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Research article

Emerging trends and hot spots on electrical impedance tomography extrapulmonary applications

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ABSTRACT

Objective: Electrical impedance tomography (EIT) develops rapidly in technology and applications. Nowadays EIT is used in multiple clinical and experimental scenarios including pulmonary, brain, and tissue monitoring, etc. The present study explores the research trends and hotspots on EIT extrapulmonary application research by bibliometrics analysis.
Approach: Publications on EIT extrapulmonary applications between 1987 and 2021 were retrieved from the Web of Science Core Collection database. For precise screening, search strategy "electrical impedance tomography" plus "hemodynamic" or "brain" or "nerve" or "cancer" or "venous" or "vessel" or "tumor" or "veterinary" or "tissue" or "cell" or "wearable" or "application" and excluding "lung", "ventilation" "respiratory", "pulmonary", "algorithm", "current", "voltage" or "electrode" were used. CiteSpace and VOSviewer were used to analyze the publication features, collaboration, keywords co-occurrence, and co-cited reference.
Main results: A total of 506 articles were finally identified. The global publication numbers on extrapulmonary applications gradually increased yearly in the past 30 years. The US, UK, and China contributed most three publications concerning EIT extrapulmonary applications. "tissues", "conductivity", "model" were research hotspots, and "cutaneous melanoma", "microstructure", "diagnosis" were recent topics (Portions of this research have previously been presented in poster form).
Significance: Overall, EIT extrapulmonary applications bibliometrics analysis provides a unique insight into research focus, current trends, and future directions.

1. Introduction

Electrical impedance tomography (EIT) is a noninvasive real-time monitory instrument without radiation [1, 2]. With the development of hardware and algorithm, the laboratory and clinical applications of EIT are widespread, especially in lung ventilation and perfusion monitoring [3, 4]. Meanwhile, progress has also been made in applications related to extrapulmonary fields such as brain, bladder, and breast [5, 6, 7]. Reviews are published to summarize the rapid development of EIT technology and applications [8, 9, 10]. An objective overview of the research status on EIT extrapulmonary applications would make the researchers more efficient in recognizing the research progress, identifying the scientific focus, and promoting further interdisciplinary collaboration. After a literature search, we noticed that such an overview was unavailable.

Bibliometric analysis identifies temporal trends in various research fields and contributes to the development of treatment and clinical guidelines through qualitative and quantitative analysis of scientific journals and books [11, 12]. Scientific publications act as messengers propagating details on EIT extrapulmonary research progress. With the combined enhancement of machine learning algorithms and software development, the recent bibliometric methods can be applied more easily for in-depth investigation of hot spots and research trends [13].

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The present study applied the bibliometric approach to analyze and visualize the developing progress of EIT extrapulmonary applications in the past three decades. The most impactful articles that highlighted the characteristics of EIT applications were identified in various kinds of extrapulmonary applications. These offered invaluable insights into the most worthwhile aspects of the investigation and forecast forthcoming direction.

2. Methods

2.1. Source database and retrieval strategies

For this study, data were extracted on the basis of Web of Science Core Collection (WoSCC) database, which is known as the world's most systematic and comprehensive literature retrieval database and is suitable for bibliometric analysis. Herein, investigators conducted the search according to the retrieval strategy of TS = ("electrical impedance tomography") AND TS = (("hemodynamic") OR ("brain") OR ("nerve") OR ("cancer") OR ("venous") OR ("vessel") OR ("tumor") OR ("veterinary") OR ("tissue") OR ("cell") OR ("wearable") OR ("application")) NOT TS = (("lung") OR ("ventilation") OR ("respiratory") OR ("pulmonary") OR ("algorithm") OR ("current") OR ("voltage") OR ("electrode")); Period: 1987.01.01 to 2021.12.31; Research types: "Article", "Review", "Letter", "Meeting abstract", "Proceeding paper", "Note," and "Early Access,"; Language: English. The keywords were mainly developed according to the recently published EIT textbook 2nd edition [14]. Data were collected by all investigators on 2022.04.23 to avoid bias in the database.

2.2. Data collection

Two authors searched the literature in WoSCC independently following the above formula to reduce subjective error, including publications, sources, authors, titles, languages, keywords, and citations. Publications less relevant to extrapulmonary biogeography applications are excluded, for example, papers regarding water resources, agriculture multidisciplinary, chemistry analytical, engineering aerospace, engineering industrial, plant sciences, agronomy, mineralogy, mining mineral processing, energy fuels, geochemistry geophysics, and metallurgy. The decision was made by two independent investigators and reviewed by all authors. The downloaded data including titles, authors, institutions, abstracts, keywords, and citations were saved in UTF-8 and text format for later statistical analysis.

2.3. Bibliometric analysis

The WoSCC database and Microsoft Excel 2021 (Microsoft Corp., Redmond, WA, the US) were used to analyze and visualize the publication features, including literature quantity, global annual publications, national publications, institutions, source journals, authors, cited references, and specific topics.

The bibliometric analysis software VOS viewer1.6.16 (Leiden University, Leiden, the Netherlands) and CiteSpace5.7R5 (Chen Meichao, Drexel University) were used to help create network maps, trace research trends, and recognize emerging hotspots in the EIT extrapulmonary applications field. VOS was used to cluster the scientific literatures based on the data of countries, institutions, authors, and keywords with appropriate thresholds (referred to the results section below). While CiteSpace was used to perform keyword burst analysis, co-citation cluster analysis, and time-evolution analysis, which may provide insight into the historical process of EIT extrapulmonary applications research.

2.4. Statistical analysis

Depending on whether the normal distribution was followed, continuous variables were separately described by mean ± standard deviation (mean ± SD) or median (interquartile range) [M(IQR)]. Categorical variables were presented by percentage or proportion of cases.

3. Results

3.1. Literature screening for bibliometric analysis

553 publications were identified from WoSCC database following the former retrieval strategy. After reviewing by two independent investigators, 11 publications were excluded due to the article types (Book chapters, Editorial Material, etc.). Further 36 publications were also excluded due to irrelevant topics (chemistry, physics, geography, agriculture, etc.). Ultimately 506 publications were downloaded for EIT extrapulmonary applications analysis (Figure 1).

3.2. Global development trend and citations of publication types

Annual global publication numbers and the top 10 prolific countries (overall) in publishing EIT extrapulmonary applications research are presented in Figure 2, the global publications showed a slowly wavy upward trend. Notably, it was not until 2005 that more than 10 published were issued all over the world. So far, countries experienced with literature (described as number of publications) on EIT extrapulmonary applications were mostly from North America, Western Europe, and East Asia. Among these, the USA (118), the UK (96), China (54), Germany (35), and South Korea (31) round out the top five prolific countries, separately accounting for 23.32%, 18.97%, 10.67%, 6.92%, and 6.13% of the total publications. The UK began earlier than any other country and has the longest publishing period, by contrast, China started late in EIT extrapulmonary applications publications with a relatively rapid growth trend.

In addition, as shown in Table 1, articles (60.1%) and proceeding papers (31.2%) are the most popular types of publications, followed by reviews (5.7%) which have the highest average cited times of 41.2.

3.3. Analysis of impactful publications and highly-cited references

The top 10 most productive institutions, journals, authors (abbreviation in the software; publication number; cited frequency), and highly cited references on EIT extrapulmonary applications were listed in Table 2. Institutions from the UK and the US took up most of the top 10 institutions, while the Chinese institute Fourth Military Medical University (Fourth Mil Med Univ; 31; 212) published the most numbers of relevant literature. The next were University College London (UCL; 23; 323) and Manchester University (Univ Manchester; 20; 181). Meanwhile, the University of California at Berkeley (Univ Calif Berkeley; 13; 1132) published only thirteen publications but owned the highest cited frequency of 1132 citations (see Table 3 and Table 4).

A total of 34 journals published articles on EIT extrapulmonary applications, Physiological Measurement (*PHYSIOL MEAS*; 55; 1000), which is an authoritative journal for biomedical instruments and systems, ranked first in the number of publications. Other top 4 journals are IEEE Transactions on Biomedical Engineering (*IEEE T BIO-MED ENG*; 19; 768), Measurement Science and Technology (*MEAS SCI TECHNOL*; 12; 165), Flow Measurement and Instrumentation (*FLOW MEAS INSTRUM*; 8; 119), and IEEE Sensors Journal (*IEEE SENS J*; 8; 122). Moreover, IEEE Transactions on Medical Imaging (*IEEE T MED IMAGING*; 7; 257) was the only journal that has an impact factor (IF) over 10.

Up to now, among 1670 authors that contributed to the 506 publications on EIT extrapulmonary applications, the top 10 prolific authors accounted for 162 articles and took up 32.02% of the total publications. Overall, Fu, F (28; 212) from the Fourth Mil Med Univ, Holder, D (21; 189) from UCL, Dong, X (18; 132) from Fourth Mil Med Univ, Zhao, Z (16; 104) from Furtwangen Univ, and Bayford, RR (15; 69) from Middlesex Univ were the most productive authors.

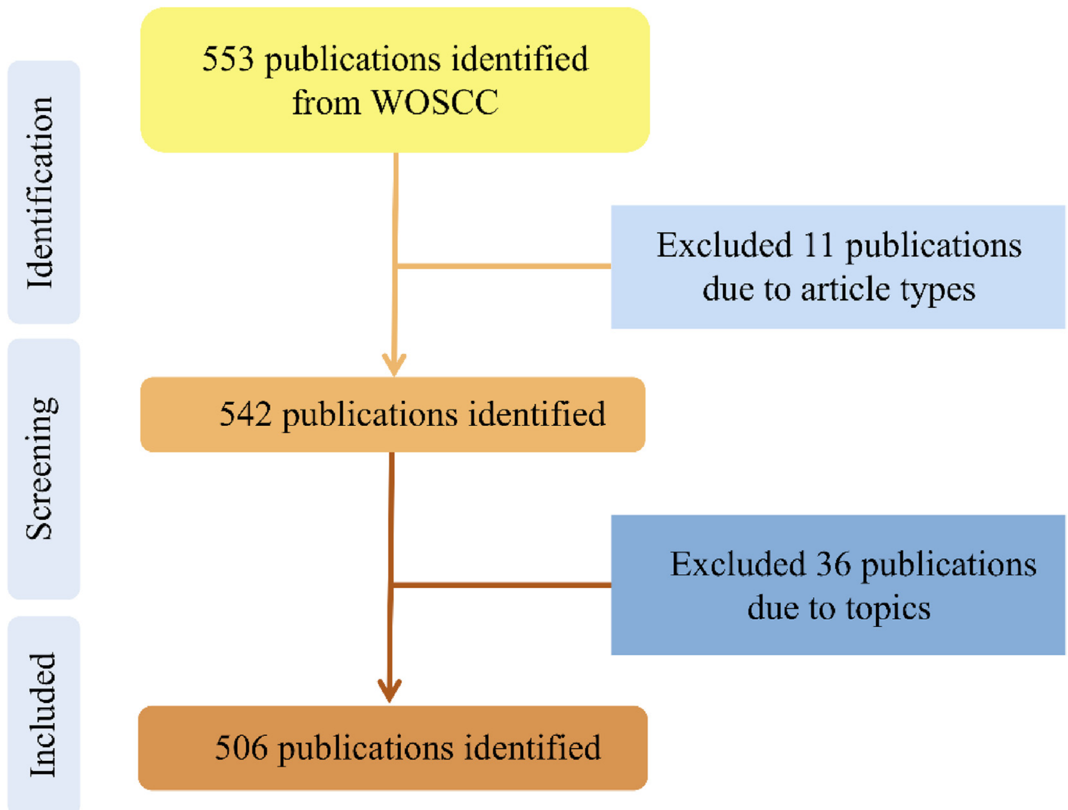


Figure 1. | Flow chart for data filtration and publication exclusion. WoSCC, Web of Science Core Collection.

The top 10 most cited references include one patent material, two reviews, and seven original articles, and the patent document by Davalos RV (cited frequency: 794) published in *ANN BIOMED ENG* [15] owned the highest cited frequency; the original article by Jossinet J (cited frequency: 169) published in *MED BIOL ENG COMPUT* [16] was the earliest top-cited article, the 10 most impactful cited references are summarized in detail in Table S1.

3.4. Cooperation of countries/regions, authors, and institutions

The global collaboration which was calculated on the number of publications cooperated by the countries (threshold: publications>5), authors (threshold: publications>2), and institutions (threshold: publications>1) on EIT extrapulmonary applications research is shown in Figure 3. Finally, a total of 25 countries, 75 authors, and 143 institutions

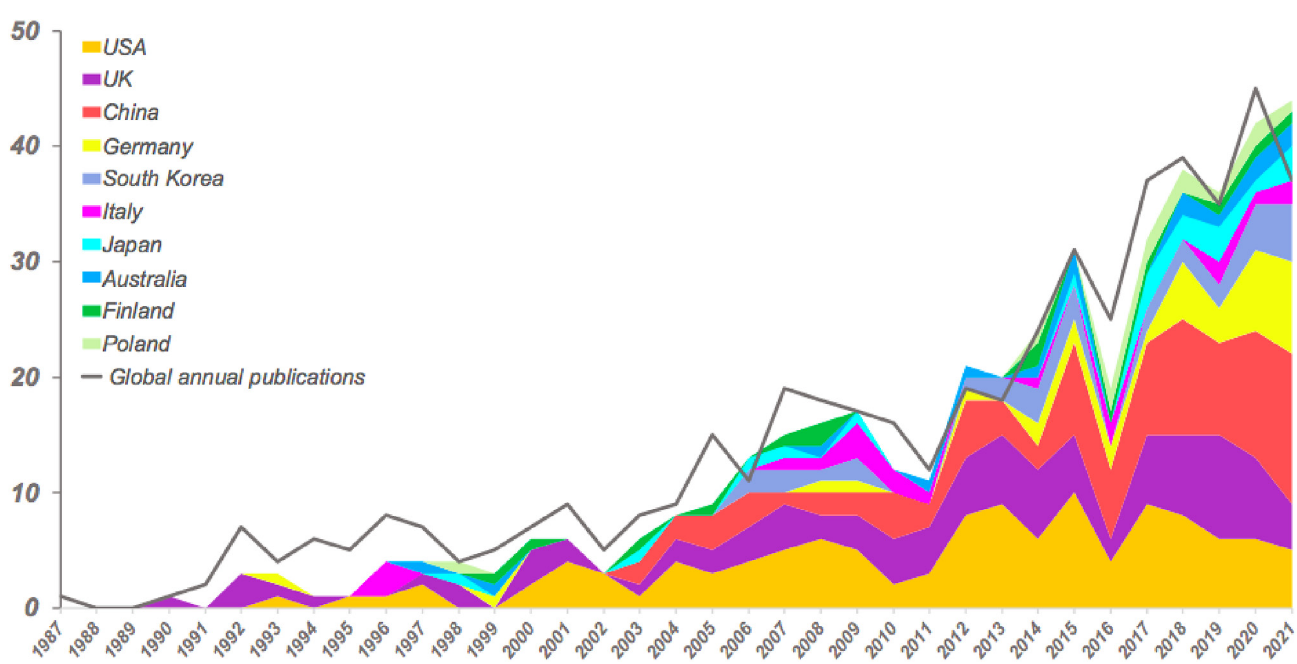


Figure 2. Annual publications trends and top 10 most productive countries on EIT extrapulmonary applications research during 1987.01.01–2021.12.31. The black line manifests trends in annual worldwide publications. The colors indicate countries, color block width indicates publications amount of each country.

Table 1. Publication Types and citations of EIT extrapulmonary applications research.

Publication Type[a]	N (Proportion)	Total cited times	Average cited times[b]
Article	304 (60.1%)	7427	24.4
Review	29 (5.7%)	1196	41.2
Proceeding Paper	158 (31.2%)	1831	11.6
Meeting Abstract	9 (1.8%)	7	0.8
Letter	4 (0.8%)	43	10.8
Note (Technical note)	2 (0.4%)	67	33.5

[a] Publication type: There were crossovers between "Article" and "Proceeding Paper".
[b] Average cited times: The total citations per type divided by the count of publications.

Table 3. The top 10 highly-occurred keywords on EIT extrapulmonary applications research.

Rank	Keyword	Occurrences	Total link strengths
1	electrical impedance tomography	216	456
2	tissues	61	224
3	conductivity	37	171
4	model	30	106
5	reconstruction	29	83
6	system	28	100
7	dielectric-properties	27	140
8	brain	25	98
9	breast	25	87
10	inverse problem	22	55

were visualized. Close collaboration (described as total link strength) between highly productive and cited countries, authors, and institutions can be observed in the network visualization map, with the USA (225), the UK (248), and China (210) holding the most active collaboration in EIT extrapulmonary applications studies with other countries. Besides, Fu, F (135), Dong, X (81), Zhao, Z (77), Frerichs, I (62), and Woo, EJ (34) were the top 5 authors with the most international cooperation. Moreover, Fourth Mil Med Univ (148) from China, UCL (132) from the UK, Kyung Hee Univ (209) from South Korea, and Middlesex Univ from England (132) were the top 4 institutions with the most international cooperation, however, less collaboration was shown in other institutions with less publications.

3.5. Specific topics of EIT extrapulmonary applications research

EIT extrapulmonary applications research was further categorized by searching the topic-related terms given in the EIT textbook 2nd edition [14] in the publication title or abstract. The topics of the 506 researches are mainly divided into "brain" 136 (27%), "Cancer" 120 (24 %), "tissue" 112 (22%), "Cell" 23 (4%), "hemodynamics" 26 (5%) and "Reviews and other applications" 89 (18%). More detailed classifications and the time trend in each specific application were presented in Figure 4. In the specific topic of brain, epilepsy [M(IQR)] 1999.5 (1998.75, 2000.25) was the earliest subcategory, the research focus was changing from anatomical structure imaging as structure and parenchyma to pathologic changes such as stroke, edema, and hemorrhage. Nerve imaging has the second most publication numbers and the latest occur year [M(IQR)] 2018.5 (2008.25, 2019). Applications on the cell and tissue showed similar results. Moreover, interdisciplinary areas such as ultrasound integrated imaging, artificial intelligence, wearable devices, implant evaluation, etc were involved in the topic of "Reviews and other applications".

3.6. Hot Topic and time trend of the Keywords

Among 1949 keywords filtrated from the selected 506 publications, 109 keywords with a co-occurrence frequency of more than four were identified for keywords co-occurrence and overlay analysis. The keywords were finally clustered into 18 clusters (Figure 5A), and the largest 5 clusters mainly focus on "basics of EIT applications", "issues related application", "tissue, cancer, cell", "clinical applications of tissue, cancer, and cell", "brain" (Table S2). Besides, the 5 keywords with the highest co-occurrence frequency were "electrical impedance tomography", "tissues", "conductivity", "model", "reconstruction" and the top 10 highly-occurred keywords are enumerated in Table 3.

The topic trends were traced by the early and late occurrence periods of keywords calculated by the average publication year (Avg. pub. year) (Figure 5B). From the map, emerging keywords focus on "in vivo", "imaging", "sensitivity", "real-time", "diagnosis", "reflectance confocal microscopy", "optical coherence tomography", and "electrical-impedance spectroscopy". In Table 4, the 10 earliest and latest keywords (occurrence frequency; Avg. pub. year) are listed and the earliest

Table 2. The top 10 prolific institutions, journals, authors, and highly-cited literature on EIT extrapulmonary applications.

Institution	Publications	Citations	Journal	Publications	Citations	IF[a]	Author	Publications	Citations	Cited reference	Citations
Fourth Mil Med Univ	31	212	PHYSIOL MEAS	55	1000	2.833	Fu, F	28	212	Davalos et al.,2005.	794
UCL	23	323	IEEE T BIO-MED ENG	19	768	4.538	Holder, D	21	189	Ellis et al., 2000.	479
Univ Manchester	20	181	MEAS SCI TECHNOL	12	165	2.046	Dong, X	18	132	Dorfler et al., 2013.	352
Furtwangen Univ	16	110	FLOW MEAS INSTRUM	8	119	2.037	Zhao, Z	16	104	Poplack et al., 2007.	224
Kyung Hee Univ	16	121	IEEE SENS J	8	122	3.301	Bayford, RR	15	69	Korjenevsky et al.,2000.	187
Middlesex Univ	15	69	INVERSE PROBL	8	98	2.407	Frerichs, I	14	83	Doyley et al., 2000.	186
Univ Leeds	15	177	PHYS MED BIOL	8	374	2.609	Woo, EJ	14	114	Martin et al., 2012.	180
Dartmouth Coll	14	496	IEEE T MED IMAGING	7	257	10.048	Sadleir. R	13	242	Jossinet et al.,1996.	169
Univ Calif Berkeley	13	1132	MED BIOL ENG COMPUT	7	206	2.602	Dai, M.	12	105	Cherepenin et al., 2001.	150
Univ Florida	12	215	ANN BIOMED ENG	5	917	3.934	Soleimani,M	11	105	Goncalves et al., 2003.	141

[a] IF: impact factor.

Table 4. The top 10 earliest and latest keywords on EIT extrapulmonary applications research.

Rank	Earliest			Latest		
	Keyword	Occurrences	Avg.pub.year[a]	Keyword	Occurrences	Avg.pub.year[a]
1	hyperthermia	4	1995.0	cutaneous melanoma	4	2019.2
2	applied potential tomography	7	1998.1	microstructure	4	2019.2
3	obesity	4	2000.5	diagnosis	6	2018.8
4	frequency	4	2003.0	reflectance confocal microscopy	6	2018.6
5	inverse conductivity problem	4	2004.5	performance	7	2018.5
6	cryosurgery	5	2004.8	optimization	4	2017.5
7	skin	6	2007.0	tissue engineering	4	2017.5
8	blood	4	2007.7	hemorrhage	7	2017.3
9	contrast	4	2007.7	coil	5	2017.2
10	bioelectrical-impedance analysis	7	2007.8	intracerebral hemorrhage	4	2017.0

[a] Avg. pub. year: average publication year of literature that the keyword occurs.

keyword was "Hyperthermia" (4; 1995.0), which was 7 years later than the first publication in 1987. The latest keyword was "cutaneous melanoma" (4; 2019.2). In addition, EIT technology-related keywords "applied potential tomography" (7; 1998.1) and "impedance analysis" (7; 2007.8) were the earliest keywords that occur most frequently; EIT application promotion-related keywords "performance" (7; 2018.5) and "hemorrhage" (7; 2017.3) were the latest keywords that occur most frequently.

3.7. Burst Value of the Keywords

The keywords with strong burst value on EIT extrapulmonary applications publications during 1987–2021 were identified to explore the past research hotspots, current forefront, and future development trends. The top 15 strongly burst keywords were summarized in Figure 6. The burst period of "applied potential tomography" lasted for the longest 7 years from 1992, compared with that of "fracture", "tissue", "brain", and

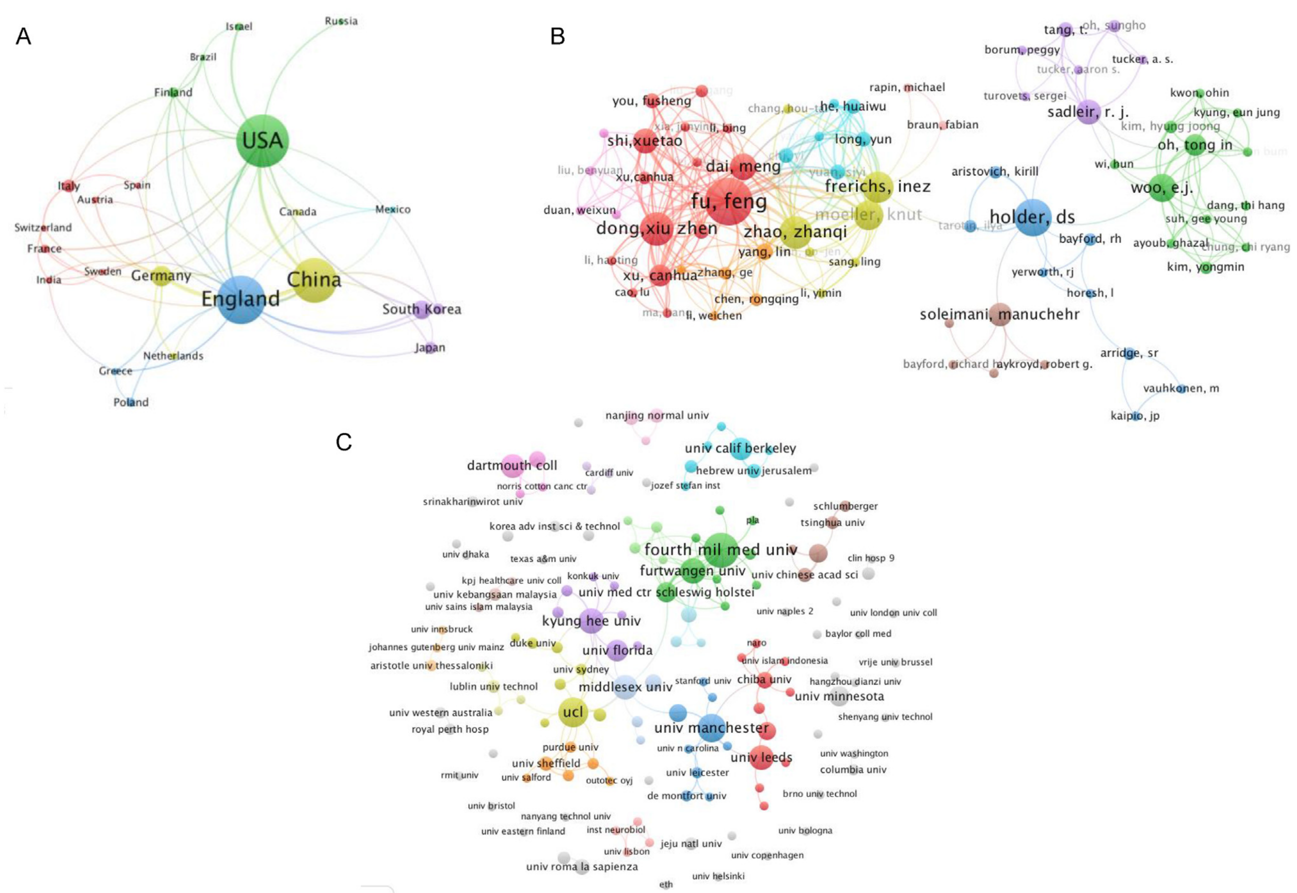


Figure 3. | Visualization map of collaboration among countries (A), authors (B), and institutions (C) regarding EIT extrapulmonary applications study during 1987.01.01–2021.12.31. The colors separately indicate cluster of countries (A), authors (B), and institutions (C); the circle size represents publication numbers; the line thickness represents the cooperation strength; Grey circles in (C) represent institutions without cooperative relationships.

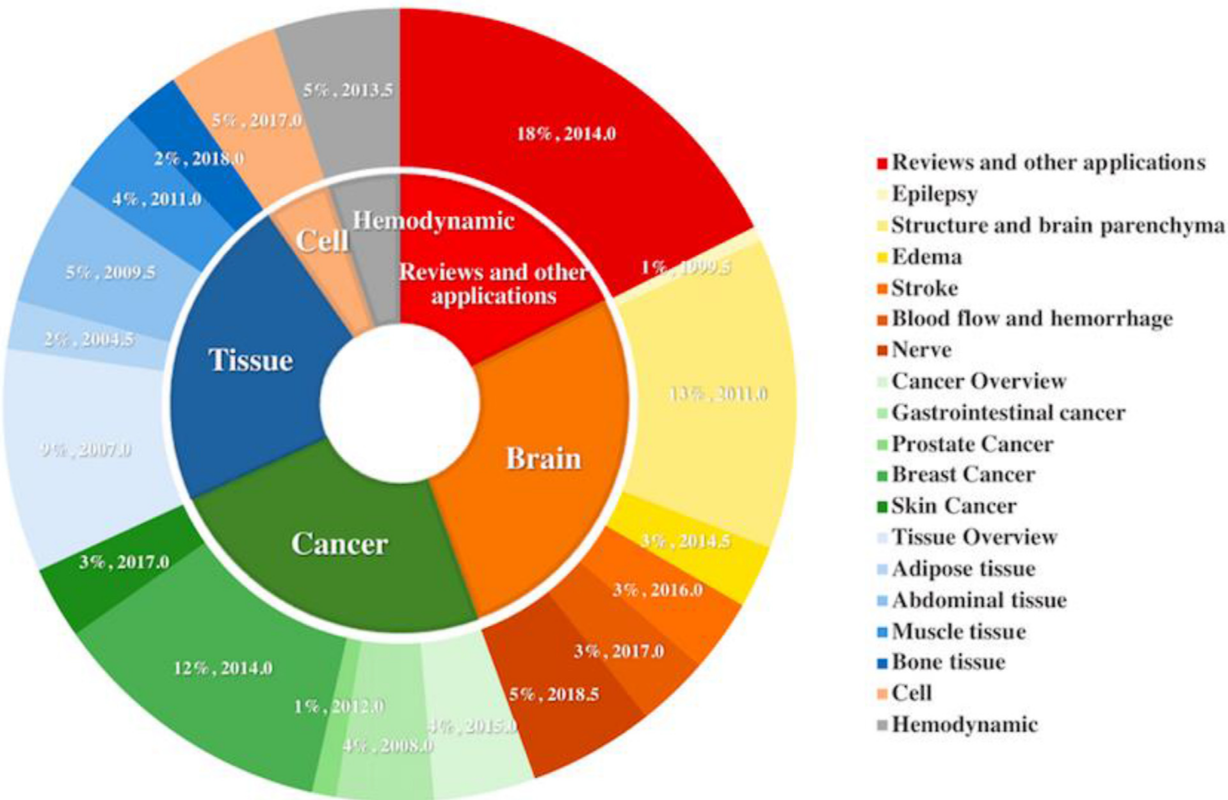


Figure 4. | Topic-specific distribution of EIT extrapulmonary applications research from 1987.01.01 to 2021.12.31. The inner color plates represent each specific research topic, the color gradient in each outer color plate described as (proportion, the average occur year) represented the subdivision in the specific topic labeled on the right. The average occurs year: the year in which the keywords of the topic appeared in the literature (to the nearest 1 decimal place).

"in vivo" which lasted for only 1–2 years. Though the keyword "tissue" just burst for 1 year, it has the strongest strength of 3.77. In addition, the keywords "model", "capacitance", and "in vivo" are still hot up to now.

3.8. Burst value of the Co-cited references

The top15 co-cited references which have the highest citation burst values were summarized in Figure 7. Among the top15 co-cited references (strength), the consensus "Frerichs I, 2017, THORAX" [17] (9.36) was the co-cited reference with the highest burst strength, and the next top 2 were "Bayford RH, 2006, ANNU REV BIOMED ENG" [18] (5.82) and "Adler A, 2017, IEEE T BIO-MED ENG" [19] (5.49). References began to burst in 2000, and most of the burst values sustain 1–3 years, except for the original article "Dai M, 2013, PLOS ONE" [20] (3.74) which lasts for 4 years.

3.9. Cluster and time evolution of the co-cited references

The co-cited references clustered in more than 43 clusters (described as cluster labor, cluster size), but only 3 clusters had weighted mean silhouettes greater than 0.7, suggesting a relatively confident clustering result. As shown in Figure 8A, the 3 eligible clusters were cluster 0, cluster 3, and cluster 41. Cluster 0 (ischemic stroke, 56) and cluster 3 (infarction deterioration, 6) were related to the brain applications, however, the cluster labels defined by the three methods lack consistency. Besides, all these three clusters were after 2015 (Figure 8B). Detailed clustering information is given in Table S4.

4. Discussion

Bibliometric analysis is a convenient way to exhibit the visual structure of research content for professional researchers and helps beginner to obtain general trends in their research field [21]. Herein, we conducted a bibliometric analysis of 506 articles to study the development of EIT extrapulmonary applications over the last three decades. These results provide a reflection of the scientific process, current trends, and hot issues concerning the research field. EIT attracts increasing attention, as indicated by the number of publications (Figure 2). Until now, it is the first bibliometric to evaluate EIT extrapulmonary application publications.

Cooperation is important in scientific research. Close connections among various research groups can guarantee knowledge exchange and accelerate the development of the field. In a previous bibliometric analysis of EIT lung monitoring [22], we demonstrated a well-established cooperation network among different research groups. In the current study, cooperation among the groups is mainly within certain topics, e.g., applications in brain. Much less cooperation was observed in other application fields. Only the USA, the UK, and China showed active collaboration (Figure 3). Therefore, the cooperation between countries and institutions on EIT extrapulmonary applications is yet to be deepened and developed in the future. In recent years, an increasing number of studies from different research teams show great potential for EIT extrapulmonary applications.

EIT biological applications involved multiple tissue and organ such as the brain [23], breast [24], prostate [25], bladder [26], stomach [27], and blood vessels [28], etc., consistent with our result that keywords were clustered into 18 topics. The cluster intensity and the specific topic analysis showed that applications in brain anatomical structure, breast cancer, and hemodynamics were hot topics over time. In the early years, brain imaging faces high technical challenges due to the extremely high electrical resistance of the skull [29]. However, after continuous research and improvement of electrical impedance characteristics, EIT has shown great potential in the diagnosis of stroke, localization of epileptic foci,

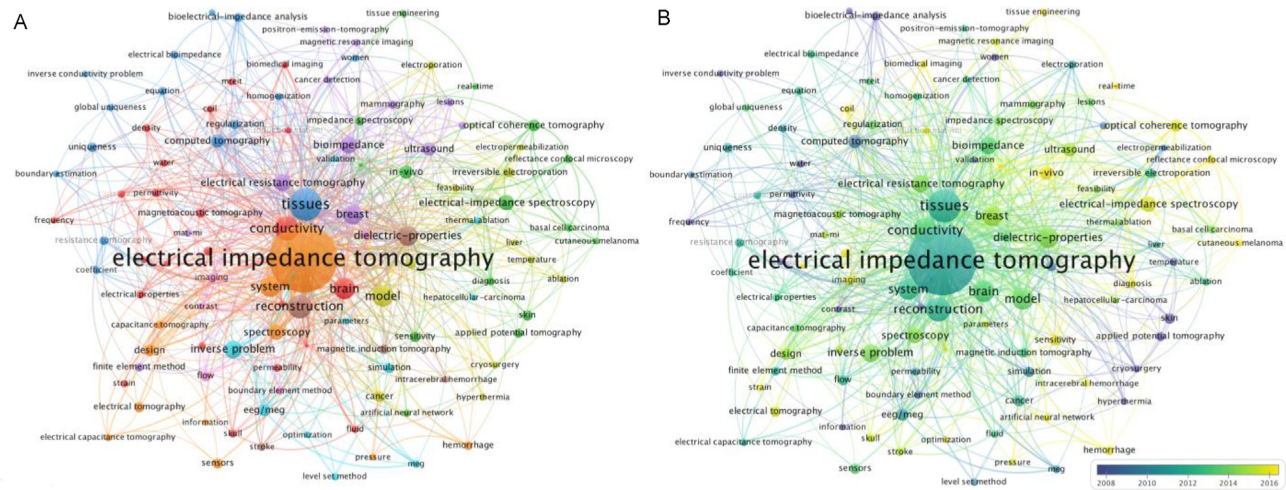


Figure 5. | Keywords co-occurrence (A) and overlay (B) visualization map of EIT extrapulmonary applications research during 1987.01.01–2021.12.31. Different circle size represents different frequency of co-occurrences, and the line thickness represents link strength. Different colors separately represent different clusters (A) and different average publication years (B). Keywords before 2008 share the same color as 2008 (B).

and intracranial edema monitoring [30]. EIT is portable enough to be used in long-term imaging on telemetry devices of epilepsy that require continuous monitoring in order to localize epileptic activity during the preoperative evaluation of epilepsy surgery, which has been verified by the UCL team via coupling a parallel EIT system with intracranial EEG monitoring [31]. It is also suitable for imaging brain impedance changes caused by cell swelling during pathological conditions such as ischemia, hypoxia, and hypoglycemia, as well as monitoring brain's fluid balance to guide the injection of mannitol to reduce cerebral edema, Manwaring et al [32] developed a neotype intracranial pressure/EIT electrode coupled sensor bedside device guiding the management of brain injury.

EIT could sensor the electrical properties change caused by tumor cells, and was able to detect breast cancer in the initial stage [33], Despite the technical imperfections and lack of clinical evidence compared to ultrasound or mammography for breast cancer diagnosis, this provides an additional method for pregnant women with a high risk of carcinogenesis (BRCA1, BRCA2 genes) [34]. Insight studies found that age was an important factor related to EIT diagnostic efficiency, available data indicated that the most appropriate age is 30–45 years old [35, 36]. Thus, for women aged 30–45, choosing the low-priced EIT modalities for early diagnosis of breast cancer may relatively reduce radiation injury [36]. Equally, as an adjunct to visual approach, EIT has improved the specificity and sensitivity of skin cancer diagnosis to 87% and 100%, respectively, showing its capacity to minimize needless biopsies [37]. In the topic of prostate cancer, EIT imaging system has been coupled to standard ultrasound probes to guide biopsy to improve detection accuracy [25].

Monitoring hemorrhage during accidents is another valuable application, detecting and tracking brain and abdomen bleeding, chest effusion and gas accumulation at bedside contributed to rapid and accurate treatment [38]. N E Beltran et al. reported that EIT detected gastric wall impedance changes caused by hypoperfusion and ischemia during surgery, which proved EIT a novel monitoring tool for gastrointestinal injury [39].

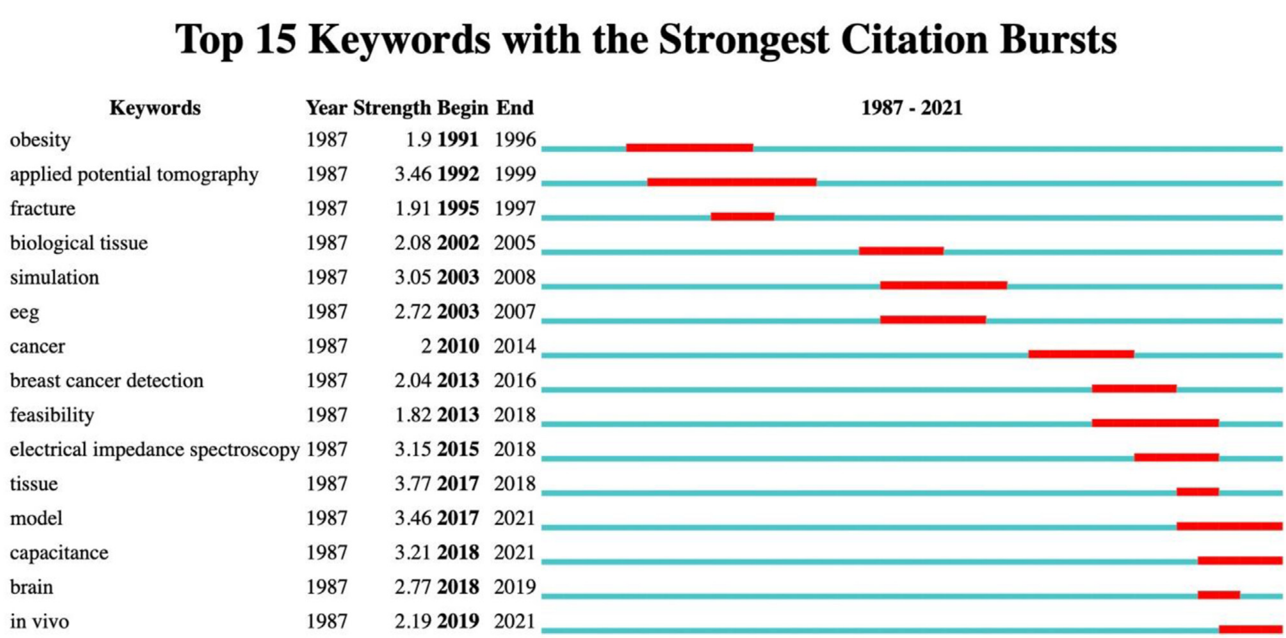
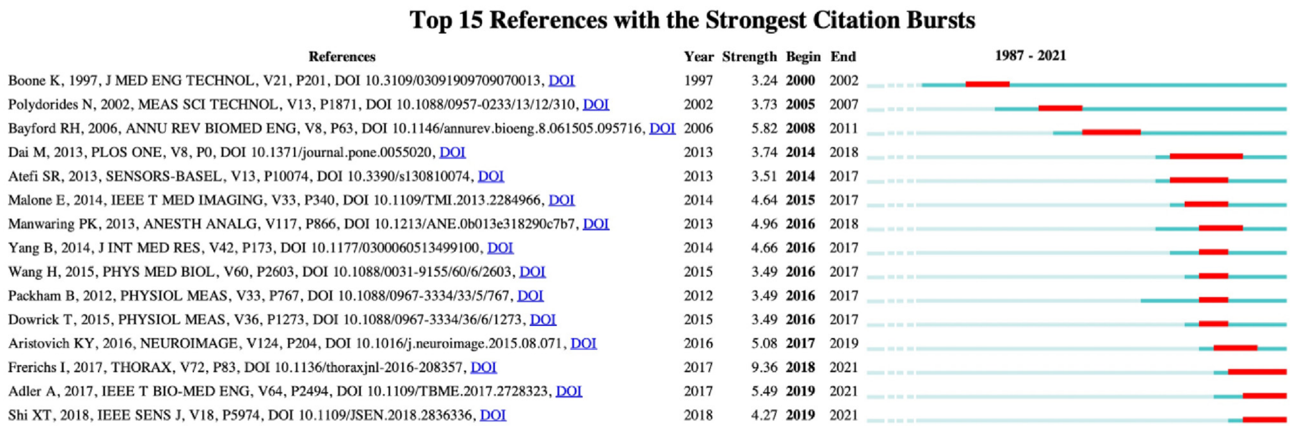


Figure 6. The top 15 strongly burst keywords on EIT extrapulmonary applications research during 1987.01.01–2021.12.31. Blue bars and red bars separately indicate a slight increase and a sharp rise in the number of keywords occurrences.



Top 15 References with the Strongest Citation Bursts

References	Year	Strength	Begin	End	1987 - 2021
Boone K, 1997, J MED ENG TECHNOL, V21, P201, DOI 10.3109/03091909709070013, DOI	1997	3.24	**2000**	2002	
Polydorides N, 2002, MEAS SCI TECHNOL, V13, P1871, DOI 10.1088/0957-0233/13/12/310, DOI	2002	3.73	**2005**	2007	
Bayford RH, 2006, ANNU REV BIOMED ENG, V8, P63, DOI 10.1146/annurev.bioeng.8.061505.095716, DOI	2006	5.82	**2008**	2011	
Dai M, 2013, PLOS ONE, V8, P0, DOI 10.1371/journal.pone.0055020, DOI	2013	3.74	**2014**	2018	
Atefi SR, 2013, SENSORS-BASEL, V13, P10074, DOI 10.3390/s130810074, DOI	2013	3.51	**2014**	2017	
Malone E, 2014, IEEE T MED IMAGING, V33, P340, DOI 10.1109/TMI.2013.2284966, DOI	2014	4.64	**2015**	2017	
Manwaring PK, 2013, ANESTH ANALG, V117, P866, DOI 10.1213/ANE.0b013e318290c7b7, DOI	2013	4.96	**2016**	2018	
Yang B, 2014, J INT MED RES, V42, P173, DOI 10.1177/0300060513499100, DOI	2014	4.66	**2016**	2017	
Wang H, 2015, PHYS MED BIOL, V60, P2603, DOI 10.1088/0031-9155/60/6/2603, DOI	2015	3.49	**2016**	2017	
Packham B, 2012, PHYSIOL MEAS, V33, P767, DOI 10.1088/0967-3334/33/5/767, DOI	2012	3.49	**2016**	2017	
Dowrick T, 2015, PHYSIOL MEAS, V36, P1273, DOI 10.1088/0967-3334/36/6/1273, DOI	2015	3.49	**2016**	2017	
Aristovich KY, 2016, NEUROIMAGE, V124, P204, DOI 10.1016/j.neuroimage.2015.08.071, DOI	2016	5.08	**2017**	2019	
Frerichs I, 2017, THORAX, V72, P83, DOI 10.1136/thoraxjnl-2016-208357, DOI	2017	9.36	**2018**	2021	
Adler A, 2017, IEEE T BIO-MED ENG, V64, P2494, DOI 10.1109/TBME.2017.2728323, DOI	2017	5.49	**2019**	2021	
Shi XT, 2018, IEEE SENS J, V18, P5974, DOI 10.1109/JSEN.2018.2836336, DOI	2018	4.27	**2019**	2021	

Figure 7. | The top 15 strongly burst cited references on EIT extrapulmonary applications research during 1987.01.01–2021.12.31. Blue bars and red bars separately indicate a slight increase and a sharp rise in the frequency of citations.

Recently, the interdisciplinary imaging method MREIT is expected to produce high-resolution conductivity images and assess magnetic flux density in 3D space, with superior resolution cross-sectional imaging features. Numerous studies have demonstrated that MREIT can be used for cancer imaging and the assessment of hemorrhagic and ischemic stroke [40, 41, 42, 43, 44]. Another recent advancement is due to the noninvasive electrodes composed of flexible materials. Kim et al. implanted microelectrode arrays loaded with biological protein substrates into cat brains [45]. Zhu et al. demonstrated a microelectrode array EIT device capable of reconstructing activity in multiple subcortical bodies simultaneously [46]. In future EIT application studies, optimizing image quality and comparing the diagnosis sensitivity with the gold standard in specific application fields is critical, which were closely related to the development of EIT algorithm, hardware, and interdisciplinary Cooperation [47].

The top 10 keywords with the highest co-occurrence frequency included consistent problems of improving EIT technology on algorithm, hardware, and simulation, as “conductivity”, “model”, “reconstruction”, “system”, “dielectric-properties” and “inverse problem”, which reflect the technical challenges of EIT extrapulmonary applications. For example, in brain, though the novel Ag/AgCl electrodes were developed to address the difficulty of the high skull resistance [48], anatomically

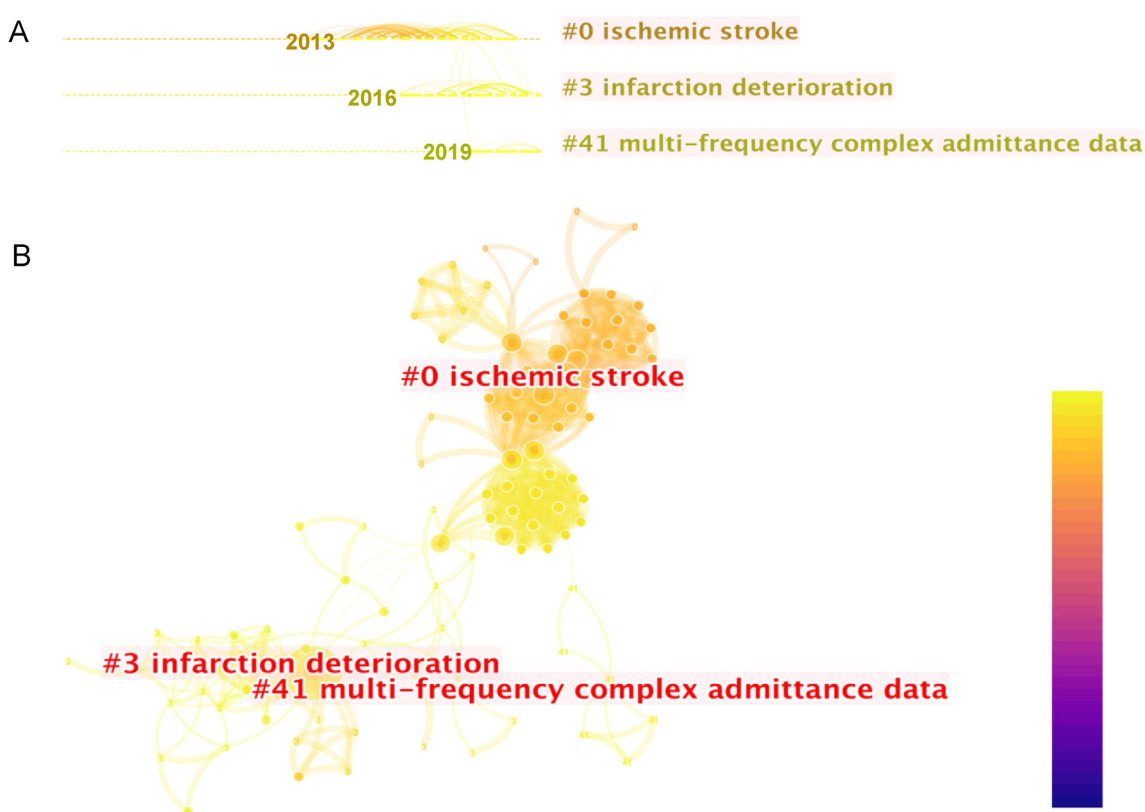


Figure 8. | Co-cited reference time evolution analysis (A) and clustering analysis (B) on EIT extrapulmonary applications research during 1987.01.01–2021.12.31 (A) Different colors indicate publication years; the color curves manifest co-cited links in the corresponding color year; large nodes represent that they are either cited frequently, with high-citation bursts, or both; the vertical descending order represents different cluster sizes (B) The color represents interdecadal variations in publication time; the vertical descending order represents different cluster sizes; the line thickness represents link strength. The modularity Q score is 0.9548, the harmonic mean (Q, S) is 0.9712, and the mean silhouette is 0.9881.

realistic geometry, inhomogeneity, and cranium completeness should also be generally considered in enhancing the precision of EIT modeling. Similarly, the reconstruction algorithm is the key point to be optimized for image qualified applied to various diseases. Other components of highly co-occurrence keywords involved the specific extrapulmonary application scenarios as “tissue”, “brain”, and “breast”. The strong burst keywords also confirmed the main focus of extrapulmonary applications of EIT (Figure 5).

Since EIT appeared in the late 1980s, a large portion of research focused on building stable measurement systems and developing robust reconstruction algorithms. Extrapulmonary applications of EIT in monitoring cerebral bleeding, gastric motility [49], and the detection of breast tumors were also reported at that time. The burst periods of keywords in Figure 5 mostly started after the 2000s. Considering the start of EIT technology, it is quite late. Strong burst value means that the keywords frequently appeared in publications within a certain period and is another essential interpretation of past research hotspots, current forefront, and future development trends. Although started late, the keywords “model”, “capacitance”, and “in vivo” keep high burst values until now, implying that these features might be important across various extrapulmonary EIT applications and might be a potential hotspot in the future.

The burst value analysis of co-cited references (Figure 6) highlighted the periods in which publications are frequently cited. It represents the special interest in the research topics of these publications. Remarkably, “Frerichs I, 2017, *THORAX* [17]”, “Adler A, 2017, *IEEE T BIO-MED ENG* [19]” and “Shi XT, 2018, *IEEE SENS J* [50]” are the latest high burst co-cited references that might represent the research interest. The consensus from Frerichs *et al.* focused on the applications in the thorax. The standardization of measurement and data interpretation could set up a good example for other application fields. In the review paper from Adler and Boyle, they introduced a broad topic covering tissue electrical properties, EIT hardware, and algorithms. They also gave an overview of EIT applications and perspectives for research and development. Shi *et al.* introduced an EIT system for brain imaging. In the experiments on healthy volunteers, they demonstrated that the proposed system could monitor minor variations in intracranial impedance regarding transitory occlusion and reperfusion of the unilateral carotid artery.

5. Strengths and limitations

The current research has some limitations. The selected keywords and searching strategy determine how many relevant papers can be found. Xiao *et al* recently conducted bibliometric research on clinical application of EIT [51]. They have limited the papers with EIT in the title, which missed a lot of relevant studies. We have selected searching keywords to restrict our results in extrapulmonary applications. On one hand, although we chose to use all citation indexes under WoSCC due to the cross fields involved in EIT, our search might have excluded some relevant studies with keywords of algorithm or hardware. On the other hand, some studies that mainly focused on algorithm or hardware development or applications in the lung might have been included, given that the algorithm or measurement system was specially designed for extrapulmonary applications. Our search included perfusion and hemodynamics, which sometimes may also refer to cardiopulmonary applications.

6. Conclusion

EIT extrapulmonary application development is relatively slow compared to pulmonary application. The USA contributed the largest number of research in this field. EIT application detection of brain hemorrhage, breast and skin cancer was the scientific focus in the last 20 years and will extend as research hotspots. More and more diverse functional imagining techniques, like imaging hemodynamics and gastrointestinal tract with EIT, are feasible future hotspots for EIT extrapulmonary applications.

Declarations

Author contribution statement

ZL and ZZ conceived and designed the experiments. SQ and SL contributed analysis tools and data. YX, SQ, RT, and ZL analyzed and interpreted the data. YD, YX, ZL, and ZZ wrote the paper. All authors approved the final version.

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Data availability statement

Data associated with this study has been deposited at WoS database http://isiknowledge.com/

Declaration of interests statement

The authors declare the following conflict of interests: One of our authors ZZ receives a consulting fee from Dräger Medical.

Additional information

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References

[1] E.L.V. Costa, R.G. Lima, M.B.P. Amato, Electrical impedance tomography, Curr. Opin. Crit. Care 15 (2009) 18–24.
[2] D. Maciejewski, Z. Putowski, M. Czok, Ł.J. Krzych, Electrical impedance tomography as a tool for monitoring mechanical ventilation. An introduction to the technique, Adv. Med. Sci. 66 (2021) 388–395.
[3] R. Bayford, P. Bertemes-Filho, I. Frerichs, Topical issues in electrical impedance tomography and bioimpedance application research, Physiol. Meas. 41 (2020), 120301.
[4] H. He, Y. Chi, Y. Long, S. Yuan, R. Zhang, Y. Yang, I. Frerichs, K. Moller, F. Fu, Z. Zhao, Three broad classifications of acute respiratory failure etiologies based on regional ventilation and perfusion by electrical impedance tomography: a hypothesis-generating study, Ann. Intensive Care 11 (2021) 134.
[5] I. Tarotin, K. Aristovich, D. Holder, Model of impedance changes in unmyelinated nerve fibers, IEEE Trans. Biomed. Eng. 66 (2019) 471–484.
[6] E.K. Murphy, A. Mahara, X. Wu, R.J. Halter, Phantom experiments using soft-prior regularization EIT for breast cancer imaging, Physiol. Meas. 38 (2017) 1262–1277.
[7] R. Li, J. Gao, Z. Zhao, Y. Li, J. Wu, A preliminary study of assessing bladder urinary volume using electrical impedance tomography, J. Med. Biol. Eng. 36 (2016) 8.
[8] T. de Castro Martins, A.K. Sato, F.S. de Moura, E.D.L.B. de Camargo, O.L. Silva, T.B.R. Santos, Z. Zhao, K. Möeller, M.B.P. Amato, J.L. Mueller, A review of electrical impedance tomography in lung applications: theory and algorithms for absolute images, Annu. Rev. Control. 48 (2019) 442–471.
[9] Z. Zhao, F. Fu, I. Frerichs, Thoracic electrical impedance tomography in Chinese hospitals: a review of clinical research and daily applications, Physiol. Meas. 41 (2020), 04TR01.
[10] I. Frerichs, M.B. Amato, A.H. van Kaam, D.G. Tingay, Z. Zhao, B. Grychtol, M. Bodenstein, H. Gagnon, S.H. Bohm, E. Teschner, O. Stenqvist, T. Mauri, V. Torsani, L. Camporota, A. Schibler, G.K. Wolf, D. Gommers, S. Leonhardt, A. Adler, Chest electrical impedance tomography examination, data analysis, terminology, clinical use, and recommendations: consensus statement of the TRanslational EIT developmeNt stuDy group, Thorax 72 (2017) 83–93.
[11] C.S. Wiysonge, O.A. Uthman, P.M. Ndumbe, G.D. Hussey, A bibliometric analysis of childhood immunization research productivity in Africa since the onset of the Expanded Program on Immunization in 1974, BMC Med. 11 (2013) 66.
[12] F. Turatto, E. Mazzalai, F. Pagano, G. Migliara, P. Villari, C. De Vito, A systematic review and bibliometric analysis of the scientific literature on the early phase of COVID-19 in Italy, Front. Public Health 9 (2021), 666669.

[13] S. Pirri, V. Lorenzoni, G. Turchetti, Scoping review and bibliometric analysis of Big Data applications for Medication adherence: an explorative methodological study to enhance consistency in literature, BMC Health Serv. Res. 20 (2020) 688.
[14] D.H. Edited By Andy Adler, Electrical Impedance Tomography: Methods, History and Applications, CRC Press, 2021.
[15] R.V. Davalos, L.M. Mir, B. Rubinsky, Tissue ablation with irreversible electroporation, Ann. Biomed. Eng. 33 (2005) 223–231.
[16] J. Jossinet, Variability of impedivity in normal and pathological breast tissue, Med. Biol. Eng. Comput. 34 (1996) 346–350.
[17] I. Frerichs, M.B. Amato, A.H. van Kaam, D.G. Tingay, Z. Zhao, B. Grychtol, M. Bodenstein, H. Gagnon, S.H. Bohm, E. Teschner, O. Stenqvist, T. Mauri, V. Torsani, L. Camporota, A. Schibler, G.K. Wolf, D. Gommers, S. Leonhardt, A. Adler, group Ts, Chest electrical impedance tomography examination, data analysis, terminology, clinical use and recommendations: consensus statement of the TRanslational EIT developmeNt stuDy group, Thorax 72 (2017) 83–93.
[18] R.H. Bayford, Bioimpedance tomography (electrical impedance tomography), Annu. Rev. Biomed. Eng. 8 (2006) 63–91.
[19] F. Braun, M. Proenca, J. Sola, J.-P. Thiran, A. Adler, A versatile noise performance metric for electrical impedance tomography algorithms, IEEE (Inst. Electr. Electron. Eng.) Trans. Biomed. Eng. 64 (2017) 2321–2330.
[20] B. Rubinsky, M. Dai, B. Li, S. Hu, C. Xu, B. Yang, J. Li, F. Fu, Z. Fei, X. Dong, In vivo imaging of twist drill drainage for subdural hematoma: a clinical feasibility study on electrical impedance tomography for measuring intracranial bleeding in humans, PLoS One 8 (2013), e55020.
[21] C. Wang, H. Jing, Z. Sun, J. Yao, X. Zhang, T. Liu, Y. Wu, A bibliometric analysis of primary aldosteronism research from 2000 to 2020, Front. Endocrinol. 12 (2021), 665912.
[22] Z. Li, S. Qin, C. Chen, S. Mei, Y. Yao, Z. Zhao, W. Li, Y. Deng, Y. Gao, Emerging trends and hot spots of electrical impedance tomography applications in clinical lung monitoring, Front. Med. 8 (2022).
[23] X.Y. Ke, W. Hou, Q. Huang, X. Hou, X.Y. Bao, W.X. Kong, C.X. Li, Y.Q. Qiu, S.Y. Hu, L.H. Dong, Advances in electrical impedance tomography-based brain imaging, Mil Med Res 9 (2022) 10.
[24] Z. Rezanejad Gatabi, M. Mirhoseini, N. Khajeali, I. Rezanezhad Gatabi, M. Dabbaghianamiri, S. Dorri, The accuracy of electrical impedance tomography for breast cancer detection: a systematic review and meta-analysis, Breast J. 2022 (2022), 8565490.
[25] Y. Wan, R. Halter, A. Borsic, P. Manwaring, A. Hartov, K. Paulsen, Sensitivity study of an ultrasound coupled transrectal electrical impedance tomography system for prostate imaging, Physiol. Meas. 31 (2010) S17–S29.
[26] S.S. Noyori, G. Nakagami, H. Sanada, Non-invasive urine volume estimation in the bladder by electrical impedance-based methods: a review, Med. Eng. Phys. 101 (2022), 103748.
[27] U. Andreis, M.F. Americo, L.A. Cora, R.B. Oliveira, O. Baffa, J.R. Miranda, Gastric motility evaluated by electrogastrography and alternating current biosusceptometry in dogs, Physiol. Meas. 29 (2008) 1023–1031.
[28] K.H. Wodack, S. Buehler, S.A. Nishimoto, M.F. Graessler, C.R. Behem, A.D. Waldmann, B. Mueller, S.H. Bohm, E. Kaniusas, F. Thurk, A. Maerz, C.J.C. Trepte, D.A. Reuter, Detection of thoracic vascular structures by electrical impedance tomography: a systematic assessment of prominence peak analysis of impedance changes, Physiol. Meas. 39 (2018).
[29] S. Hannan, M. Faulkner, K. Aristovich, J. Avery, M.C. Walker, D.S. Holder, In vivo imaging of deep neural activity from the cortical surface during hippocampal epileptiform events in the rat brain using electrical impedance tomography, Neuroimage 209 (2020), 116525.
[30] T. Tang, M.D. Weiss, P. Borum, S. Turovets, D. Tucker, R. Sadleir, In vivo quantification of intraventricular hemorrhage in a neonatal piglet model using an EEG-layout based electrical impedance tomography array, Physiol. Meas. 37 (2016) 751–764.
[31] K. Boone, A.M. Lewis, D.S. Holder, Imaging of cortical spreading depression by EIT: implications for localization of epileptic foci, Physiol. Meas. 15 (Suppl 2a) (1994) A189–198.
[32] P.K. Manwaring, K.L. Moodie, A. Hartov, K.H. Manwaring, R.J. Halter, Intracranial electrical impedance tomography: a method of continuous monitoring in an animal model of head trauma, Anesth. Analg. 117 (2013) 866–875.
[33] O.V. Trokhanova, M.B. Okhapkin, A.V. Korjenevsky, Dual-frequency electrical impedance mammography for the diagnosis of non-malignant breast disease, Physiol. Meas. 29 (2008) S331–344.
[34] M. Akhtari-Zavare, L.A. Latiff, Electrical impedance tomography as a primary screening technique for breast cancer detection, Asian Pac. J. Cancer Prev. APJCP 16 (2015) 5595–5597.
[35] A. Stojadinovic, O. Moskovitz, Z. Gallimidi, S. Fields, A.D. Brooks, R. Brem, R.N. Mucciola, M. Singh, M. Maniscalco-Theberge, H.E. Rockette, D. Gur, C.D. Shriver, Prospective study of electrical impedance scanning for identifying young women at risk for breast cancer, Breast Cancer Res. Treat. 97 (2006) 179–189.
[36] A. Stojadinovic, A. Nissan, C.D. Shriver, E.A. Mittendorf, M.D. Akin, V. Dickerson, S. Lenington, L.D. Platt, T. Stavros, S.R. Goldstein, O. Moskovitz, Z. Gallimidi, S.I. Fields, A. Yeshaya, T.M. Allweis, R. Manassa, I. Pappo, R.X. Ginor, R.B. D'Agostino, D. Gur, Electrical impedance scanning as a new breast cancer risk stratification tool for young women, J. Surg. Oncol. 97 (2008) 112–120.
[37] U. Anushree, S. Shetty, R. Kumar, S. Bharati, Adjunctive diagnostic methods for skin cancer detection: a review of electrical impedance-based techniques, Bioelectromagnetics 43 (2022) 193–210.
[38] R. Rojas, B. Rubinsky, C.A. Gonzalez, The effect of brain hematoma location on volumetric inductive phase shift spectroscopy of the brain with circular and magnetron sensor coils: a numerical simulation study, Physiol. Meas. 29 (2008) S255–S266.
[39] J.C. Newell, P.M. Edic, X. Ren, J.L. Larson-Wiseman, M.D. Danyleiko, Assessment of acute pulmonary edema in dogs by electrical impedance imaging, IEEE Trans. Biomed. Eng. 43 (1996) 133–138.
[40] O.I. Kwon, S.Z.K. Sajib, I. Sersa, T.I. Oh, W.C. Jeong, H.J. Kim, E.J. Woo, Current density imaging during transcranial direct current stimulation using DT-MRI and MREIT: algorithm development and numerical simulations, Ieee T Bio-Med Eng 63 (2016) 168–175.
[41] S.Z.K. Sajib, T.I. Oh, H.J. Kim, O.I. Kwon, E.J. Woo, In vivo mapping of current density distribution in brain tissues during deep brain stimulation (DBS), AIP Adv. 7 (2017).
[42] R.J. Sadleir, F.R. Fu, C. Falgas, S. Holland, M. Boggess, S.C. Grant, E.J. Woo, Direct detection of neural activity in vitro using magnetic resonance electrical impedance tomography (MREIT), Neuroimage 161 (2017) 104–119.
[43] R.J. Sadleir, F.R. Fu, M. Chauhan, Functional magnetic resonance electrical impedance tomography (fMREIT) sensitivity analysis using an active bidomain finite-element model of neural tissue, Magn. Reson. Med. 81 (2019) 602–614.
[44] Lee SY, Oh SH, Lee BI, Woo EJ, Cho MH. Magnetic Resonance Electrical Impedance Tomography: Theory and Phantom Experiments.
[45] D.H. Kim, J. Viventi, J.J. Amsden, J.L. Xiao, L. Vigeland, Y.S. Kim, J.A. Blanco, B. Panilaitis, E.S. Frechette, D. Contreras, D.L. Kaplan, F.G. Omenetto, Y.G. Huang, K.C. Hwang, M.R. Zakin, B. Litt, J.A. Rogers, Dissolvable films of silk fibroin for ultrathin conformal bio-integrated electronics, Nat. Mater. 9 (2010) 511–517.
[46] D.Y. Zhu, A. McEwan, C. Eiber, Microelectrode array electrical impedance tomography for fast functional imaging in the thalamus, Neuroimage 198 (2019) 44–52.
[47] S. Qin, Y. Yao, Y. Xu, D. Xu, Y. Gao, S. Xing, Z. Li, Characteristics and topic trends on electrical impedance tomography hardware publications, Front. Physiol. 13 (2022).
[48] S.W. Xu, M. Dai, C.H. Xu, C.S. Chen, M.X. Tang, X.T. Shi, X.Z. Dong, Performance evaluation of five types of Ag/AgCl bio-electrodes for cerebral electrical impedance tomography, Ann. Biomed. Eng. 39 (2011) 2059–2067.
[49] Z.Y. Li, C.S. Ren, Gastric motility measurement and evaluation of functional dyspepsia by a bio-impedance method, Physiol. Meas. 29 (2008) S373–S382.
[50] X. Shi, W. Li, F. You, X. Huo, C. Xu, Z. Ji, R. Liu, B. Liu, Y. Li, F. Fu, X. Dong, High-precision electrical impedance tomography data acquisition system for brain imaging, IEEE Sensor. J. 18 (2018) 5974–5984.
[51] L. Xiao, K. Yu, Y. Cao, X. Lin, X. Liu, H. Qiao, H. Miao, T. Li, Technique innovation and clinical application of electrical impedance tomography: bibliometric research from 2001 to 2020, Med. Sci. Monit. 28 (2022).