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The application of infrared thermography technology in flap: A perspective from bibliometric and visual analysis

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Abstract

The application of infrared thermography technology (IRT) in flap has become a major focus of research, as it provides a non-invasive, real-time, and quantitative approach for monitoring flap perfusion. In this regard, we conducted a comprehensive visualization and scientometric analysis to systematically summarize and discuss the current state of research in this field. We systematically reviewed publications on the application of IRT in flap procedures from 1999 to 2022, using the Web of Science Core Collection (WoSCC). Through scientometric analysis, we examined annual trends, affiliations, countries, journals, authors, and their relationships, providing insights into current hotspots and future developments in this area. We analysed 522 English studies and found a steady increase in annual publications. The United States and Germany had the highest publication rates, with Beth Israel Deaconess Medical Center and Shanghai Jiaotong University being leading institutions. Notably, Lee BT and Alex Keller emerged as influential authors in this field. Compared to existing techniques, infrared-based technology offers significant advantages for non-invasive monitoring of flap perfusion, including simplicity of operation and objective results. Future trends should focus on interdisciplinary collaborations to develop new infrared devices and achieve intelligent image processing, enabling broader application in various clinical scenarios. This bibliometric study summarizes the progress and landscape of research on ‘the Application of infrared thermography technology in flap’ over the past two decades, providing valuable insights and serving as a reliable reference to drive further advancements and spark researchers' interest in this field.

KEYWORDS
CiteSpace, flap, infrared thermography technology, scientometric, VOSviewer

Yilei Lu and Nianzhe Sun contributed equally to this work.

Key Messages

- the systematic review provided a panoramic view of the field by examining publications on the application of infrared thermography technology (IRT) in flap procedures from 1999 to 2022
- the study compared IRT with other flap perfusion monitoring techniques to evaluate its position and merits in the field
- the paper revealed the research trends in infrared technology and aimed to provide reliable references for scholars

1 | INTRODUCTION

Infrared thermography technology (IRT) is a non-invasive technique[1] based on optoelectronic technology that utilizes an optical system to focus the infrared energy emitted by an object onto an infrared detector, thereby forming an infrared image. By comparing the infrared thermal image of the target under measurement with a standard infrared thermal image, the temperature distribution of the target can be calculated.[2] With advancements in infrared technology, it is now possible to perform multi-wavelength detection,[3] simultaneously detecting temperatures in multiple different spectral bands, thereby overcoming the limitations of previous single-wavelength detection due to atmospheric absorption and environmental temperature effects. This technology enables real-time, rapid, and accurate detection of target temperatures,[4] making it of significant importance. In the field of medicine, the value of modern infrared thermography primarily lies in its ability to generate digital images and present infrared thermal images in real-time, aiding in the assessment of temperature distribution on the surface of the human body.[5] Additionally, this technique offers advantages such as non-invasiveness, speed, safety, and efficiency, resulting in its widespread application in surgical procedures.[6]

Flap surgery is commonly employed for wound repair or tissue transplantation,[7] with the key objective of ensuring flap viability. To achieve optimal surgical outcomes, it is crucial to preoperatively select the most suitable vascular pedicle for blood supply.[8] IRT can provide thermal distribution images of blood vessels, revealing temperature variations in different regions.[9] Generally, areas with larger vessel diameters and faster blood flow tend to exhibit higher surface temperatures. Therefore, infrared imaging can be utilized to identify these regions as optimal perforator vessel locations. Furthermore, IRT can assist intraoperative decision-making by providing real-time monitoring of blood flow dynamics and temperature distribution, facilitating the evaluation of blood perfusion and vascular functionality.[10,11] Vascular compromise is one of the most dangerous complications following flap surgery, including vascular spasm and arterial or venous thrombosis.[12] Previous studies have indicated that IRT can aid in the early identification of vascular compromise, enabling timely intervention[13] and mitigating postoperative complications associated with flap surgery.[14]

Over the past two decades, a significant body of research has been published on the application of infrared technology in flap surgery. However, these studies have yet to undergo systematic organization and analysis. Moreover, there is an ongoing dispute regarding the efficacy and appropriate contexts for different techniques, frequently placing clinicians in a predicament when selecting the optimal course of action. Systematically evaluating current research can assist clinical practitioners and scholars in better determining the optimal indications for these technologies and provide valuable insights for future technological advancements. Bibliometrics is a method that employs statistical and quantitative analysis of literature data to objectively and systematically evaluate the scale, impact, and trends of scientific research.[15,16] Currently, commonly used software tools for bibliometric analysis include VOSviewer,[17–19] CiteSpace,[16,20–22] HistCite™,[17,23] and R-bibliometrix.[24–26] Nonetheless, in the specific domain of 'infrared technology in flaps', no prior attempts have been made to apply bibliometric methods for analysing relevant studies. Therefore, this analysis aims to utilize bibliometric approaches to explore the published research and summarize the application of infrared technology in flap surgery through information visualization, thereby enhancing the existing knowledge base and providing new research directions.

2 | MATERIALS AND METHODS

2.1 | Sources of bibliometric data and search strategy

On 1 April 2023, we conducted a computer search at Xiangya Hospital, Central South University, using The Web of Science Core Collection (WoSCC) to retrieve publications indexed from the initial publication to

31 December 2022, based on the search vector 'infrared thermography' and 'flap'. The database source was set to Science Citation Index Expanded (SCIE), and the research type was limited to 'article' or 'review'. A detailed search strategy is provided in Appendix S1. Only publications in English were considered. To ensure the accuracy and reliability of the data, two independent reviewers (NS and YL) simultaneously downloaded all eligible data in TXT format. Irrelevant and duplicate publications were excluded. Any discrepancies between the two authors (NS and YL) were resolved through discussion, and unresolved agreements were consulted with a third party (JT).

2.2 | Statistical analysis

The data, encompassing highly cited authors, journals, countries, and institutions, was imported into Microsoft Excel 2016 for the purpose of meticulous analysis, ranking, and statistical evaluation. Bar graphs were meticulously constructed utilizing GraphPad Prism 9. In order to establish and visually represent bibliometric maps, and to conduct comprehensive analyses including co-authorship, co-citation, co-occurrence, and network visualization, we employed the advanced VOSviewer software (v 1.6.17) developed by Leiden University, renowned for its expertise in this field. Each distinct term, ranging from keywords, countries, institutions, to authors, was elegantly portrayed by a circle, wherein the proximity of circles reflected the intensity of their associations. Diverse colour codes were thoughtfully utilized to delineate discrete term clusters. The dimensions of the circles were proportionally linked to the frequency of term occurrence, while the thickness of the lines elegantly conveyed the strength of connections between the terms. CiteSpace is one of the most widely used software tools for bibliometric analysis, which allows for exploring the development trends within specific research domains. In this study, we applied CiteSpace 6.1. R2 64-bit (Pro. Chaomei Chen from Drexel University) to extract and construct references characterized by significant citation bursts and overlay dualmaps for journals. This approach aimed to investigate the development trends within a particular field. The parameters for CiteSpace were configured as follows: the link retaining factor was set to 3 (LRF = 3), the value for top N was set to 1 ($e = 1$), the time interval was specified as 1999–2022, each time slice represented a span of 1 year, the look back years were set to 5 (LBY = 5), links (strength: cosine, scope: within slices), selection criteria relied on the g-index with a threshold of 15 ($k = 15$), and the minimum duration was set to 1 (MD = 1).[16] Moreover, we utilized the bibliometric analysis platform (https://bibliometric.com/) and R-bibliometrix to meticulously investigate the frequency of keyword usage and to comprehensively explore the intricate academic collaboration networks among diverse countries.

3 | RESULTS

3.1 | Publication output and trends

A total of 559 publications were retrieved from the period between 1999 and 2022. After screening, the remaining 522 articles were analysed (Figure 1). From 1999 to 2022, there was an overall increasing trend in the annual publication output. The number of publications in 2022 was seven times higher than that in 1999 (Figure 2A). Concurrently, the citation counts also showed an upward trend, with a significant surge observed from 2017 to 2022 (Figure 2B).

3.2 | Most prolific countries and institutions analysis

A total of 46 countries made significant contributions to this research field (Figure 3A). The top five countries with the highest publication output were the United States ($n = 178$, 34.1%), Germany ($n = 80$, 15.3%), China ($n = 71$, 13.6%), Japan ($n = 52$, 10.0%), and the United Kingdom ($n = 30$, 5.7%), while the remaining countries had fewer than 30 publications. At the same time, the United States was also the country that published the highest number of Single Country Publications (SCP) and Multiple Country Publications (MCP). SCP refers to independent research or publications focused on specific countries, providing valuable references for studying and analysing various aspects within those countries by delving into their characteristics.[27] Conversely, MCP encompasses comparative studies involving multiple countries, offering comprehensive perspectives that facilitate understanding of interactions between nations and the influencing factors on global development.[28,29] Also, as shown in Figure 3B, the United States consistently led in terms of publication output and experienced rapid growth starting from 2008, indicating the country's continuous investment and strong presence in this field. Other countries such as Germany, China, and Japan also witnessed an increase in publications from 2006 onwards. Close collaborations were observed between the United States and Germany, Japan, and South Korea (Figure 3C). Figure 3D displayed the citation count in descending order, with the United States, Germany, Japan, the Netherlands, and China occupying the top positions. The citation count for the United States

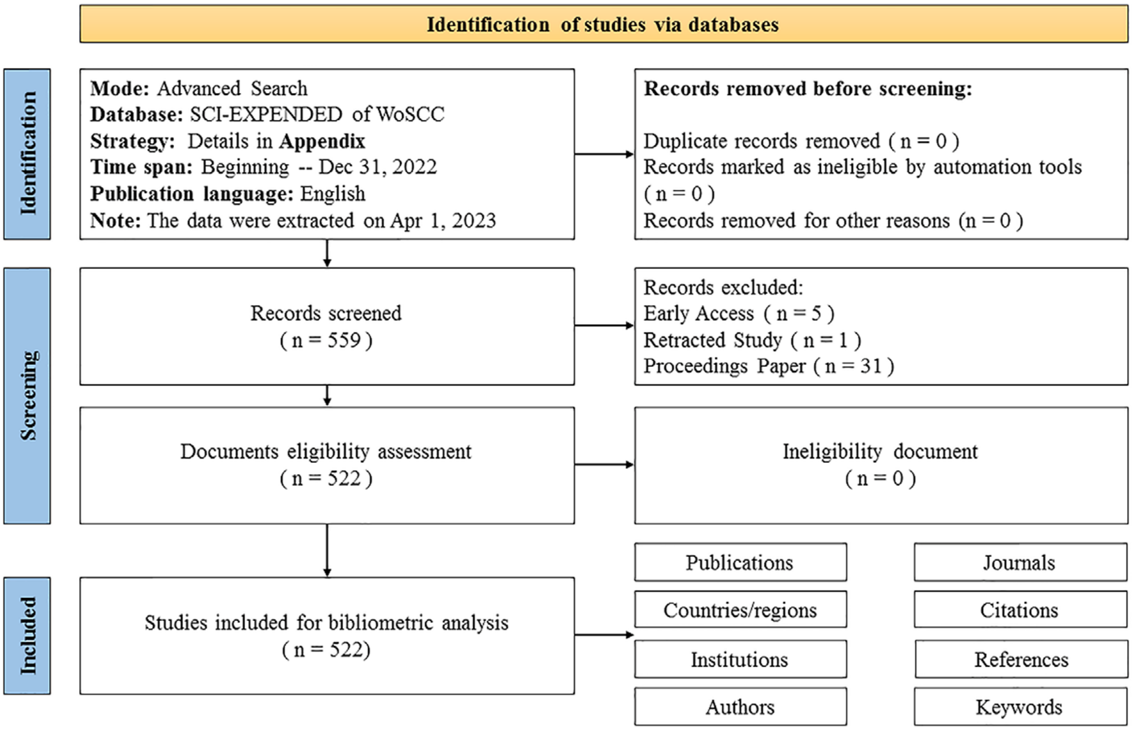

FIGURE 1 The flow chart.

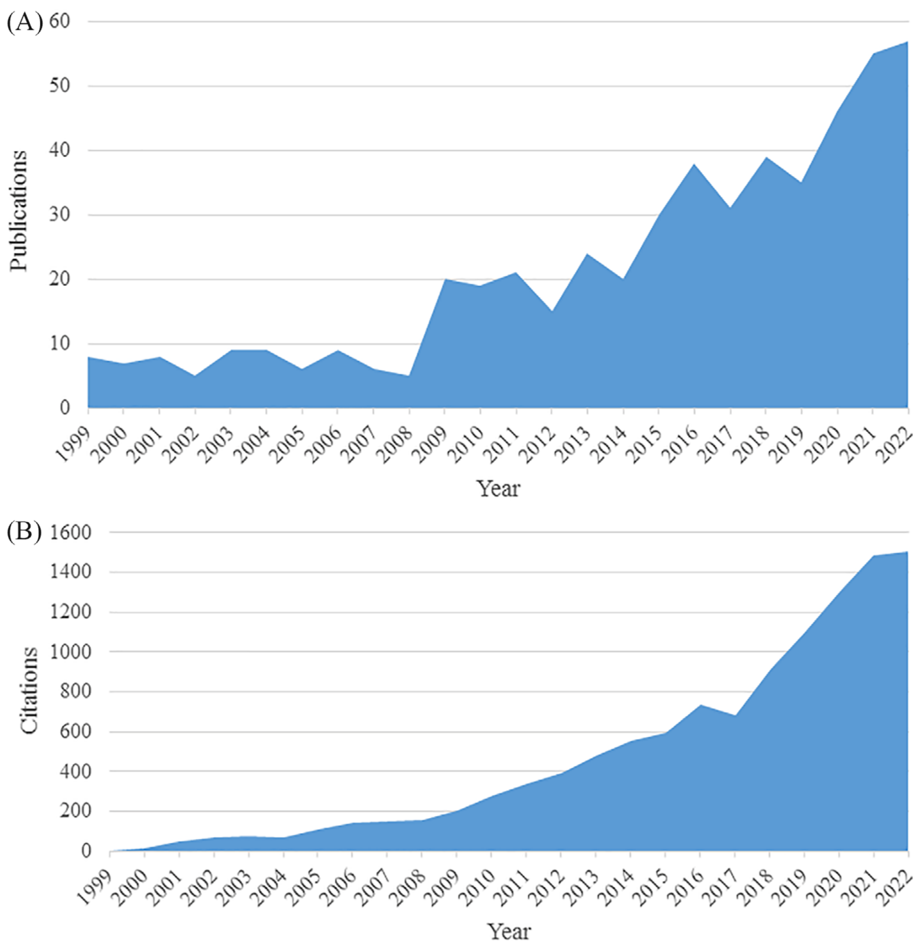

FIGURE 2 The trend analysis of annual publications and citations engaged in the application of infrared thermography technology (IRT) in flap from 1999 to 2022.

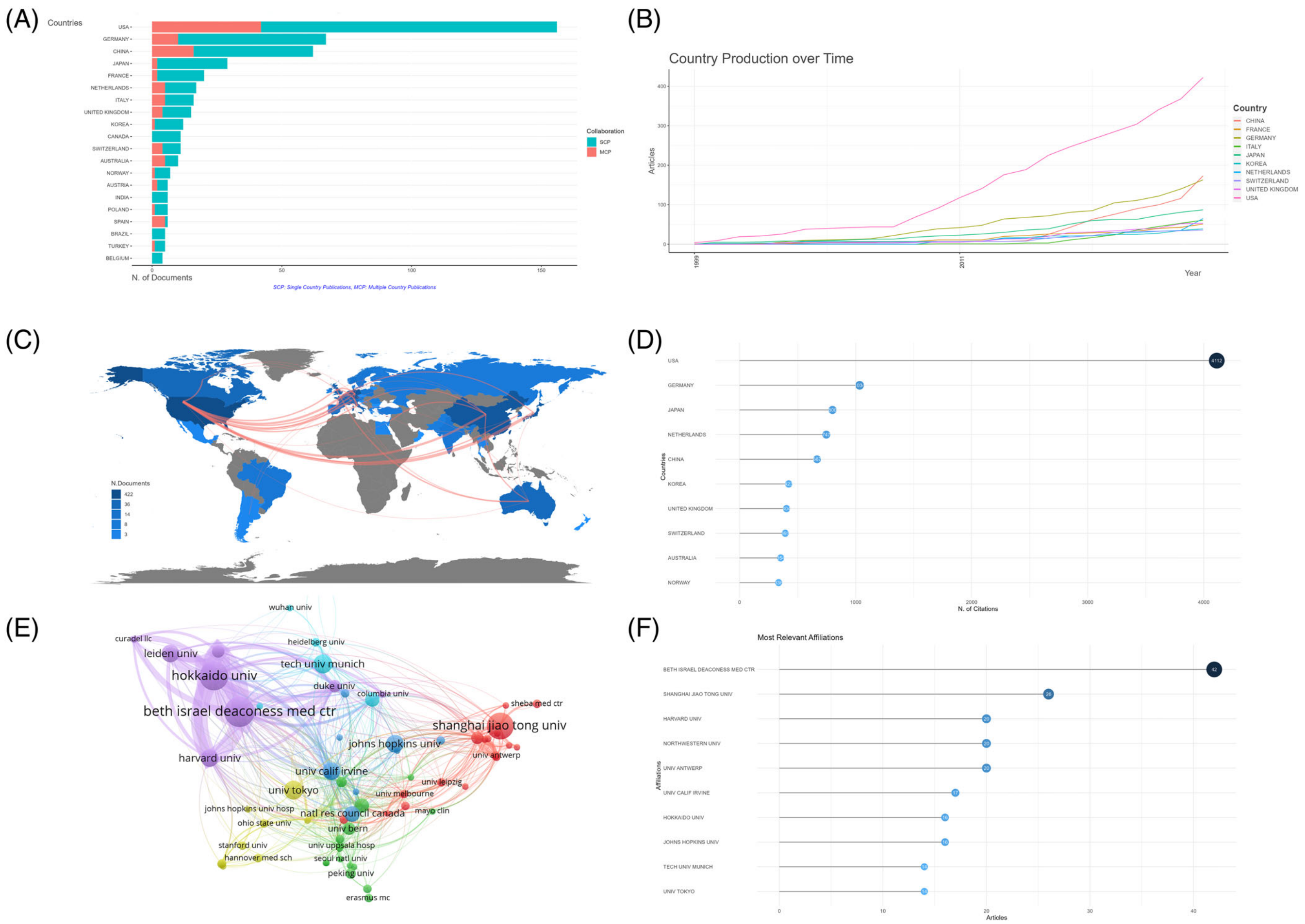

FIGURE 3 Analysis of countries and institutions engaged in the application of infrared thermography technology (IRT) in flap. (A) The top 20 most productive SCP and MCP countries. SCP, Single country publications, MCP, Multiple country publications. (B) The dynamic publications analysis of the top 10 most productive countries. (C) The distribution and cooperative relationship of countries in terms of publications. (D) The countries ranking list about citations. (E) The cooperative relationship of institutions ($T \geq 3$, $N = 66$) in terms of publications via VOSviewer. (F) The affiliations ranking list about documents.

was approximately four times higher than that of Germany ($n = 1034$), which indicated that the research achievements of America had a high impact and significance. Additionally, South Korea, the United Kingdom, Switzerland, Australia, and Norway did not exceed 500 citations. Figure 3E illustrated the institution-based co-authorship network for publications with three or more articles ($T \geq 3$). Nodes representing Beth Israel Deaconess Medical Center and Shanghai Jiaotong University were relatively larger, denoting a higher number of publications. Active collaborations were observed among different institutions. For instance, there was close cooperation between Beth Israel Deaconess Medical Center and Hokkaido University, as well as Harvard University. Moreover, Hokkaido University also had positive collaborations with Harvard University, Leiden University, and Duke University. In Figure 3F, Beth Israel Deaconess Medical Center ($n = 42$) emerged as the institution with the highest number of published papers, followed by Shanghai Jiaotong University ($n = 26$), Harvard University ($n = 20$), Northwestern University ($n = 20$), and the University of Antwerp ($n = 20$). It could be observed that Beth Israel Deaconess Medical Center had the highest number of published papers in this field, showing its prominent position. Furthermore, active collaborations were evident between Beth Israel Deaconess Medical Center and other institutions, which contributed to the productivity and impact of research outcomes.

3.3 | Analysis of journals and co-cited academic journals

H-index, a metric that quantifies both the productivity and impact of a researcher's publications, measures the number of papers a researcher has published and the number of citations those papers have received.[30] In

TABLE 1 The top 10 academic journals and co-cited journals involved in the application of infrared thermography technology (IRT) in flap.

Rank	Journals	Counts	H-index	Co-cited Journals	Citations	TLS
1	Plastic and Reconstructive Surgery	41	19	Plastic and Reconstructive Surgery	2439	72 526
2	Journals of Reconstructive Microsurgery	36	14	Annals of Plastic Surgery	818	31 089
3	Annals of Plastic Surgery	28	15	Journals of Reconstructive Microsurgery	652	27 216
4	Microsurgery	25	11	Microsurgery	611	25 564
5	Journal of Plastic Reconstructive & Aesthetic Surgery	18	8	Journal of Plastic Reconstructive & Aesthetic Surgery	528	23 018
6	Journal of Surgical Research	13	8	British Journal of Plastic Surgery	442	15 986
7	Lasers in Surgery and Medicine	6	5	Journals of Biomedical Optics	190	5250
8	Journals of Biomedical Optics	6	4	The Journal of Chemical Physics	162	5210
9	Journal of Personalized Medicine	6	3	Clinics in Plastic Surgery	152	5293
10	Gland Surgery	6	5	Journal of Surgical Research	122	3716

Abbreviation: TLS, total link strength.

the context of this study, Table 1 revealed that *Plastic and Reconstructive Surgery* ($n = 41$, 7.85%) had the highest publication volume in the field of IRT in flap, followed by Journals of *Reconstructive Microsurgery* ($n = 36$, 6.9%). Among the top 10 journals with the highest output, seven were from the United States, one from the United Kingdom, one from Switzerland, and one from China. Notably, *Plastic and Reconstructive Surgery* also demonstrated the highest H-index, indicating its significant impact and influence in the field. Total link strength, which can be used to measure the degree of interconnection between nodes in an academic collaboration network,[31] becomes particularly evident when examining specific examples. For instance, in the co-cited Journals analysis, *Plastic and Reconstructive Surgery* stood out with the highest number of citations ($n = 2439$) and demonstrated the strongest Total link strength (TLS = 72 526). This journal accounted for 33.75% of the top 10 co-cited Journals, illustrating its significant influence and extensive connections within the network.

As shown in Figure 4A, *Plastic and Reconstructive Surgery* consistently led in publication volume, with a rapid increase starting from 2008. Other journals such as *Journal of Reconstructive Microsurgery*, *Annals of Plastic Surgery*, *Microsurgery*, and *Journal of Plastic Reconstructive & Aesthetic Surgery* also demonstrated an increase in publication volume since 2008. *Plastic and Reconstructive Surgery* was closely associated with *Journal of Reconstructive Microsurgery*, while *Journal of Reconstructive Microsurgery* had a strong connection with *Microsurgery* (Figure 4B). In addition, the co-cited academic journals map revealed the close associations of *Plastic and Reconstructive Surgery* with *Annals of Plastic Surgery*, *Microsurgery*, *Journal of Plastic Reconstructive & Aesthetic Surgery* (Figure 4C).

In Figure 5, the thematic distribution of journals was represented through the dual-map coverage of citations and co-citations. Citations and co-citations were displayed on both sides. From left to right, colours indicated citation relationships, such as green, grey, and red paths, while different clusters represent different regions. There were seven main citation pathways, two of which were green, four were grey, and one was red. The green paths showed that the main citation cluster consisted of papers published in Medicine/Medical/Clinical journals, while the main co-cited cluster consisted of documents published in Health/Nursing/Medicine journals. The grey paths reflected the frequent citation of researches published in Dermatology/Dentistry/Surgery journals co-cited by studies published in Dermatology/Dentistry/Surgery journals and Health/Nursing/Medicine journals. Similarly, researches published in Molecular/Biology/Genetics journals and Chemistry/Materials/Physics journals was frequently co-cited by studies published in Dentistry/Dermatology/Surgery journals. The red path revealed that research published in Physics/Materials/Chemistry journals represented the primary source of citations, while papers published in Chemistry/Materials/Physics journals emerged as the predominant cluster being co-cited.

3.4 | Authors and co-cited author analysis

A total of 2427 researchers had contributed to publications in the field of IRT in flap, with Lee BT ($n = 21$) and Frangioni JV ($n = 18$) being the top two most productive researchers (Table 2). At the same time, their high H-index rankings as the first and second, respectively, reflected their significant scholarly contributions in the field and

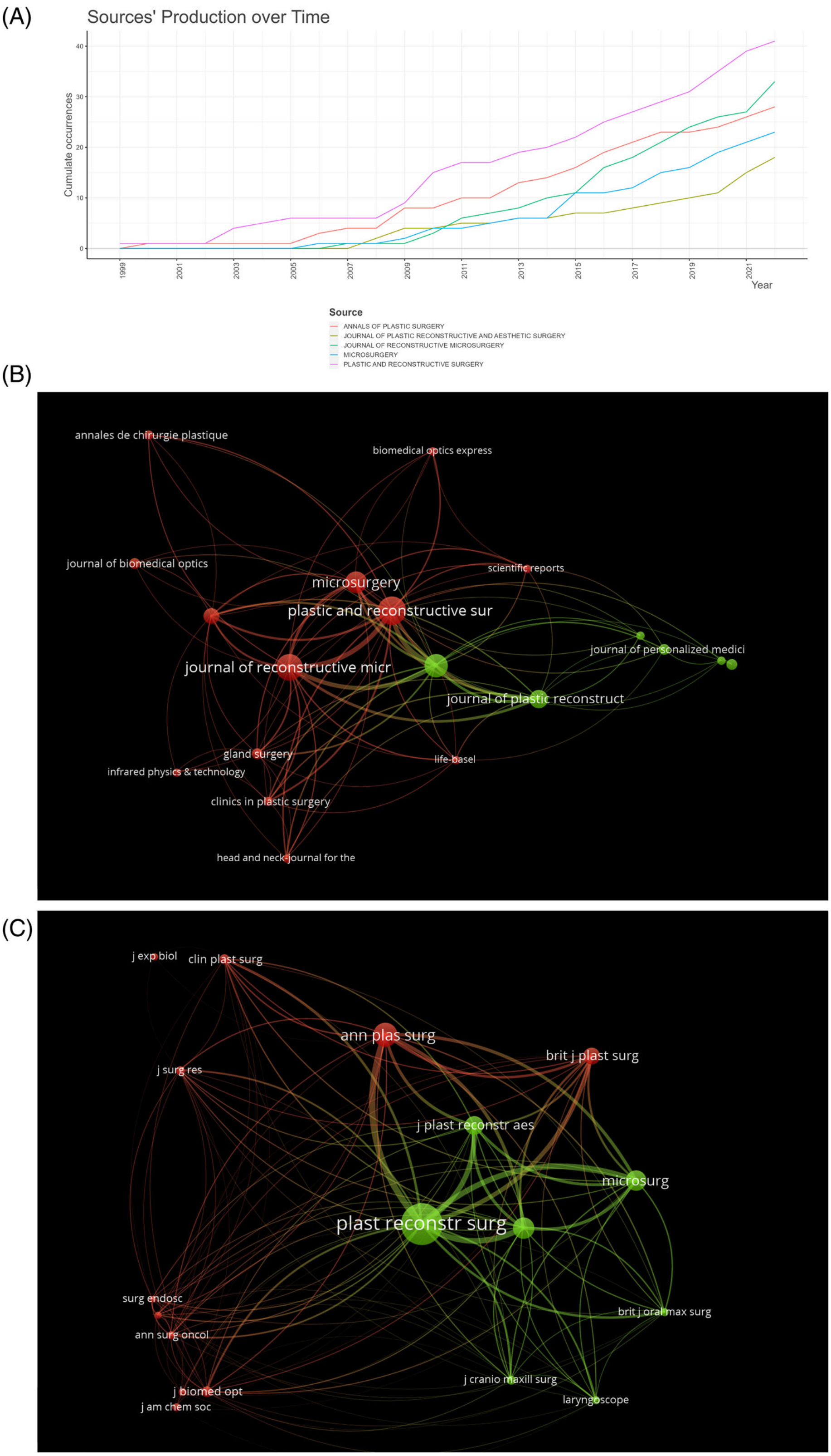

FIGURE 4 The dynamic publications analysis (A, top 5 productive journals) and network map of academic journals (B, $T \geq 4$, $N = 19$) and co-cited academic journals (C, $T \geq 80$, $N = 18$) for the application of IRT in flap.

demonstrated their substantial academic impact.[30] Besides, the three most co-cited authors were Holm C ($n = 152$), de Weerd L ($n = 129$), and Rozen WM ($n = 123$).

VOSviewer was used to analyse the co-authorship and citation networks[32] among researchers in the field of IRT in flap (Figure 6). Consistent with the findings in Table 2, Lee BT ($n = 21$) and Frangioni JV ($n = 18$) had much larger nodes compared to other authors due to their higher publication output. The co-occurrence relationships in Figure 6A depicted the close collaborations among different authors, revealing that more active authors tend to have higher co-occurrence frequencies with other researchers.[33]

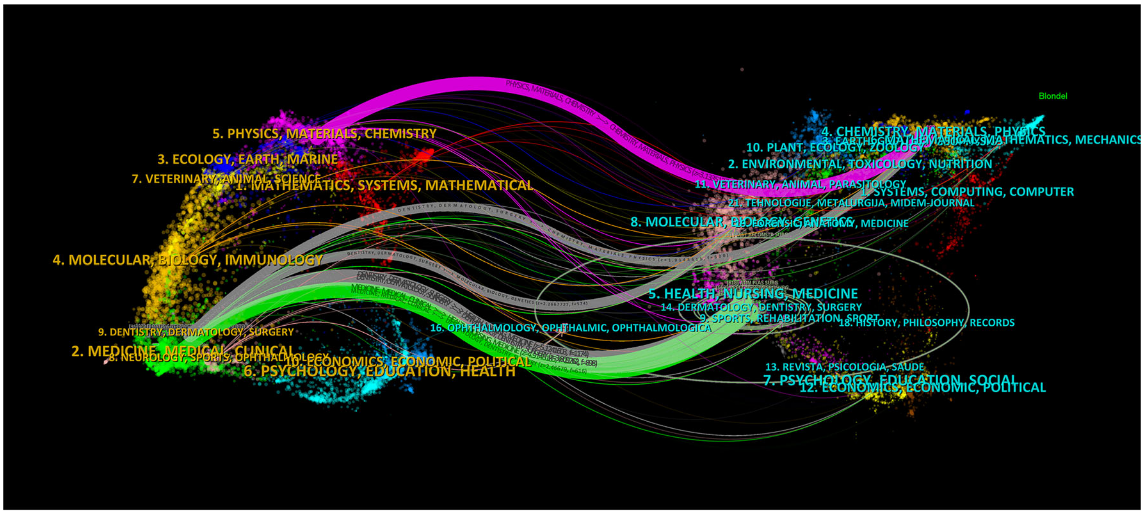

FIGURE 5 The dual-map overlay of journals related to the application of IRT in flap. On the left were the citing journals (orange), on the right were the cited journals(blue), and the coloured path represented the citation relationship.

TABLE 2 The top 10 academic authors and co-cited authors involved in the application of infrared thermography technology (IRT) in flap.

Rank	Authors	Counts	H-index	Co-cited Authors	Citations	TLS
1	Lee BT	21	13	Holm C	152	1962
2	Frangioni JV	18	12	de Weerd L	129	1393
3	Zhang Y	11	4	Rozen WM	123	2304
4	Lin SJ	9	9	Smit JM	117	1919
5	Ashitate Y	9	8	Matsui A	102	1138
6	Laane J	9	6	Keller A	97	1397
7	Gioux S	8	8	Whitaker IS	74	1493
8	Feng S	8	4	Khouri RK	68	923
9	Narushima M	7	6	Taylor GI	63	748
10	Koshima I	7	6	Lohman RF	61	883

Abbreviation: TLS, total link strength.

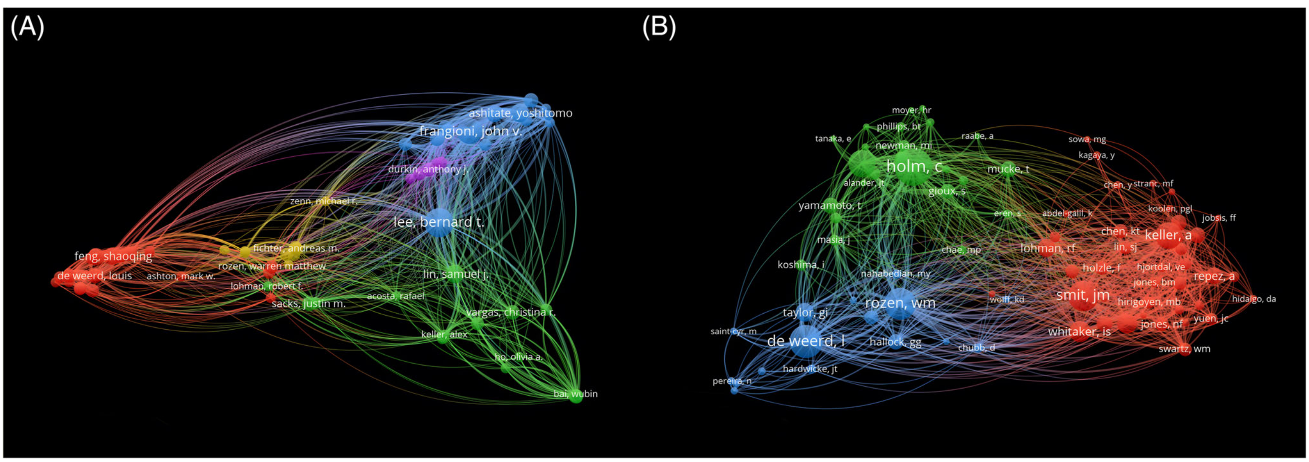

FIGURE 6 The network map of academic authors (A, $T \geq 3$, $N = 80$) and co-cited authors (B, $T \geq 18$, $N = 82$) involved in the application of infrared thermography technology (IRT) in flap.

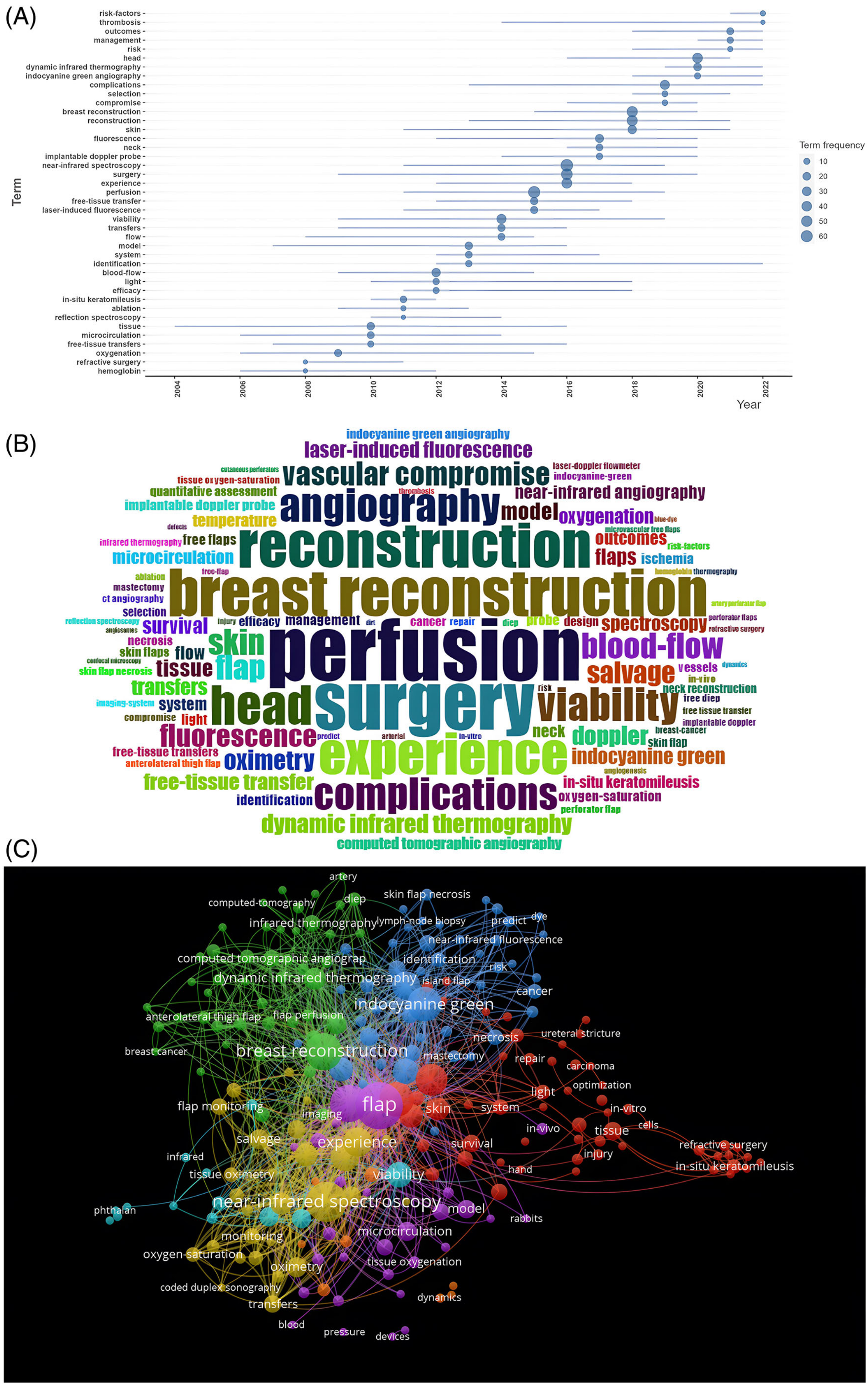

FIGURE 7 (A) The frequency analysis and burstness of keywords topics terms. (B) The visualization keywords cloud ($N = 100$). (C) The network map of all keywords ($T \geq 4$, $N = 226$) involved in the application of IRT in flap.

Co-citation refers to the situation where at least one publication from two authors appears together in the same reference list.[34] Consistent with Table 2, the co-citation map constructed by VOSviewer highlighted the largest circle for Holm C, illustrating a positive co-citation relationship with de Weerd L and Rozen WM. Additionally, de Weerd L and Rozen WM demonstrate a strong co-citation relationship with each other.

3.5 | Keyword co-occurrence and frequency

Figure 7A displayed the frequency and burstness of keywords in IRT in flap research. Over the past two decades, the following keywords had shown relative stability and high occurrence: perfusion, surgery, breast reconstruction, reconstruction, experience, head, and so forth, with a concentration between 2014 and 2018.

A word cloud (Figure 7B) was generated using the top 100 most frequent keywords, and the results aligned with the findings depicted in Figure 7A. The size of each word represented its frequency of occurrence, while the colour demonstrated the time of burstness. VOSviewer constructed a network map of all keywords (Figure 7C). All nodes were roughly divided into four clusters. The first cluster, depicted in red, primarily focused on location-related prognostic factors (skin, system, survival, tissue, light, necrosis, etc.). The second cluster, represented in green, centered around breast reconstruction, computed tomography techniques, and the selection of flaps, as well as the perfusion of flaps (Breast reconstruction, flap perfusion, dynamic infrared thermography [DIRT], computed tomographic angiography, etc.). The terms in the yellow cluster were mainly associated with near-infrared spectroscopy, oxygen supply, and salvage (near-infrared spectroscopy, experience, oximetry, salvage). Additionally, the blue cluster encompassed terms related to indocyanine green and island flaps. The purple cluster emphasized experimental model studies. Lastly, the blue-green cluster included terms related to viability, tissue oximetry, and other relevant aspects.

3.6 | Co-cited references analysis and burstness

Among the analysed 522 studies, a total of 1503 publications were cited. Local citation (LC) refers to the number of times a publication is cited by other publications within the same field or the same country, while global citation (GC) refers to the number of times a publication is cited by publications worldwide.[35,36] The ratio of LC to GC can be used to assess the influence and significance of a publication within its local domain. In this context, Table 3 presented the top 10 articles that had received significant LCs ($N \geq 50$ citations). For instance, Alex Keller's survey[37] titled 'A new diagnostic

TABLE 3 The top 10 local citation references involved in the application of infrared thermography technology (IRT) in flap.

Rank	Type	Documents	LC	GC	LC/GC Ratio (%)	NLC	NGC
1	Article	Keller A, 2009, Ann Plas Surg, DOI: 10.1097/SAP.0b013e3181a47ce8	56	103	54.37	5.05	2.78
2	Ariticle	Repez A, 2008, J Plast Reconstr Aes, DOI: 10.1016/j.bjps.2007.04.003	55	106	51.89	3.24	2.72
3	Review	Smit JM, 2010, Plast Reconstr Surg, DOI: 10.1097/PRS.0b013e3181c49580	47	177	26.55	5.45	2.51
4	Ariticle	Lin SJ, 2011, Plast Reconstr Surg, DOI: 10.1097/PRS.0b013e31820436cb	39	96	40.63	4.38	2.12
5	Ariticle	Lohman RF, 2013, J Reconstr Microsurg, DOI: 10.1055/s-0032-1326741	37	75	49.33	8	1.8
6	Ariticle	Steele MH, 2011, Ann Plas Surg, DOI: 10.1097/SAP.0b013e31820909f9	35	61	57.38	3.93	1.34
7	Ariticle	Keller A, 2007, J Reconstr Microsurg, DOI: 10.1055/s-2007-974655	34	83	40.96	4.86	1.57
8	Ariticle	De Weerd L, 2006, Ann Plas Surg, DOI: 10.1097/01.sap.0000218579.17185.c9	31	62	50	6.97	1.75
9	Ariticle	Cai ZG, 2008, J Plast Reconstr Aes, DOI: 10.1016/j.bjps.2007.10.047	30	52	57.69	1.76	1.33
10	Ariticle	De Weerd L, 2011, Clin Plast Surg, DOI: 10.1016/j.cps.2011.03.013	27	70	38.57	3.03	1.54

Abbreviations: GC: global citations; LC, local citations; NGC, normalized global citations; NLC, normalized local citations.

algorithm for early prediction of vascular compromise in 208 microsurgical flaps using tissue oxygen saturation measurements' published in the *Annals of Plastic Surgery* held the first position due to its high LC count ($n = 56$). Besides, it ranked third in the LC/GC ratio, further demonstrating the persuasive impact of this article in its field. The remaining nine references will be extensively discussed in the discussion section, with LC counts ranging from 27 to 55. Additionally, both Alex Keller[38,39] and Louis de Weerd[40,41] had two papers among the top 10 cited articles.

The term 'Citation burstness of references' refers to studies within a specific discipline that have been widely cited over any given period of time.[42] It serves to illustrate the exploration process and predict research directions. Figure 8 displayed the top 20 references with the strongest citation bursts, using lines to represent the timespan, with red lines reflecting the year of citation burstness. Among them, 20% (4/20) of the references had a strength score of 7 or higher, with the strongest burst (strength = 9.42) attributed to the examination titled 'A prospective analysis

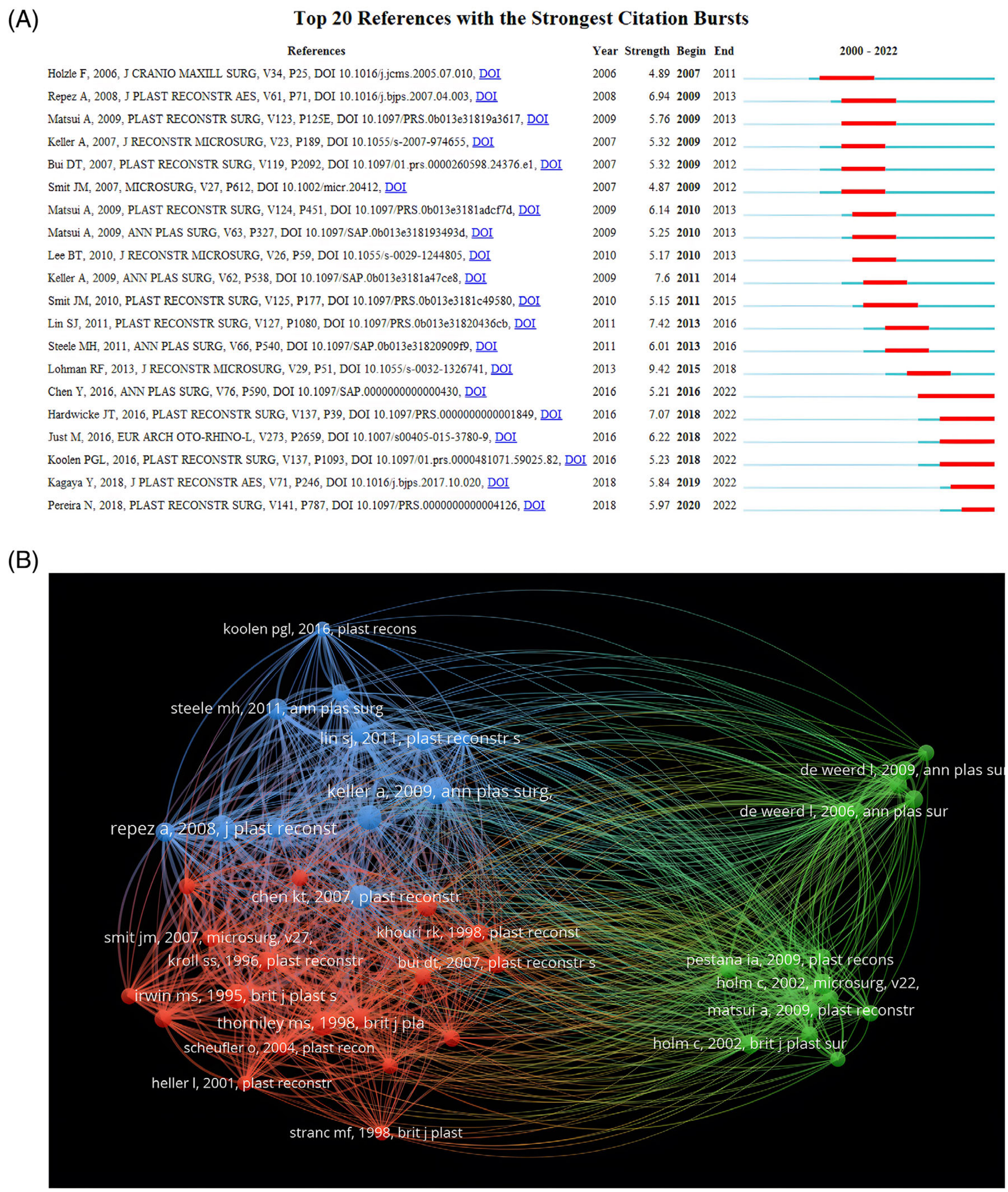

FIGURE 8 (A) Top 20 references with strong citation burstiness. The red bars mean some references cited frequently; the blue bars were references cited infrequently. (B) The network map of all references ($T \geq 20$, $N = 46$) involved in the application of IRT in flap.

of free flap monitoring techniques: physical examination, external Doppler, implantable Doppler, and tissue oximetry' by Robert F Lohman,[43] spanning from 2015 to 2018. The remaining three references had burst years in 2011, 2013, and 2018, respectively. The research by Alex Keller[37] titled 'A new diagnostic algorithm for early prediction of vascular compromise in 208 microsurgical flaps using tissue oxygen saturation measurements' published in the *Annals of Plastic Surgery* experienced a citation burst from 2011 to 2014 (strength = 7.6), followed by Samuel J Lin's study[44] titled 'Tissue oximetry monitoring in microsurgical breast reconstruction decreases flap loss and improves rate of flap salvage' published in *Plastic And Reconstructive Surgery*, which had a burst from 2013 to 2016 (strength = 7.42). Moreover, Joseph T Hardwicke's paper[45] titled 'Detection of Perforators Using Smartphone Thermal Imaging' in *Plastic and Reconstructive Surgery* experienced a burst from 2018 to 2022 (strength = 7.07). Among the references analysed up until 2022, six papers had peaks that persisted until the time of analysis and the research 'Free Flap Monitoring Using Near-Infrared Spectroscopy: A Systemic Review' by Ying Chen[46] had the longest duration of citation burstness (6 years). Overall, the strength of the top 20 references ranged from 4.87 to 9.42, with durations spanning from 2 to 6 years. And the main topics of these six papers could be listed as follows: (1) smartphone thermal imaging is used to identify, map and monitor perforators, as well as define perforasomes; (2) Perforator detection via smartphone thermal imaging and computed tomographic angiography: sensitivity and specificity comparisons; (3) an evidence-based systematic review of post-operative flap monitoring using near-infrared spectroscopy (NIRS), examining its appropriateness and usability; (4) an exploratory clinical study of tissue oximetry monitoring on flap reexploration rates and salvage; (5) Using NIRS to monitor free flaps during and after oropharyngeal reconstruction; (6) a systematic review of Near-infrared spectroscopy and its future applications. All of them intensively showed that the trends would focus on the development of novel infrared imaging devices and the integration of multimodal detection techniques to enhance the quality of flap perfusion images and the accuracy of blood flow parameter measurements, while also considering the possibility of remote monitoring of perfusion. And then the exploration of multicenter collaborations in the medical field for the application of infrared technology would test the sensitivity, specificity, reliability and practicality.

4 | DISCUSSION

4.1 | General information

Based on our bibliometric analysis of research data from the WoSCC in the SCI-Expanded database from 1999 to 2022, a total of 522 English research papers were published in 687 academic journals by 761 institutions from 46 countries and regions. These papers cited a total of 1503 references. These studies cover the current status, development trends, and future hot topics in the field.

During the period from 1999 to 2022, research reports related to 'IRT in flap' showed an increasing trend annually, indicating that research in this field has achieved significant progress and influence in recent years. The United States, Germany, and China ranked as the top three contributors. The United States consistently had the highest number of publications, and its citation count was approximately four times that of Germany, which ranked second. The United States' leadership position in single country and comparative research underscored its significant contributions to academic research, cultural exchanges, and global advancement. China was the only developing country in the top 10, indicating a certain gap between developed and developing countries in this research field. Among the highly productive research institutions, the Beth Israel Deaconess Medical Center in the United States ranked first, followed by Shanghai Jiao Tong University in China. Additionally, collaborations between different institutions were active, particularly with US institutions actively collaborating with others. For example, the Beth Israel Deaconess Medical Center in the US had closer collaborations with Hokkaido University in Japan and Harvard University in the US, showing broader opportunities for collaboration with US institutions. Among the top 10 journals with the highest publication volume, the majority ($n = 7$) were US journals, indicating their significant academic influence. The journal *Plastic and Reconstructive Surgery* had the highest publication and citation counts, as well as the highest H-index and Total link strength. It showed close connections and co-citation with other journals, signifying that it represents the core literature and important research achievements in the field of 'IRT in flap' with substantial academic impact and contributions.[15] Through the analysis of dual-map overlays of journals, we identified interdisciplinary research directions and hotspots. Among the authors, Lee BT and Frangioni JV made significant contributions in terms of publication output, while Holm C ranked first in co-citations, reflecting their significant scholarly contributions in the field and demonstrating their substantial academic impact. The VOSviewer visualization map displayed stable and positive collaborations among these active authors and co-authors.

In terms of keywords co-occurrence and frequency, those findings mentioned in Figure 7A implied that those topics had been consistently studied and had received ongoing attention in the context of IRT in flap. And Figure 7C mainly showed four clusters based on all keywords: (1) a keen interest in understanding the impact of location-related factors on the prognosis of flaps, such as skin condition, tissue perfusion, and potential risk of necrosis; (2) the critical role of techniques such as breast reconstruction and computed tomography scans in evaluating flap perfusion and selecting appropriate flap methods within the realm of IRT in flap; (3) the utilization of near-infrared spectroscopy to assess tissue oxygen saturation of flaps and implementing salvage measures in the event of complications; (4) the combined use of indocyanine green contrast imaging and tissue oxygen saturation measurement to assess flap perfusion, along with validation through animal experiments, was an important research direction.

4.2 | Knowledge base

In general, LC is typically evaluated by synthesizing the references that cite it to determine its citation frequency within the research field.[47] These citing references reveal the extent to which the relevant research is referenced in other academic studies. The collection of highly cited LC literature represents core literature and important research achievements in the field. Therefore, LC can be considered as a hallmark of a specific field's knowledge base. In this study, we established a knowledge base for the research on 'IRT in flap' by evaluating the research domain and selecting the top 10 widely local cited references.

In 2009, Alex Keller et al.[37] published the most highly cited paper, with a total of 56 citations. They assessed the application of near-infrared tissue oximetry monitoring in the early detection of vascular complications and successfully predicted vascular flap complications within 1 h of occlusive events, providing an opportunity for earlier intervention and improved surgical outcomes. In 2007, Andrej Repez et al.[38] explored the capability of NIRS in detecting and identifying free flap vascular compromise, demonstrating reliable early detection and identification of arterial and venous thrombosis with NIRS monitoring, offering a reliable method for postoperative flap perfusion monitoring with potential clinical applications. In 2010, Jeroen M Smit et al.[48] conducted a review of existing free flap monitoring devices, with implantable Doppler systems, near-infrared spectroscopy, and laser Doppler flowmetry identified as the current optimal monitoring devices. In 2011, Samuel J Lin et al.[44] reviewed 614 cases of microsurgical flap breast reconstructions and compared the effectiveness of clinical symptom monitoring with tissue oxygen saturation monitoring, showing that measuring tissue oxygen saturation and real-time flap perfusion can aid in the early detection of vascular compromise and improve flap salvage rates. In 2013, Robert F Lohman et al.[43] evaluated the effectiveness of various flap monitoring methods, including physical examination, Doppler, and near-infrared spectroscopy, and found that near-infrared spectroscopy detected vascular complications earlier than other monitoring methods. In 2011, Matthew H Steele[49] used NIRS tissue oximetry to monitor postoperative flaps and demonstrated the high reliability of NIRS tissue oximetry in monitoring flap viability for postoperative free tissue transfers. In 2007, Alex Keller focused on evaluating the ViOptix Tissue Oximeter, a new device based on near-infrared spectroscopy, for assessing flap perfusion in DIEP breast reconstruction patients. The examination demonstrated the device's ability to detect early formation of venous thrombosis, highlighting its significant role in flap salvage. In 2006, Louis de Weerd conducted a clinical investigation demonstrating the efficacy of intraoperative DIRT in detecting compromised blood perfusion resulting from vascular anastomosis failure or vascular compression. In 2007, Zhi-gang Cai's research on NIRS technology quantitatively examined tissue oxygen saturation after fibular flap transplantation. The findings confirmed NIRS as a reliable non-invasive method for monitoring blood circulation in transplanted tissues, especially for buried flaps. In 2011, the study by Louis de Weerd centered on the application of DIRT in DIEP breast reconstruction. It showed the potential use of DIRT in preoperative planning, intraoperative evaluation of blood perfusion, and postoperative assessment of perfusion status.

Overall, among the top 10 locally cited references, the topics revolve around the effectiveness of infrared monitoring of flap blood perfusion (perfusion, surgery, breast reconstruction, experience), which aligns with the results of keyword co-occurrence analysis.

4.3 | Emerging topics

4.3.1 | Comparison of IRT and other flap perfusion monitoring techniques

Through bibliometric analysis of the literature on 'IRT in flap', we can gain an understanding of its widespread application and positive effects in flap perfusion monitoring. However, to comprehensively evaluate the position and merits of infrared technology in the field of flap perfusion monitoring, it is necessary to compare it with other commonly used techniques.

Figure 9 depicted a range of approaches for monitoring flap perfusion, including the clinical observation method, infrared technology, Doppler ultrasound (DU), magnetic resonance angiography (MRA), computed tomography angiography (CTA), and digital subtraction

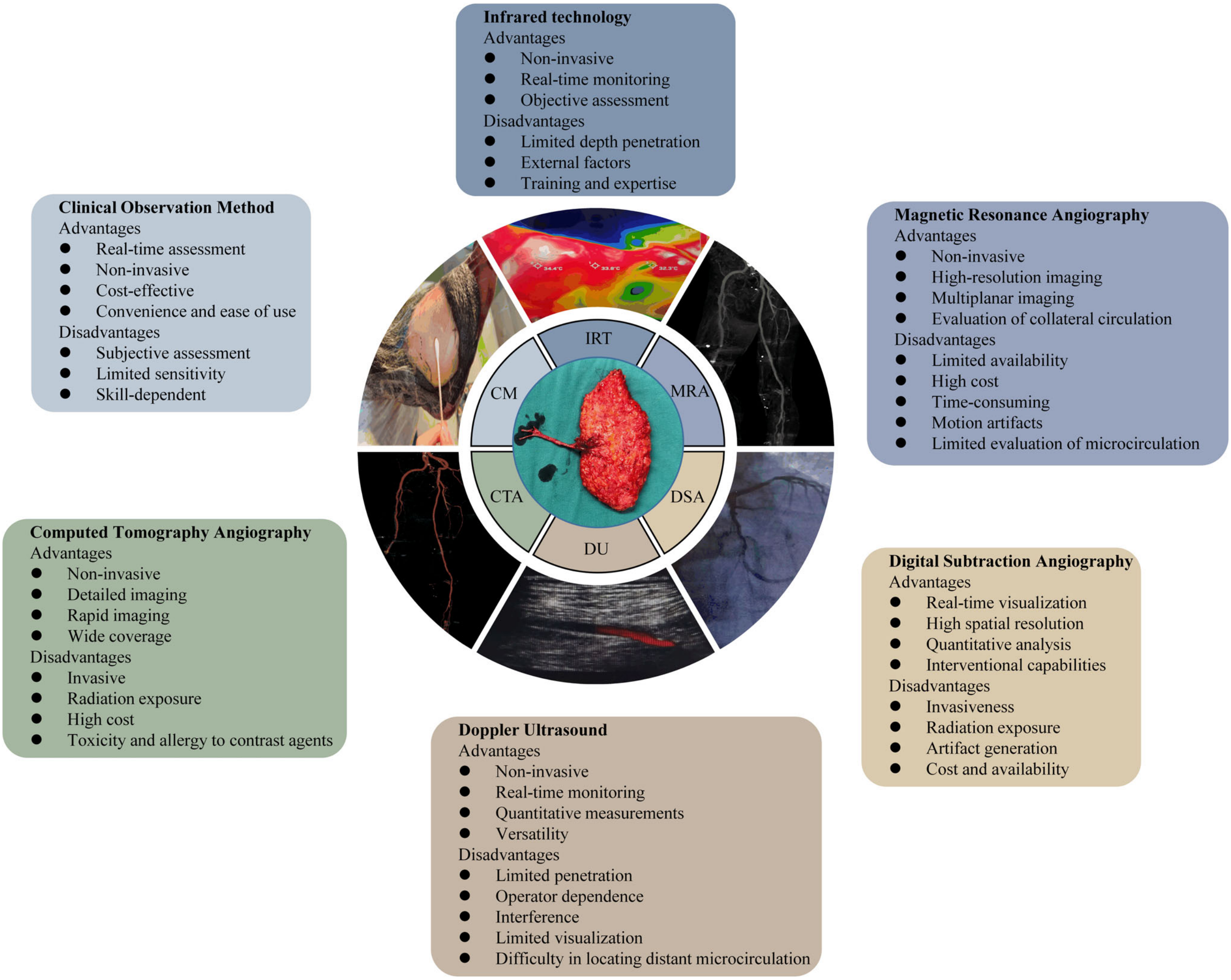

FIGURE 9 Comparison of Blood Supply Monitoring Methods for Flaps: The figure showed a comparison of different methods, including IRT (infrared thermography), MRA (Magnetic Resonance Angiography), DSA (digital subtraction angiography), DU (duplex ultrasonography), CTA (computed tomography angiography), and CM (clinical observation), for monitoring blood supply in flaps. Each method's advantages and disadvantages were indicated, providing a comprehensive evaluation of blood supply monitoring techniques.

angiography (DSA).[50–52] These methods are widely used in flap surgery to assess the blood supply of flaps and monitor any vascular abnormalities.[53] Clinical observation method offers real-time assessment and non-invasive monitoring of skin flap perfusion,[14] making it a cost-effective and convenient approach. However, it relies on subjective assessment, exhibits limited sensitivity, and is dependent on the skills of the healthcare professional.[54,55] Conversely, DU provides quantitative information on blood flow by utilizing the Doppler effect of sound waves.[56] However, it has limited penetration capabilities, and the operator's skill level can impact the accuracy of results.[12,56] MRA, as another commonly employed technique, utilizes magnetic resonance technology to acquire high-resolution vascular imaging, offering advantages such as non-invasiveness and multiplanar imaging.[57] Nevertheless, it is costly and susceptible to artefacts caused by overlapping vessels, making it unsuitable for patients with internal metallic implants. Comparably, Computed Tomography Angiography (CTA) employs X-ray and computer reconstruction techniques to provide detailed vascular imaging with wide coverage. However, it carries the risk of radiation exposure and requires the injection of contrast agents, which is an invasive procedure and may induce contrast agent allergies and hepatorenal toxicity.[58] Similarly, DSA is a real-time visualization method with high spatial resolution and interventional capabilities. However, it necessitates invasive procedures and carries the possibility of radiation exposure.[59]

In comparison to traditional monitoring methods, infrared technology offers several notable advantages. Firstly, infrared technology is a non-invasive method that does not require contact with the patient's skin or dye injection,[60] reducing the risks of infection and trauma. Secondly, infrared technology can provide real-time and continuous monitoring data,[61] enabling the detection of blood flow abnormalities or vascular complications within the flap. This allows doctors to promptly identify any issues and take necessary intervention measures. Additionally, infrared technology can provide quantitative blood flow parameters,[62] such as tissue oxygen saturation and flow velocity,[63] which contribute to a more accurate assessment of flap blood supply. However, infrared technology also has certain limitations. The thickness and tissue characteristics of the flap may affect the propagation and reception of infrared signals,[64,65] leading to signal attenuation or distortion.[66] As a result, infrared technology may encounter limitations in monitoring deep blood vessels, yielding suboptimal outcomes.

The existing infrared technologies for monitoring flap perfusion can be mainly divided into three methods: NIRS, FI, and DIRT. Their principles, representative device models and application scenarios are listed in Table 4. NIRS can be used in combination with blood oxygen indicators to monitor flap perfusion, offering advantages such as non-invasiveness, real-time monitoring, and portability. Previous literature has indicated that postoperative flap monitoring using NIRS exhibits high accuracy and enables early detection,[67] resulting in a higher flap salvage rate compared to the clinical observation method.[14] The FI (Fluorescence Imaging) technique, represented by indocyanine green angiography, offers the advantage of visualizing tissue hemodynamics.[68] Literature reports indicate its suitability for intraoperative monitoring of free flap tissue perfusion, leading to an enhanced flap survival rate.[69] The DIRT technique offers the advantage of detecting tissue thermal abnormalities. Previous literature reports its utility in preoperative assistance for identifying dominant perforators, intraoperative monitoring for surgical adjustments, and postoperative early detection of vascular supply.[70] These three techniques each possess distinct advantages and can play a crucial role in monitoring flap perfusion, providing support for successful surgeries and patient recovery.

4.3.2 | The trends in infrared technology research

After conducting a comprehensive bibliometric analysis of the literature in the field of 'IRT in flap', we have gained important insights into the use of infrared

TABLE 4 Instrument comparison based on infrared technology.

Technology	Principle	Representative device models	Application scenarios	Advantages	Previous literature findings	References
NIRS	Measures tissue oxygenation and blood flow using near-infrared light	OMEGAWAVE NIRS system, NIRSport2	Assessment of flap perfusion in microsurgery	Non-invasive, real-time monitoring, portability	Postoperative flap monitoring exhibits high accuracy and enables early detection; the flap salvage rate is higher compared to clinical observation method	14,67,71, 80–85
FI	Observes blood flow distribution using fluorescent dyes such as indocyanine green	ICG fluorescence imaging systems, LSCI devices	Fluorescent image acquisition using cameras or sensors	Tissue hemodynamics visualization	Suitable for intraoperative monitoring of free flap tissue perfusion to enhance flap survival rate	69,86–93
DIRT	Observes changes in skin temperature using infrared thermography	FLIR infrared cameras	Skin temperature data acquisition using thermal imagers	Detection of tissue thermal anomalies	Pre-operative assistance in identifying dominant perforators; intra-operative monitoring for surgical adjustments; post-operative early detection of vascular supply	40,41,50,70, 94–97

technology in this domain. However, relying solely on existing research findings may not fully reveal the complete potential of infrared technology. Future studies will focus on further advancements and applications of infrared technology to drive cutting-edge developments in the field of flap surgery.

Firstly, there has been a gradual increase in research related to infrared technology in flap perfusion monitoring in recent years. Through bibliometric analysis, we observed a growing number of publications from 1999 to 2022 that are relevant to the application of infrared technology in flap perfusion monitoring. This indicates an increasing research interest within the academic community regarding the use of infrared technology in this field.

A major trend for the future is the development of novel infrared imaging devices and the integration of multimodal detection techniques to enhance the quality of flap perfusion images and the accuracy of blood flow parameter measurements, while also considering the possibility of remote monitoring of perfusion. Many research teams are dedicated to optimizing infrared imaging systems in terms of hardware and algorithms and combining them with advanced technologies to improve spatial resolution and sensitivity, aiming to obtain clearer and more accurate flap perfusion images. For instance, Marjolein Klop et al.[71] achieved comprehensive monitoring of cerebral blood flow status by combining near-infrared technology with Doppler technology. Zhuoran Ma et al.[72] developed an infrared imaging system based on deep learning, achieving significant breakthroughs in resolution and accuracy through algorithm optimization and enhanced image processing techniques. Additionally, the application of wireless transmission and cloud computing technologies enables the possibility of monitoring and assessing flap perfusion status at any time and location, providing timely intervention and guidance for physicians.[73–75] These studies are expected to further enhance the practicality and precision of infrared technology in flap surgery, bringing convenience in diagnosis and treatment for patients.

Another notable research trend is the exploration of multicenter collaborations in the medical field for the application of infrared technology. Collaborations among physicians, biologists, and engineers have fostered innovation in infrared technology and laid the foundation for its application in flap surgery. For example, the study conducted by Chalapathi Charan Gajjela et al.[76] combined infrared spectroscopy technology with knowledge from digital histopathology, resulting in the development of a novel infrared spectroscopic imaging technique for the automated and quantitative histological identification of ovarian tissue subtypes without the need for labeling. Meanwhile, the collaboration between medical professionals and researchers emphasizes the importance of establishing clinical guidelines and standardization for infrared technology in flap surgery,[77] highlighting the need for consistent operational protocols and data analysis methods to ensure the reproducibility and comparability of infrared technology. This multicenter collaborative research not only expands the application scope of infrared technology in medicine but also provides innovative ideas for its future development in flap surgery, offering a stronger foundation for its practical implementation in the field.

Furthermore, the research trends of infrared technology in the field of flap surgery include the exploration of more types of flaps and surgical scenarios. Currently, research primarily focuses on the application of infrared technology in DIEP (deep inferior epigastric perforator) flap breast reconstruction.[44,53,70,75] However, there is limited research on other types of flaps, such as myocutaneous flaps and transfer flaps, as well as the application in different surgical scenarios.[12,67] Therefore, future research can expand the sample range to investigate the application effectiveness of infrared technology in different types of flaps and surgical scenarios.[70] Conducting clinical trials will provide more empirical data to evaluate the accuracy and reliability of infrared technology in intraoperative blood flow monitoring and predicting flap survival rates, further validating its effectiveness and feasibility in flap surgery.[14]

In summary, the application of infrared technology in the field of flap surgery is showing a significant growth trend. Future research will focus on technological innovations, multicenter interdisciplinary collaborations, and further exploration in clinical practice. These efforts will further promote the application of infrared technology in flap perfusion monitoring and flap surgery, providing patients with more accurate, reliable, and convenient means of blood flow monitoring, thus enhancing flap survival and improving prognosis.

5 | STRENGTHS AND LIMITATIONS

Our research possesses several advantages in the application of IRT in flap surgery. Firstly, to the best of our knowledge, this is the pioneering bibliometric study in this specific area, thereby filling a significant gap in the existing literature. Secondly, we presented annual trends in a precise and objective manner, providing comprehensive information to guide clinical surgeons and researchers engaged in the field of flap surgery. Multiple bibliometric software tools were employed to explore the interrelationships among various entities, including countries, authors, institutions, journals, funding agencies, keywords, citations/co-citations, and references, thereby strengthening the robustness of our findings. However, it is important to acknowledge certain limitations. Firstly. our study focused solely on publications in the English language, thus introducing potential linguistic bias. Secondly, we restricted our analysis to literature published within the past two decades (1999–2022) which may not encompass the complete landscape of developments in this field. Furthermore, studies published in 2023 were excluded due to insufficient data, potentially impacting the comprehensiveness of our results. Notably, we chose the Web of Science (WoS) databases for their mentioned advantages, such as the accuracy of analysis and methods, journal classification system, standardization and consistency of publication records, and enhanced visualization effects. Nonetheless, this approach may have led to a non-exhaustive search of the literature.[78,79]

6 | CONCLUSION

The application of VOSviewer, CiteSpace and bibliometric analysis platforms enabled the comprehensive analysis of general information, knowledge base, and emerging topics in the application of IRT in flap from 1999 to 2022. Notably, the United States emerged as a leading contributor in this field, with the majority of publications originating from Beth Israel Deaconess Medical Center. The preeminent status of *Plastic and Reconstructive Surgery* as the authoritative journal in this domain is evident. In the field of flap research, the knowledge foundation of IRT primarily focuses on evaluating the effectiveness of infrared monitoring in assessing flap perfusion. Due to its non-invasive nature, real-time monitoring capability, and the ability for quantitative assessment, we firmly believe that infrared technology will bring significant benefits to patients. At the same time, we anticipate the application of infrared technology in a broader range of flap types and surgical scenarios and eagerly look forward to future innovative breakthroughs in infrared technology and the establishment of standardized evaluation metrics, which will open up new prospects for flap surgery.

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CONFLICT OF INTEREST STATEMENT

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/Supplementary Materials, further inquiries can be directed to the corresponding author.

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