

Knowledge Mapping of Ultrasound-guided Thermal Ablation Combined with Immunotherapy for Hepatocellular Carcinoma: A Systematic Bibliometric Analysis

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Background: Hepatocellular carcinoma (HCC) represents the sixth most prevalent cancer worldwide and ranks as the third leading cause of cancer-related mortality. Confronting therapeutic limitations including chemoresistance, tumor recurrence and high financial burdens, the integration of ultrasound-guided thermal ablation with targeted immunotherapy demonstrates potential transformative paradigm. Utilizing bibliometric methodologies, this study systematically delineates the scientific landscape and evolutionary trajectory of this combined therapeutic approach for HCC.

Methods: Our study systematically reviewed the Science Citation Index Expanded (SCI-Expanded) database (2000 to 6 November 2024) to retrieve studies on ultrasound-guided thermal ablation combined with immunotherapy for HCC. Bibliometric analysis using CiteSpace and VOSviewer analyzed geographical distribution, institutional collaborations, journal contributions, author networks, references, and keyword dynamics. Analytical methods included timeline visualization, co-occurrence networks, and citation burst detection.

Results: A total of 931 publications (560 articles, 371 reviews) from 6,252 authors at 3,766 institutions worldwide were identified. These works were published in 341 journals and cited 4,522 references. Publications demonstrated a marked annual increase from 2000 to 2024, with China contributing 42.7% of total output, followed by the United States ($n = 288$) and Italy ($n = 78$). Sun Yat-sen University emerged as the most productive institution and Ping Liang authored the most papers ($n = 13$). *Hepatology* and *Radiology* ranked as top journals by impact factor and academic reputation. Keyword analysis revealed shifting research priorities, with current hotspots diverging significantly from prior decade trends.

Conclusion: This bibliometric analysis outlines two decades of progress in ultrasound-guided thermal ablation combined with immunotherapy for HCC, delineating key contributors (countries, institutions, authors) while highlighting needs for long-term efficacy studies and emerging research trajectories.

Key words: Thermal ablation; Immunotherapy; Hepatocellular carcinoma; A bibliometric analysis; Publications

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Primary liver cancer is the third leading cause of cancer-related death worldwide and ranks sixth in cancer incidence, with significant regional differences [1,2]. Hepatocellular carcinoma (HCC) is the most

common type of primary liver cancer, accounting for approximately 75%-85% [3]. Morbidity and mortality rates remain high in most countries, and the number of men affected is approximately two to three times that of

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women [3,4]. The development of HCC results from the combined action of multiple risk factors. The main etiological risk factors are chronic infection with hepatitis B virus (HBV) and hepatitis C virus (HCV); concurrently, alcohol and metabolic dysfunction-related fatty liver disease contribute to increasing HCC incidence and mortality [5,6]. Additionally, aflatoxin exposure, overweight, type 2 diabetes, and smoking are cofactors for the development of HCC [7-10]. With the progress of antiviral treatment for HBV and HCV, HCC associated with them has stabilized or declined in most developed countries, while HCC associated with metabolic dysfunction-related fatty liver disease has become an important public health issue [3,11].

The treatment strategies for HCC mainly include surgical treatment, local treatment and systemic treatment, depending on the tumor burden, the degree of liver dysfunction and the performance status. Local ablation therapy induces tumor tissue destruction through different physical or chemical mechanisms. Chemical ablation, exemplified by percutaneous ethanol injection, induces tumor cell necrosis via direct chemical toxicity effects. Thermal ablation techniques, including radiofrequency ablation (RFA), microwave ablation (MWA), and high-intensity focused ultrasound, result in protein denaturation and cell membrane damage through high temperature [12,13]. Cryoablation employs the cryogenic-rewarming cycle to induce intracellular ice crystal formation and microvascular damage [14,15]. In addition, non-thermodynamic ablation such as irreversible electroporation achieves tumor ablation by destroying cell membrane integrity through high-voltage pulses [16,17]. These techniques have different characteristics and indications. With significant improvements in image-guided technology, especially innovations in real-time ultrasound-guided technology, thermal ablation has made significant progress in the clinical management of HCC. At present, ultrasound-guided thermal ablation is included in the recommendations of international guidelines and has become an important treatment option for HCC from early to advanced stages [18-20]. The development of this technology not only achieves millimeter-level precise positioning of tumor lesions, but also monitors the ablation range in real time, significantly improving treatment safety and effectiveness. Many studies have confirmed that, with strict indication control, ultrasound-guided thermal ablation provides HCC patients of different stages with a similar local control rate to that of surgical resection, while offering advantages of reduced trauma and faster recovery [12,21,22]. It is worth noting that with the application of new technologies such as fusion imaging and shear wave elastography, the value of thermal ablation for tumor in special locations (e.g.,

diaphragm, heart, gastrointestinal tract, and gallbladder) continues to expand. Furthermore, thermal ablation demonstrates good synergistic therapeutic potential and complements other treatment modes such as radiotherapy, chemotherapy, immunotherapy, and systemic treatments [23-25].

At present, the most widely used percutaneous local thermal ablation technologies are RFA and MWA. Both techniques involve inserting treatment electrodes or ablation needles directly into the tumor, and puncture procedures become more efficient with image-guided. In RFA, high-frequency current transmitted between the electrode and the surface electrode induces ion oscillations in the tumor tissue, thereby generating heat to destroy tumor cells [26]. In MWA, high-frequency electromagnetic energy causes rapid rotation of polar water molecules in the tumor tissue, generating heat that ultimately leads to coagulative necrosis of the tumor under high temperatures, achieving the desired therapeutic effects [21]. Compared with RFA, MWA can achieve higher tissue temperatures and ensure more effective tumor inactivation; moreover, its treatment duration is significantly shorter, improving clinical operation efficiency; most importantly, MWA can significantly reduce the impact of vascular heat sink effects [26,27]. Thermal ablation can not only directly kill tumor cells and reduce tumor burden, but also can release tumor-associated antigens, weaken the immunosuppression of tumor cells, activate neighboring immune cells, and break immunosuppressive states—thus enhancing immune responses [25]. However, thermal ablation alone cannot completely eradicate tumors and overcome immune escape, and the anti-tumor immune response activated by thermal ablation is typically weak and transient, which can lead to tumor residue, recurrence and metastasis. Therefore, the combination strategy of thermal ablation and immunotherapy has emerged as a hot topic in current research.

Over the past decades, an increasing number of papers have been published on ultrasound-guided thermal ablation combined with immunotherapy for HCC, while no systematic analysis has been conducted to date. Bibliometrics uses mathematical and statistical methods to quantitatively analyze knowledge carriers (usually literature) within a specific field. This method can explore the most influential authors, papers, or countries/regions, build collaborative networks, and identify research hotspots in specific fields [28]. Therefore, we conducted this bibliometric analysis to summarize the knowledge map of the field of ultrasound-guided thermal ablation combined with immunotherapy for HCC and comprehensively outlined its evidence base to help researchers easily understand the development of this

field and explored research hotspots.

Methods and Materials

Data collection

Data between 2000 and 2024 in the field of ultrasound-guided thermal ablation combined with immunotherapy of HCC were obtained from the Web of Science Core Collection (WoSCC) database on Nov 6, 2024. The database source was limited to Science Citation Index Expanded (SCI-EXPANDED). "Article" and "Review article" were selected as document types, while "Editorial Materials", "Meeting Abstract", "Proceedings Paper", "Book Chapters", "Early Access" and "Retracted Publication" were excluded. The language was confined to English. Medical Subject Headings (MeSHs) from the National Library of Medicine were used for topic entry. The main search terms were "thermal ablation", "immunotherapy", and "hepatocellular carcinoma". To avoid database update bias, all searches were performed within the same day. The file format was set as "Plain Text File" and "Tab Delimited File". The "Record Content" was set as "Full Record and Cited References" to obtain all necessary details. The flowchart of the data searching and screening process is shown in figure 1.

It is important to note that restricting the search to the SCI-Expanded database and English-language publications, while ensuring consistency and quality for bibliometric comparison, may introduce selection bias by excluding relevant high-quality research published in

other languages, such as Chinese. This potential limitation is further addressed in the Discussion section.

Search strategy

((Ablation Techniques) OR (Ablation Technique) OR (Technique, Ablation) OR (Techniques, Ablation) OR (Radiofrequency Ablation) OR (Ablation, Radiofrequency) OR (Radio Frequency Ablation) OR (Ablation, Radio Frequency) OR (Radio-Frequency Ablation) OR (Ablation, Radio-Frequency) OR (Laser Ablation) OR (Ablation, Laser) OR (Microwave ablation) OR (High-Intensity Focused Ultrasound Ablation) OR (thermal ablation) OR (ablation) OR (ablative) OR (RFA) OR (MWA) OR (HIFU) OR (Cryoablation)) AND ((Immunotherapy) OR (Immunotherapies) OR (Immunity) OR (Immune Process) OR (Immune Processes) OR (Process, Immune) OR (Immune Response) OR (Immune Responses) OR (Response, Immune)) AND ((Carcinomas, Hepatocellular) OR (Hepatocellular Carcinomas) OR (Liver Cell Carcinoma, Adult) OR (Liver Cancer, Adult) OR (Adult Liver Cancer) OR (Adult Liver Cancers) OR (Cancer, Adult Liver) OR (Cancers, Adult Liver) OR (Liver Cancers, Adult) OR (Liver Cell Carcinoma) OR (Carcinoma, Liver Cell) OR (Carcinomas, Liver Cell) OR (Cell Carcinoma, Liver) OR (Cell Carcinomas, Liver) OR (Liver Cell Carcinomas) OR (Hepatocellular Carcinoma) OR (Hepatoma) OR (Hepatomas) OR (Carcinoma, Hepatocellular) OR (Neoplasms, Hepatic) OR (Neoplasms, Liver) OR (Liver Neoplasm) OR (Neoplasm, Liver) OR (Hepatic Neo-

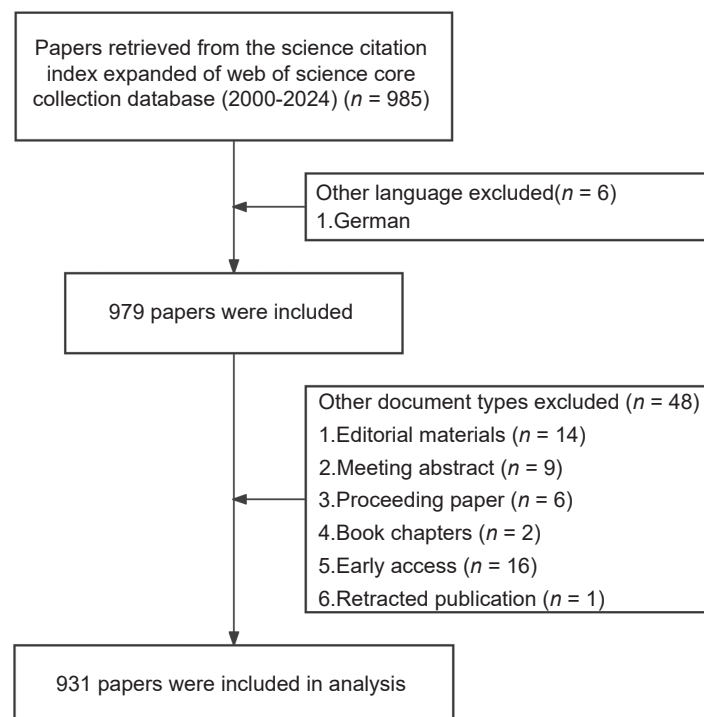


Figure 1 Flowchart of the data searching and screening in the study.

plasms) OR (Hepatic Neoplasm) OR (Neoplasm, Hepatic) OR (Cancer of Liver) OR (Hepatocellular Cancer) OR (Cancers, Hepatocellular) OR (Hepatocellular Cancers) OR (Hepatic Cancer) OR (Cancer, Hepatic) OR (Cancers, Hepatic) OR (Hepatic Cancers) OR (Liver Cancer) OR (Cancer, Liver) OR (Cancers, Liver) OR (Liver Cancers) OR (Cancer of the Liver) OR (Cancer, Hepatocellular) OR (Carcinoma, Hepatocellular) OR (Liver Neoplasms)).

Statistical analysis

All raw data were analyzed and visualized using the bibliometric package of R software (version 4.2.1), CiteSpace (version 6.1.6), and VOSviewer (version 1.6.18). The bibliometric package converts and outputs simplified bibliographic information while performing comprehensive data analysis and visualization. In VOSviewer and CiteSpace, the size of the node represents the number of researches or co-occurrence frequencies, the size of the links indicates the co-occurrence frequencies between two nodes, and nodes presenting the same color in VOSviewer represent the same cluster. CiteSpace is a bibliometric software tool that reveals trends, dynamics, and pivotal developments within a certain research field. As all raw data were obtained from a public database [28], institutional review board or ethics committee approval was not applicable and informed consent was not required.

Results

The investigation encompassed contributions from 6252 authors across 3766 institutions worldwide, culminating 931 publications (560 original research articles and 371 reviews). These works were published in 341

journals and cited a total of 4522 references.

Publication characteristics

A total of 931 publications on ultrasound-guided thermal ablation combined with immunotherapy for hepatocellular carcinoma were included, comprising 560 articles and 371 reviews. Annual publication trends in this research field are presented in [figure 2](#). The number of articles has dramatically increased from zero in 2000 and one in 2001 to 115 in 2024, highlighting a consistent upward trajectory. The predictive equation for cumulative publication count (Y) as a function of publication year (X) is a polynomial regression model ($Y = -0.0172X^3 + 1.0478X^2 - 21.86X + 162.44$), forecasting annual publication counts with an R-squared value of 95% ($R^2 = 0.9516$). In particular, the annual average output was 37 publications, with 2023 registering the highest number ($n = 141$). The escalating in publications within this field over time implies a surge in research interest and activity.

Country (or region) analysis

The number of articles per country is shown in [figure 3A](#). China led with 398 publications, followed by the USA ($n = 288$), Italy ($n = 78$), Japan ($n = 75$), Germany ($n = 72$), The United Kingdom ($n = 50$), France ($n = 37$), South Korea ($n = 27$). Spain and The Netherlands shared the 10th position ($n = 20$ each). The remaining countries collectively published fewer than 200 articles. [Figure 3B](#) illustrates international collaboration networks, revealing China, the USA, Germany, and Italy conducted the most research collaborations. In terms of frequency of cooperation, the strongest partnerships were China-USA (frequency = 45), Germany-USA (frequency = 23), and Italy- USA (frequency = 19) successively.

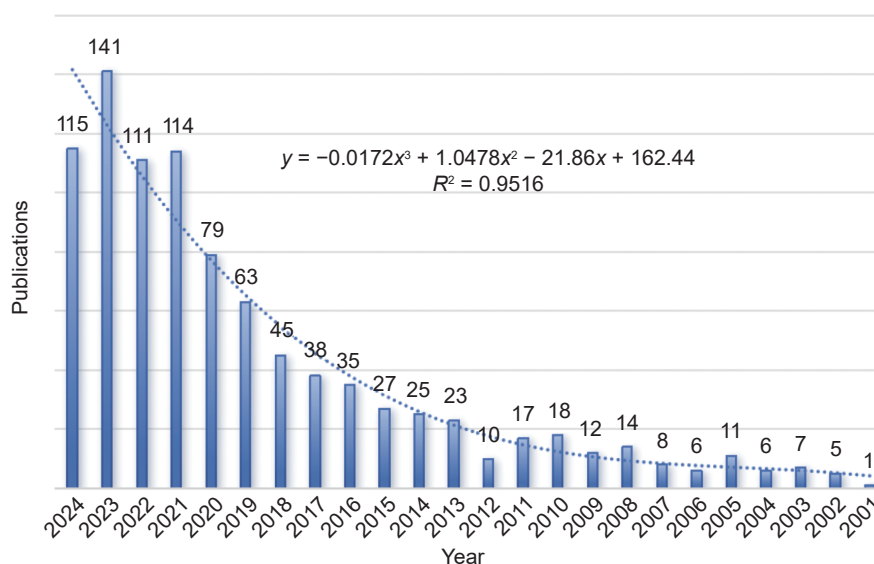


Figure 2 Annual publication trend from 2001 to 2024.

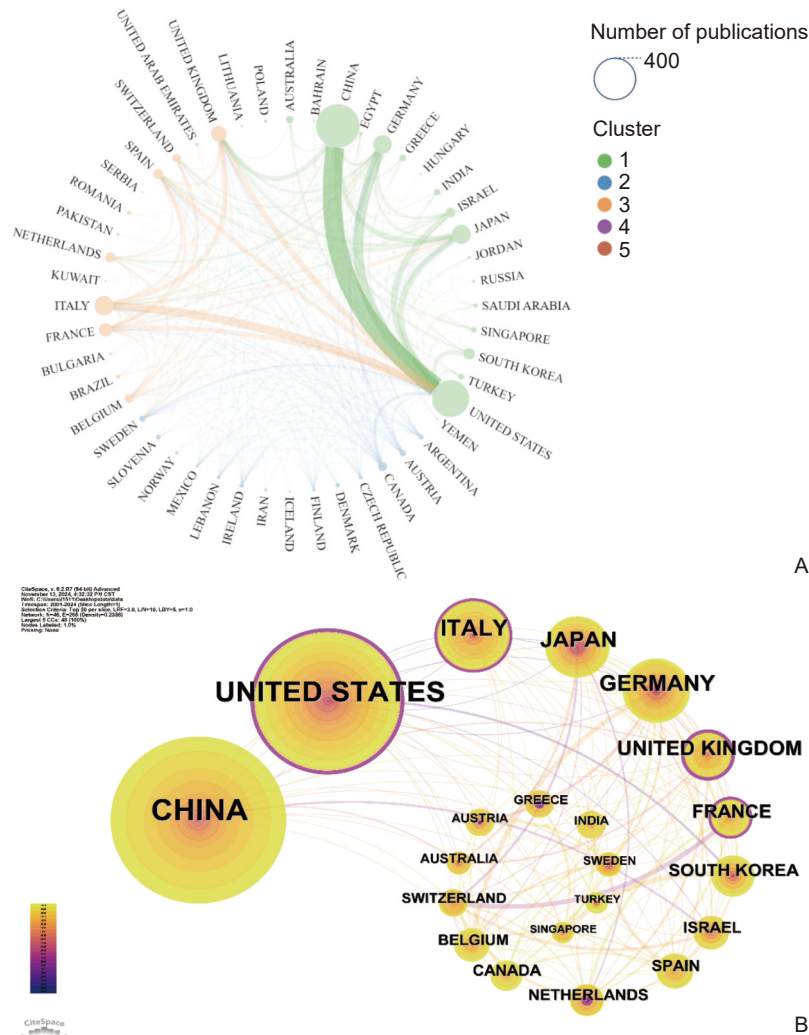


Figure 3 (A) Number of publications by country/region; (B) International collaboration network between countries/regions.

Institution analysis

The analysis drew upon contributions from a total of 3,766 institutions. An overview of the productive institutions was displayed in figure 4. Sun Yat-sen University

held the top rank with the highest number of published papers ($n = 46$). China dominated the top 10 institutions, contributing seven entries (Table 1). These findings offer valuable insights into the predominant countries

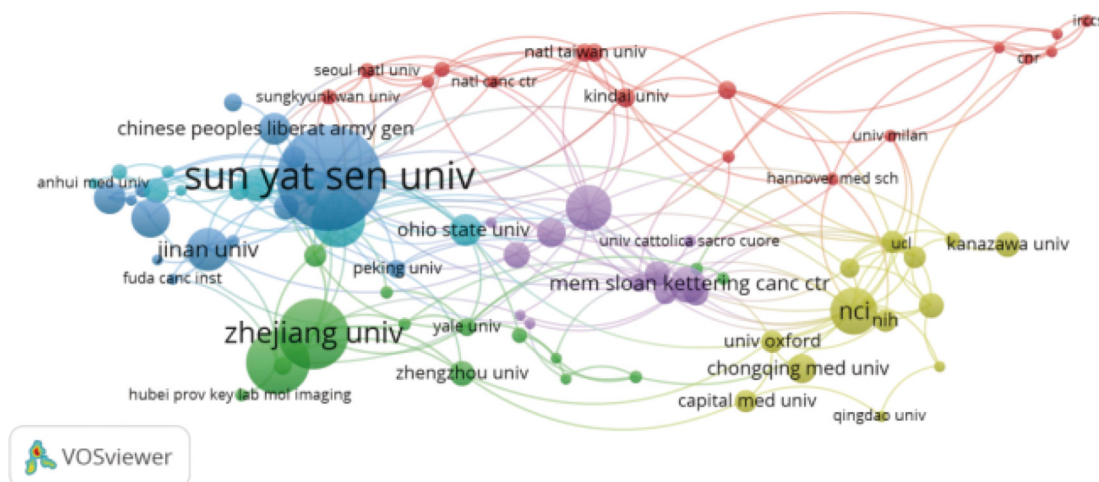


Figure 4 Network visualization of productive institutions and their collaborations.

ultrasound-guided thermal ablation combined with immunotherapy for HCC. Among them, 3 prolific authors have published over 10 papers on this subject. The published author is Ping Liang, with 13 papers. Tim F Greten and Chuansheng Zheng followed closely, each with 11 publications. S. Nahum Goldberg, along with three other authors, has individually published 10 papers. Notably, 9 authors are tied for tenth, having published 7 articles (Table 2).

Co-citation Analysis A co-citation analysis generated a network of interconnected authors. The results of the author analysis and co-cited author analysis showed a close correlation. Highly productive authors tended to appear together more frequently than others. Among the top ten cited authors, Josep M. Llovet ranks first with 3383 citations, followed by Riccardo Lencioni with 3236 citations and Augusto Villanueva with 2897 citations (Fig. 6A). Several active co-citation relationships were notable, such as those between Josep M. Llovet and Richard S. Finn, and Andrew X Zhu and Masatoshi Kudo. This symbiotic analysis provides insights into the collaborative relationships and thematic influence among these authors. In addition, a cluster diagram of collaborative relationships among researchers is shown in figure 6B. It showed that cooperation between research teams remained underdeveloped in the field of ultrasound-guided thermal ablation and immunotherapy for hepatocellular carcinoma, since the links among research communities were sparse. Ping Liang and Ming Kuang, representing Chinese research teams, were establish research networks, while S. Nahum Goldberg and Bradford J. Wood, representing U.S. research groups, were doing the same. These analyses offered a clearer

perspective on the research landscape in this area.

Most-cited references

The most highly cited articles could be assessed through citation analysis. The frequency of citations could reflect the influence of articles in a particular research field. The ten most cited articles were listed in table 3. These articles were published between 2017 and 2022, and all received over 60 citations. The top two were clinical trial articles published in *The New England Journal of Medicine* and *Lancet*. Specifically, the article entitled "Atezolizumab plus Bevacizumab in Unresectable Hepatocellular Carcinoma" had received 170 citations, making it the top-cited article in this research field.

Occurrence frequency and citation burst of keywords

Keyword analysis generated a co-occurrence map and visualize the relationship between keyword (Fig. 7A). This strategy efficiently reflected the core framework and research hotspots of this field, and to a certain extent, indicated emerging research breakthroughs. Figure 7B illustrated the timeline visualization of keywords. Earlier appearing keywords were presented on the left, whereas newer appearing keywords were on the right. Keywords such as "hepatocellular carcinoma", "radiofrequency ablation", "thermal ablation" and "immunotherapy" were the major topics in the early period. In contrast, keywords "tumor microenvironment", "immune checkpoint inhibitors" and "atezolizumab plus bevacizumab" had become popular

Table 2 Top 10 most productive authors and their co-citation counts.

Rank	Author	Articles	Co-cited author	Citations
1	Ping Liang	13	Josep M. Llovet	3383
2	Tim F Greten	11	Riccardo Lencioni	3236
3	Chuansheng Zheng	11	Augusto Villanueva	2897
4	S. Nahum Goldberg	10	Amit G. Singal	2836
5	Shuichi Kaneko	10	Kazuhiko Koike	2774
6	Eishiro Mizukoshi	10	Eli Pikarsky	2755
7	Xin Li	10	Richard S. Finn	2750
8	Bradford J. Wood	9	Robin Kate Kelley	2750
9	Xinhua Chen	8	Sasan Noayaie	2750
10	Kuniaki Arai Jun Wang Tatsuya Yamashita Jibing Chen Zhen Xu Jie Yu Xuefeng Kan Feng Wu	7	Jessica Zucman-Rossi	2750

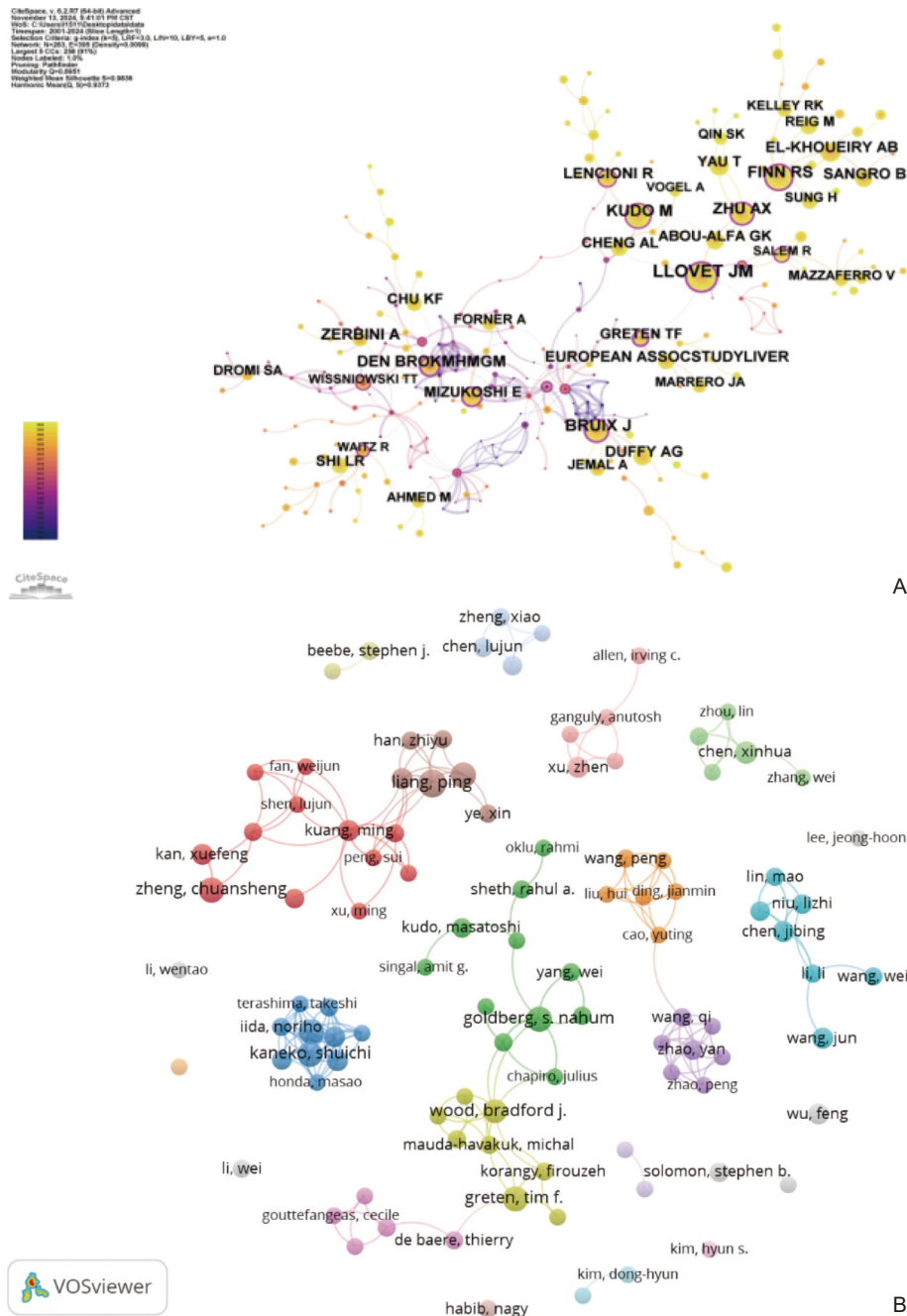


Figure 6 (A) An overview and co-citation analysis of the productive authors; (B) An overview of the author collaboration network.

Table 3 Top 10 most cited articles.

Frequence	Author	Year	Journal	DOI
170	Richard S Finn	2020	<i>New England Journal of Medicine</i>	10.1056/NEJMoa1915745
118	Anthony B El-Khoueiry	2017	<i>The Lancet Oncology</i>	10.1016/S0140-6736(17)31046-2
92	Andrew X Zhu	2018	<i>The Lancet</i>	10.1016/S1470-2045(18)30351-6
87	Masatoshi Kudo	2018	<i>The Lancet</i>	10.1016/S0140-6736(18)30207-1
86	Richard S Finn	2020	<i>Journal of Clinical Oncology</i>	10.1200/JCO.19.01307
86	Austin G Duffy	2017	<i>Journal of Hepatology</i>	10.1016/j.jhep.2016.10.029
83	Maria Reig	2022	<i>Journal of Hepatology</i>	10.1016/j.jhep.2021.11.018
74	European Association for the Study of the Liver	2018	<i>Journal of Hepatology</i>	10.1016/j.jhep.2018.03.019
73	Hyuna Sung	2021	<i>CA: A Cancer Journal for Clinicians</i>	10.3322/caac.21660
68	Ghassan K Abou-Alfa	2018	<i>New England Journal of Medicine</i>	10.1056/NEJMoa1717002

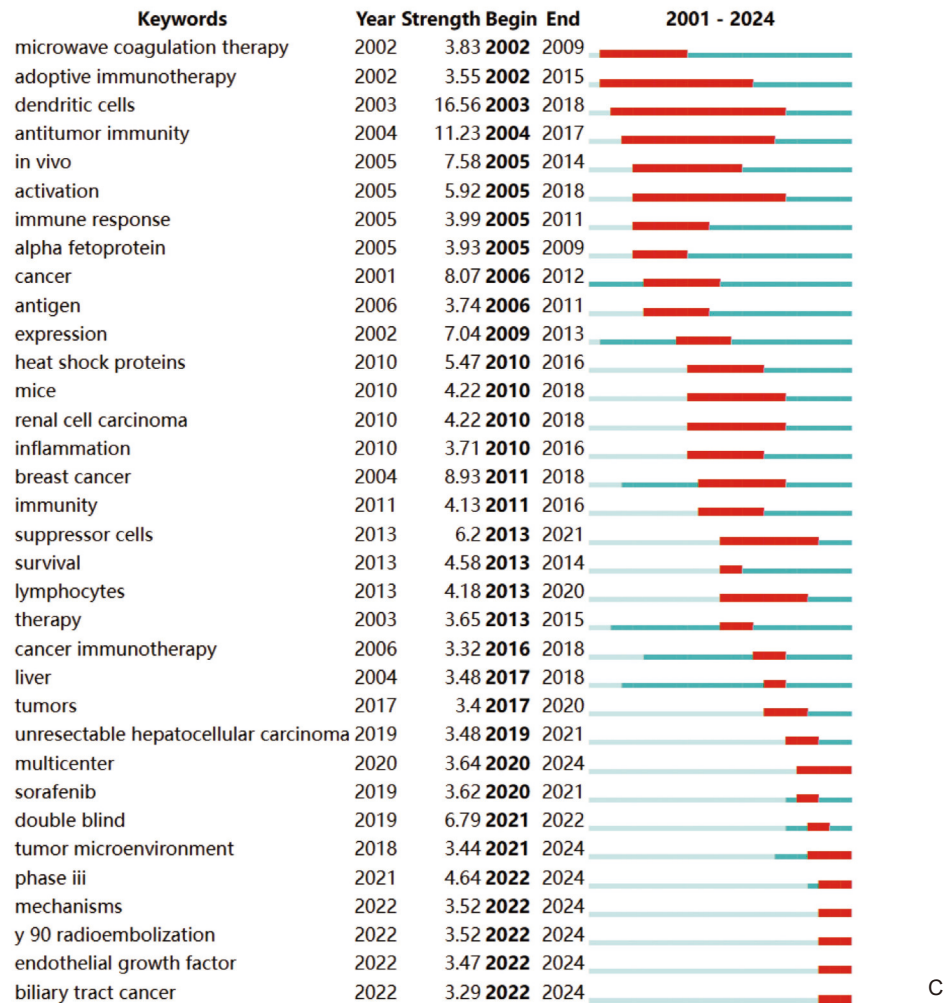


Figure 7 (A) An overview of Keyword networks; (B) The timeline visualization of the keywords; (C) All the strongest bursts of citations.

Table 4 Top 10 most frequent keywords.

Keyword	Frequence	Year
Hepatocellular carcinoma	546	2002
Radiofrequency ablation	396	2002
Cancer	171	2001
Thermal ablation	124	2004
Dendritic cells	123	2003
Therapy	123	2003
Immunotherapy	121	2004
Transarterial chemoembolization	114	2016
Ablation	89	2007
Sorafenib	89	2019

sen University, Zhejiang University and Huazhong University of Science and Technology, had conducted more recent researches in this area.

Our bibliometric data also sheds light on the research focus across different thermal ablation modalities. The keyword analysis revealed that “radiofrequency ablation” (RFA) was the second most frequent keyword ($n = 396$), significantly surpassing the broader term “thermal abla-

tion” ($n = 124$) and specific mentions of “microwave ablation” (MWA), which did not appear among the top keywords. This reflects the historically dominant role of RFA in both clinical practice and investigational settings for HCC. However, the timeline visualization (Fig. 7B) indicates a sustained and parallel interest in the overarching concept of “thermal ablation” throughout the study period. The lower specific mention of MWA in keywords may not fully capture its growing research footprint in recent years, which is often embedded within broader comparative or combinatorial studies [21,26]. Future bibliometric studies with more granular search strategies could better delineate the evolving publication trends and collaborative networks specifically around MWA, cryoablation, and other emerging modalities in combination with immunotherapy.

The majority of the publishers of the ten most active journals were from the USA and Europe. Hepatology was the journal with the highest impact factor. As the premier publication in liver disease research and the official journal of the American Association for the

Study of Liver Diseases, *Hepatology* published original, peer-reviewed articles concerning all aspects of liver structure, function and disease. Each month, the distinguished Editorial Board monitored and selected only the highest-quality research on subjects such as immunology, chronic hepatitis, viral hepatitis, cirrhosis, genetic and metabolic liver diseases and their complications, liver cancer, and drug metabolism.

Citation analysis further underscored the journal's academic influence, revealing its central role in shaping research trends through frequently referenced articles. The highest-cited reference was "Atezolizumab plus Bevacizumab in Unresectable Hepatocellular Carcinoma" published in *The New England Journal of Medicine* in 2020 [29]. The results of this clinical research indicated that in patients with unresectable HCC, the combination of atezolizumab and bevacizumab resulted in better overall and progression-free survival outcomes than sorafenib. This suggested that researchers were increasingly focusing on combination therapy strategies rather than single one. Building on these insights, researchers might leverage bibliometric data from this study to identify high-impact journals for disseminating findings on HCC ablation-combination therapies. By aligning manuscript submissions with journals exhibiting strong citation networks in this domain, scholars could strategically enhance the visibility and translational impact of their work on emerging therapeutic synergies.

Current clinical guidelines universally recognize ablation therapy as a cornerstone in the management of HCC [18,19]. This is further emphasized in the recently updated Chinese guidelines for hepatocellular carcinoma (2024 edition), which provide detailed recommendations for the application of thermal ablation across different Barcelona Clinic Liver Cancer (BCLC) stages and specifically highlight the promising role of combining local ablation with systemic therapies, including immunotherapy, as an important research direction for advanced HCC [20]. Curative ablation was particularly recommended for patients with solitary HCC who were unsuitable for or decline surgical intervention. The American Association for the Study of Liver Diseases specified that local ablation should be prioritized for solitary tumors ≤ 5 cm in non-surgical candidates, while thermal ablation (RFA or MWA) was preferred for early-stage HCC ≤ 3 cm [18]. Notably, ablation techniques had undergone substantial evolution, as evidenced by bibliometric analyses: early-phase research predominantly focused on "HCC" and "RFA" as key themes [12,30,31]. Subsequent technological advancements shifted attention to MWA, which gained global adoption due to its rapid ablation kinetics, higher intratumoral temperatures, and reduced susceptibility to heat

sink effects [12,30,31]. More recently, cryoablation had emerged as an innovative modality. This technique employed high-pressure argon/nitrogen to cool tumor tissue to -140°C to -160°C , followed by controlled rewarming to 20°C – 40°C . The freeze-thaw cycles induced intracellular ice crystallization, disrupting cellular membranes and metabolic processes, ultimately achieving tumor necrosis [14,32]. This progression from RFA to MWA and subsequently to cryoablation reflected the field's commitment to optimizing therapeutic efficacy while minimizing invasiveness, paralleled by a paradigm shift from purely local tumor destruction to immunomodulatory strategies.

Critical differences existed among ablation modalities in their immunogenic effects. Thermal ablation (RFA/MWA), while effective in tumor eradication, generated hyperthermic conditions that might denature proteins and compromise the immunogenicity of intact tumor antigens [12]. In contrast, cryoablation induced tumor destruction through mechanical disruption of cellular architecture, preserving antigenic epitopes and enhancing antigen-presenting cell efficiency, thereby potentiating immune recognition of tumor-specific antigens [14,15]. Such immunomodulatory properties elevated ablation beyond a localized therapeutic intervention. Emerging evidence suggested that antigen release during ablation remodeled the tumor immune microenvironment, creating a foundation for synergistic systemic therapies [33].

Leveraging this immunogenic potential, HCC treatment strategies were rapidly evolving toward multimodal integration. Sorafenib, a multi-target tyrosine kinase inhibitor blocking vascular endothelial growth factor receptor pathways, marked a milestone as the first systemic therapy demonstrating survival benefits in advanced HCC [34–36]. Lenvatinib further expanded therapeutic options by establishing non-inferiority to sorafenib in the phase III REFLECT trial [37]. Current research prioritized combinatorial approaches, with numerous clinical trials investigating sequential administration of PD-1/L1 inhibitors and ablation to optimize synergistic mechanisms [23,38–40]. Bibliometric analyses of co-occurrence clusters and citation trajectories systematically delineated this conceptual transition from standalone local ablation to integrated "ablation-immunotherapy-systemic treatment" paradigms. These methodologies provided critical insights into knowledge evolution, guiding future investigations toward personalized, mechanism-driven therapeutic frameworks.

It was undeniable that this study had some limitations. First and foremost, this study has inherent selection bias due to its data source and language criteria. We exclusively retrieved publications from the Web of Sci-

ence Science Citation Index Expanded (SCI-Expanded) database, which is dominated by English-language journals. Consequently, a substantial body of high-quality research published in other languages, particularly Chinese, was not included. Given that China is the leading country in publication output in this field (as identified in our analysis), the exclusion of Chinese-language journals likely leads to a significant underestimation of the total research volume and the contribution of Chinese researchers. While this approach is common in bibliometric studies to ensure database consistency and impact factor-based journal representation, it limits the comprehensiveness of the global research landscape depicted. Future studies could benefit from incorporating multilingual databases (e.g., CNKI for Chinese literature) to provide a more balanced view. Secondly, despite WoSCC being a reliable source, our specific search strategy and the dynamic nature of database updates mean some relevant publications may have been missed. The literature search was concluded on November 6, 2024, and ongoing database updates thereafter are not reflected. Thirdly, literature screening was conducted on November 6, 2024, while the Web of Science database remained in continuous update during the completion phase of this study. Consequently, some relevant articles might have been excluded. Fourthly, some unavoidable subjective speculations might, reduce the persuasiveness of certain conclusions, and results derived from burst key words, co-citation analysis, and other statistical methodologies might not fully represent field-wide consensus. Fifthly, in publications with multiple authors, accurately assessing individual contributions remained challenging when relying solely on unquantified metrics such as author order. Lastly, inconsistencies might occur in various aspects. For instance, variability in author affiliations or institution names presented considerable challenges during the bibliometric analysis process. A new strategy was needed to continuously track research in this field and periodically update data to narrow limitations and made research more persuasive and instructive. Despite these constraints, this study offered valuable macroscopic insights into the field and served as a robust foundation for guiding future research.

In conclusion, this study represented the first bibliometric analysis to systematically map global research trends in ultrasound-guided thermal ablation combined with immunotherapy for HCC since 2000. We identified leading countries, institutions, journals, and seminal references shaping this field, highlighting key contributors and intellectual milestones. These findings provided a foundation for identifying emerging research priorities. While current evidence supported the short-

term benefits of this combination therapy, its long-term efficacy and safety required validation through multicenter prospective studies with extended follow-up. Future efforts should prioritize international collaboration to decipher tumor microenvironment modulation mechanisms, optimize ablation-immunotherapy synergies using AI-driven predictive models, and standardize personalized therapeutic protocols via large-scale clinical trials. Collectively, these efforts would address critical gaps in HCC management and advanced precision oncology strategies. Our analysis served as a foundational resource for guiding innovative research and accelerating clinical translation in this evolving domain.

Acknowledgment

Not applicable.

Authors' Contributions

Yajuan Sui and Wenyi Meng contributed to conceptualization, data curation, investigation, and writing – original draft; Renjie Li contributed to methodology, visualization, and writing – review and editing; Lujing Li contributed to supervision, project administration, resources, and writing – review and editing; Zuofeng Xu contributed to conceptualization, funding acquisition, supervision, and writing – review and editing.

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Data Availability

The authors confirm that the data supporting the findings of this study are available within the article.

Declarations

Ethics approval and consent to participate

This study is a bibliometric analysis based on publicly available literature and does not involve human or animal subjects. Therefore, ethical approval and informed consent are not applicable.

Conflict of interest

The authors have no conflict of interest to declare.

Consent for publication

Not applicable.

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