | MREIT; b-z algorithm; J-substitution algorithm; magnetic flux density; contrast; ultrasound; magnetic induction; anisotropy; thermoacoustic tomography; current-density distribution; ablation; conductivity tensor; d-bar method. |
| Cluster 4: Key problems in the reconstruction algorithm | artefact; inverse conductivity problem; uniqueness; boundary-value problem; convergence; Calderon problem; Tikhonov regularization; stability; prior information; ill-posed problems; Neumann-to-Dirichlet map; level set; nonlinear inverse problems; shape optimization; minimization; convergence-rates; Lipschitz stability; topology optimization; imperfectly known boundary. |
| Cluster 5: Optimization in the algorithm | factorization method; identification; boundary measurements; shape reconstruction; asymptotic formulas; hybrid imaging; small-diameter; linear sampling method; optical tomography; elliptic problems; inverse scattering; monotonicity method; location; acousto-electric tomography; current projection method; microwave imaging. |
| Cluster 6: Extrapulmonary clinical application | breast cancer; cancer detection; diagnosis; mammography; prostate cancer; intracerebral hemorrhage. |
| Cluster 7: Electromagnetic induction | forward problem; hardware; electromagnetic tomography; magnetic induction tomography (MIT); phantoms; sensitivity maps. |
| Cluster 8: Others | inclusion boundary reconstruction. |

**TABLE 7: Major keywords in each keyword co-occurrence cluster on the EIT algorithm**

EIT: Electrical impedance tomography; MREIT: Magnetic resonance electrical impedance tomography.

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| Cluster ID | Size | Silhouette | Label (LSI) | Label (LLR) | Label (MI) | Average Year |
|---|---|---|---|---|---|---|
| 0 | 149 | 0.883 | Dynamic brain | Magnetic resonance (505.63, 1.0E-4) | Measurement (3.2) | 2014 |
| 1 | 137 | 0.942 | Nonlinear reconstruction | Shape reconstruction (579.83, 1.0E-4) | Measurement (0.88) | 2017 |
| 2 | 121 | 0.904 | D-bar method | Using Calderon's method (936.56, 1.0E-4) | Quasistatic reconstruction (1.43) | 2007 |
| 3 | 112 | 0.905 | Factorization method | Boundary measurement (520.3, 1.0E-4) | Reconstructing isotropic conductivities (0.24) | 2000 |
| 4 | 85 | 0.946 | Human brain activity | Human brain activity (440.04, 1.0E-4) | Tomography (0.32) | 2001 |
| 5 | 84 | 0.952 | Magnetic resonance | Magnetic resonance (1913.35, 1.0E-4) | Inductive magnetic resonance (0.66) | 2004 |
| 6 | 81 | 0.968 | Magnetic induction | Magnetic induction (808.48, 1.0E-4) | Measurement (0.34) | 2010 |
| 7 | 65 | 0.917 | Nonlinear reconstruction | Second section (146.24, 1.0E-4) | Finite element method (0.02) | 1994 |

**TABLE 8: The largest eight clusters in co-cited reference on the EIT algorithm**

LSI: Latent semantic indexing; LLR: Log-likelihood ratio; MI: Mutual information; EIT: Electrical impedance tomography.

| Rank | Title | Type | Author | Year | Journal | Strength | Reference |
|------|-------|------|--------|------|---------|----------|-----------|
| 1 | Electrical impedance tomography | Article | Cheney et al. | 1999 | Siam Rev | 24.18 | [13] |
| 2 | Magnetic resonance electrical impedance tomography (MREIT): simulation study of J-substitution algorithm | Article | Kwon et al. | 2002 | IEEE T Bio-Med Eng | 33.03 | [37] |
| 3 | Conductivity and current density image reconstruction using harmonic Bz algorithm in magnetic resonance electrical impedance tomography | Article | Oh et al. | 2003 | Phys Med Biol | 27.4 | [38] |
| 4 | Reconstruction of conductivity and current density images using only one component of magnetic field measurements | Article | Seo et al. | 2003 | IEEE T Bio-Med Eng | 25.32 | [23] |
| 5 | J-substitution algorithm in magnetic resonance electrical impedance tomography (MREIT): phantom experiments for static resistivity images | Article | Khang et al. | 2002 | IEEE T Med Imaging | 21.17 | [33] |
| 6 | Electrical conductivity imaging using gradient B/sub z/ decomposition algorithm in magnetic resonance electrical impedance tomography (MREIT) | Article | Park et al. | 2004 | IEEE T Med Imaging | 20.95 | [39] |
| 7 | Static conductivity imaging using variational gradient Bz algorithm in magnetic resonance electrical impedance tomography | Article | Park et al. | 2004 | Physiol Meas | 19.68 | [40] |
| 8 | A Matlab toolkit for three-dimensional electrical impedance tomography: a contribution to the Electrical Impedance and Diffuse Optical Reconstruction Software project | Article | Polydorides et al. | 2002 | Meas Sci Technol | 18.81 | [41] |
| 9 | Current constrained voltage scaled reconstruction (CCVSR) algorithm for MR-EIT and its performance with different probing current patterns | Article | Birgul et al. | 2003 | Phys Med Biol | 18.33 | [42] |
| 10 | Uniqueness and reconstruction in magnetic resonance–electrical impedance tomography (MR—EIT) | Article | Ider et al. | 2003 | Physiol Meas | 17.08 | [43] |
| 11 | Electrical impedance tomography (1st edition) | Book | Wang G | 2005 | Institute of Physics Publishing, Bristol and Philadelphia | 26.87 | [22] |
| 12 | Electrical conductivity images of biological tissue phantoms in MREIT | Article | Oh et al. | 2005 | Physiol Meas | 19.31 | [36] |
| 13 | GREIT: a unified approach to 2D linear EIT reconstruction of lung images | Article | Adler et al. | 2009 | Physiol Meas | 28.12 | [17] |
| 14 | Magnetic resonance electrical impedance tomography (MREIT) for high-resolution conductivity imaging | Review | Woo and Seo | 2008 | Physiol Meas | 25.17 | [44] |
| 15 | Whither lung EIT: Where are we, where do we want to go and what do we need to get there? | Review | Adler et al. | 2012 | Physiol Meas | 18.72 | [24] |

**TABLE 9: Top 15 references with the strongest citation bursts**

## Additional Information

### Author Contributions

All authors have reviewed the final version to be published and agreed to be accountable for all aspects of the work.

**Concept and design:** Shiyue Lu, Zhe Li, Zhangjun Tan, Lin Yang, Meng Dai, Zhanqi Zhao

## Disclosures

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