

Twenty-Five Years of Strain Imaging in Cardiac Function Assessment: Bibliometrics and Emerging Frontiers (2000–2025)

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Abstract: *Objective:* To perform a bibliometric analysis of global research trends in strain imaging for cardiac function assessment between 2000 and 2025. *Methods:* Publications were retrieved from the Web of Science Core Collection using terms related to “strain imaging” and “cardiac function.” Only English-language articles and reviews were included. A total of 2,890 publications were analyzed with VOSviewer to assess publication trends, key contributors, journals, keywords, and collaboration networks. *Results:* Annual publications increased exponentially, peaking in 2024, with nearly 2,400 cumulative papers by 2025. Chinese scholars, led by Mingxing Xie and Li Zhang, dominated in publication output, whereas international authors such as Thomas H. Marwick achieved higher citation impact. Huazhong University of Science and Technology ranked first in output, while the University of Oslo showed the highest average citation rate. Echocardiography was the most prolific journal, whereas Circulation: Cardiovascular Imaging and JACC achieved the greatest impact. Keyword analysis revealed a shift from methodological innovation to clinical applications and guideline-driven standardization. Collaboration networks highlighted the United States and China as global hubs, with Europe forming dense clusters. *Conclusion:* Strain imaging research has rapidly expanded and matured into an evidence-based clinical tool. Future efforts should focus on standardization, AI integration, disease-specific thresholds, and international collaboration.

Keywords: Strain imaging; Global longitudinal strain; Speckle-tracking echocardiography; Cardiac function; Bibliometrics

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1. Introduction

Strain imaging has emerged as a sensitive and reproducible method for quantifying myocardial deformation, providing incremental value beyond conventional measures such as left ventricular ejection fraction. Speckle-tracking echocardiography (STE) and global longitudinal strain (GLS) have gained widespread use for detecting

subclinical myocardial dysfunction and predicting adverse cardiovascular outcomes ^[1]. The clinical utility of GLS has been emphasized in the 2022 ESC Guidelines on cardio-oncology, which recommend its use for early identification of cancer therapy–related cardiac dysfunction ^[2]. Moreover, recent advances in multimodality imaging, including cardiac magnetic resonance feature tracking and artificial intelligence–assisted strain analysis, are further expanding the applicability and standardization of strain imaging ^[3]. Despite these advances, the global research landscape, collaboration networks, and evolving hotspots in strain imaging remain inadequately characterized. A comprehensive bibliometric analysis is therefore essential to map scientific output, identify influential contributors, and highlight emerging research directions.

2. Methods

2.1. Data source and search strategy

A comprehensive bibliometric search was conducted in the Web of Science Core Collection to identify publications on strain imaging and cardiac function. The search strategy combined terms related to “cardiac function” (e.g., heart function, ventricular function) and “strain imaging” (e.g., myocardial strain, speckle-tracking echocardiography, deformation imaging). The time frame was restricted to 2000–2025, and only English-language articles and reviews were included. The initial search yielded 3,257 records, which were refined by document type and language, resulting in 2,890 publications (2,605 original articles and 285 reviews) for final analysis.

2.2. Data analysis tools

Bibliometric analyses were performed to assess publication trends, leading authors, institutions, journals, keyword co-occurrence, and collaboration networks. Visualization maps were generated using VOSviewer 1.6.20.

3. Results

3.1. Top 10 authors by publication output

Figure 1 shows the annual publication trends in strain imaging from 2000 to 2025. The blue line represents the number of publications per year (left axis), the blue bars indicate the cumulative number of publications (right axis), and the dashed line shows the exponential fitting curve ($y = 11.215e^{0.2338x}$, $R^2 = 0.896$). In the early 2000s, fewer than 10 papers were published annually. Since 2005, the publication output has accelerated: the annual number of publications increased from 14 in 2006 to 22 in 2008, reaching 49 in 2010. Strain imaging research then entered a phase of rapid expansion, with steady increases during the mid-to-late 2010s. In 2021, the annual number of publications exceeded 150 for the first time, and from 2022 to 2024, more than 190 papers were published each year, peaking at 219 in 2024. The cumulative number of publications rose exponentially, reaching approximately 2,256 by the end of 2024. As of 2025, nearly 2,400 articles had been published, with 34 already recorded for the year (a lower figure due to the incomplete data for the current year). Overall, the trend demonstrates sustained and robust growth in the field.

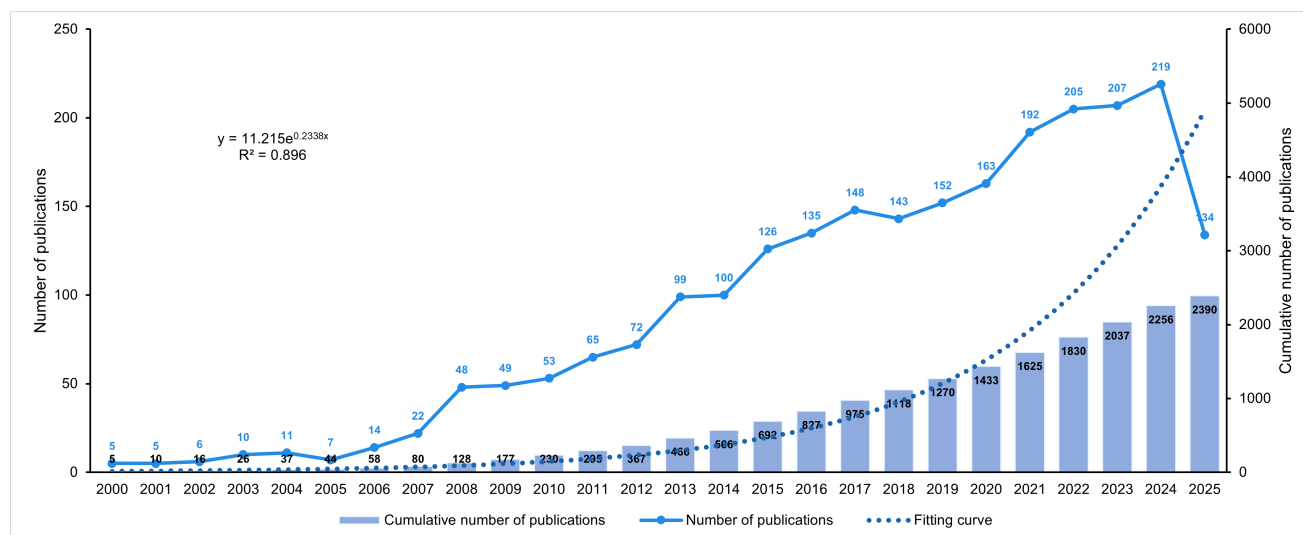


Figure 1. Annual publication trends of strain imaging research in cardiac function assessment (2000–2025).

3.2. Author productivity and collaboration network

The most prolific authors in the field of strain imaging were Chinese scholars, with Mingxing Xie publishing 32 papers, followed by Li Zhang (28) and Yuman Li (24), ranking among the global leaders in publication output. Among international scholars, Thomas H. Marwick ranked fourth with 23 papers but demonstrated outstanding academic influence, with a total of 2,327 citations and an average of 101 citations per paper. Other authors within the top ten included Luc Mertens, Giovanni Di Salvo, Shelby Kutty, Thor Edvardsen, Antonello D’Andrea, and Erwan Donal, each contributing between 17 and 20 publications. Notably, Edvardsen authored 18 papers with a total of 1,047 citations (58 citations per paper), and D’Andrea published 17 papers with 900 citations (52.9 citations per paper). Overall, Chinese scholars dominated in terms of publication quantity, while European and North American authors achieved higher impact indicators such as average citations, reflecting the joint advancement of the field by multiple active research teams. On the one hand, Chinese researchers (e.g., the group led by Mingxing Xie) produced a large volume of work; on the other hand, highly cited papers from Western scholars such as Marwick, Edvardsen, and Donal also played pivotal roles (**Table 1**).

Table 1. Top 10 authors by publication output in strain imaging research for cardiac function assessment (2000–2025)

Author name	Total number of articles	Total citations	Average citations
Xie, Mingxing	32	735	22.9688
Zhang, Li	28	641	22.8929
Li, Yuman	24	705	29.375
Marwick, Thomas H.	23	2327	101.1739
Mertens, Luc	20	477	23.85
Di Salvo, Giovanni	20	439	21.95
Kutty, Shelby	20	638	31.9
Edvardsen, Thor	18	1047	58.1667
D’Andrea, Antonello	17	900	52.9412
Donal, Erwan	17	356	20.9412

Analysis of the author collaboration network revealed several stable research clusters within the field (**Figure 2**). Chinese researchers, led by Mingxing Xie and Li Zhang, formed a tightly connected domestic group that contributed many studies. Meanwhile, European and North American scholars established extensive cross-border collaborations. For example, Thomas H. Marwick co-authored with Otto A. Smiseth and Erwan Donal, while Thor Edvardsen and his Scandinavian team maintained strong links with Western European partners. Similarly, Italian researchers such as Antonello D’Andrea and Giovanni Di Salvo developed a regional collaboration cluster. There were also cross-links between these groups, indicating that strain imaging research is characterized by international collaboration rather than isolated efforts.

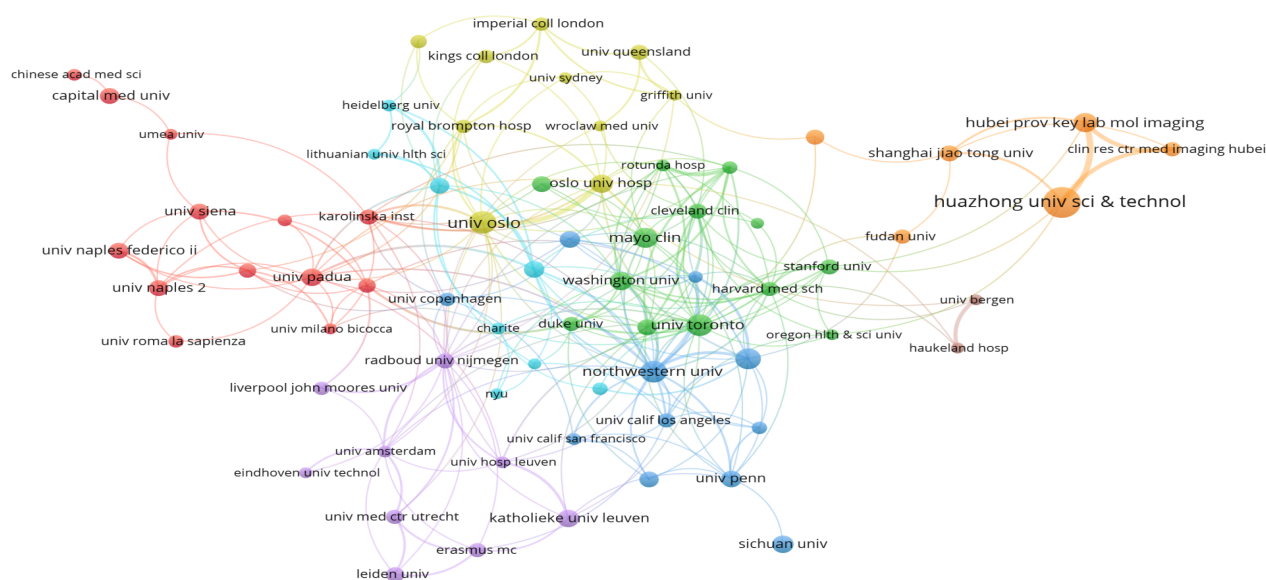


Figure 2. Author collaboration network of strain imaging research in cardiac function assessment (2000–2025).

3.3. Institutional analysis

Based on institutional output, Huazhong University of Science and Technology ranked first with 51 publications, highlighting its substantial contribution to the field. It was followed by the University of Oslo (30 publications) and Northwestern University in the United States (29). The University of Toronto (28), Johns Hopkins University (27), and Mayo Clinic (25) also ranked among the top contributors. In addition, the Hubei Provincial Key Laboratory of Molecular Imaging published 23 papers, while Washington University in St. Louis and Oslo University Hospital each produced 22, and KU Leuven contributed 21 publications. Notably, although Huazhong University of Science and Technology published the largest number of articles, its total citations amounted to 896, with an average of only 17.6 citations per paper. In contrast, the University of Oslo achieved 1,832 total citations with an average of 61.1 per paper, the highest among all institutions, while Northwestern University averaged 50 citations per paper. These findings suggest that leading international institutions, although publishing fewer papers, tend to produce more highly influential research, reflecting higher quality and broader international recognition (**Table 2**).

Table 2. Top 10 institutions by publication output in strain imaging research for cardiac function assessment (2000–2025)

Institution name	Total number of articles	Total citations	Average citations
Huazhong Univ Sci & Technol	51	896	17.5686
Univ Oslo	30	1832	61.0667
Northwestern Univ	29	1451	50.0345
Univ Toronto	28	703	25.1071
Johns Hopkins Univ	27	1268	46.963
Mayo Clin	25	951	38.04
Hubei Prov Key Lab Mol Imaging	23	539	23.4348
Washington Univ	22	1072	48.7273
Oslo Univ Hosp	22	850	38.6364
Katholieke Univ Leuven	21	417	19.8571

The institutional collaboration network further illustrates distinct clustering patterns influenced by geographic proximity and established partnerships (**Figure 3**). For instance, Huazhong University of Science and Technology, together with its collaborators such as Shanghai Jiao Tong University, Fudan University, and local imaging centers in Hubei, formed a closely connected cluster dominated by Chinese institutions (orange nodes). The University of Oslo occupied a central hub position in another cluster (green), maintaining strong collaborative ties with renowned institutions in North America and Europe, including Mayo Clinic, Harvard Medical School, Stanford University, and Washington University. Italian universities, such as the University of Naples Federico II and the University of Siena, constituted a distinct red cluster, while Dutch and Belgian institutions, including Utrecht University Medical Center, KU Leuven, and Leiden University, formed a purple cluster. Additionally, leading institutions from the United Kingdom and Australia, such as King's College London and the University of Queensland, appeared in the yellow cluster. Overall, the field demonstrated multiple geographically defined collaborative groups interconnected through several international hub institutions, reflecting a globalized research network.

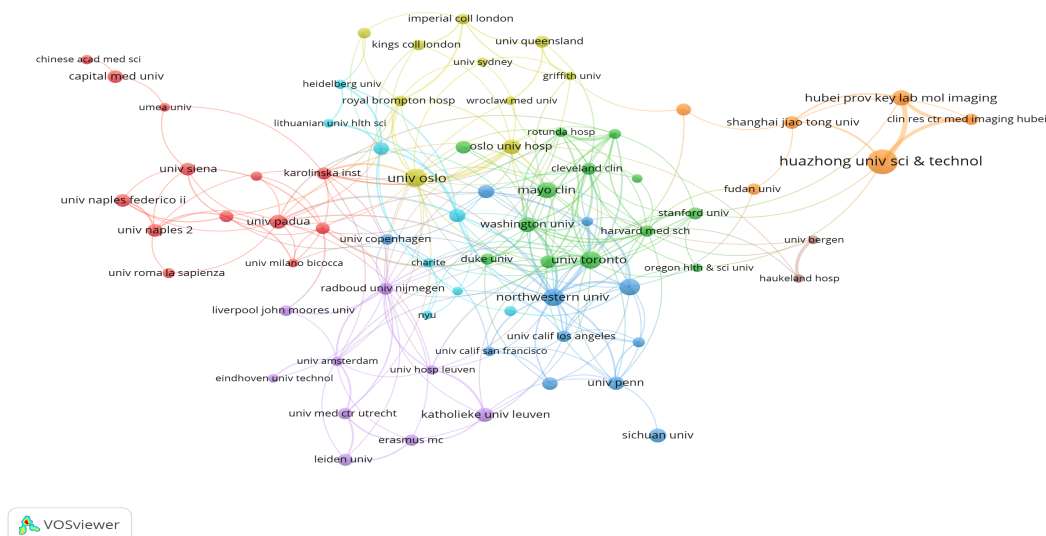


Figure 3. Institutional collaboration network of strain imaging research in cardiac function assessment (2000–2025)

3.4. Journal productivity and impact

Between 2000 and 2025, research on strain imaging was primarily published in specialized journals in the fields of cardiovascular ultrasound and imaging. Echocardiography published the largest number of relevant articles (192), followed by the Journal of the American Society of Echocardiography (145), and the International Journal of Cardiovascular Imaging (111). In addition, several general or thematic journals also contributed significantly, including the European Heart Journal – Cardiovascular Imaging (66), Pediatric Cardiology (52), and the International Journal of Cardiology (50), demonstrating the dissemination of strain imaging research across different journal types (Table 3).

Table 3. Top 10 journals by publication output in strain imaging research for cardiac function assessment (2000–2025)

Journal name	Total number of articles	Total citations	Average citations
Echocardiography-A Journal of Cardiovascular Ultrasound and Allied	192	2895	15.0781
Journal of the American Society of Echocardiography	145	5950	41.0345
International Journal of Cardiovascular Imaging	111	1421	12.8018
European Heart Journal-Cardiovascular Imaging	66	2081	31.5303
Pediatric Cardiology	52	474	9.1154
International Journal of Cardiology	50	848	16.96
Jacc-Cardiovascular Imaging	28	2146	76.6429
Circulation-Cardiovascular Imaging	27	3264	120.8889
American Journal of Cardiology	24	922	38.4167
European Journal of Echocardiography	23	1265	55

The impact of publications varied considerably across journals. Although dedicated echocardiography journals published a large volume of articles, their average citations per paper were relatively modest. For example, articles in Echocardiography averaged approximately 15 citations each. In contrast, the Journal of the American Society of Echocardiography achieved a total of 5,950 citations, with an average of 41 citations per article, representing a higher level of influence. The highest impact was observed in top-tier cardiovascular imaging journals: Circulation: Cardiovascular Imaging published only 27 relevant articles, yet these received a total of 3,264 citations (120.9 per paper), the highest among all journals. Similarly, JACC: Cardiovascular Imaging published 28 papers, with a total of 2,146 citations and an average of 76.6 citations per article. By comparison, more general journals such as the International Journal of Cardiovascular Imaging averaged 12.8 citations per paper, while Pediatric Cardiology averaged 9.1. The European Heart Journal – Cardiovascular Imaging fell in between, with an average of 31.5 citations per paper. These findings indicate that while strain imaging research is widely disseminated in specialized journals, a smaller number of high-impact papers in leading cardiovascular journals have attracted greater academic attention.

3.5. Keyword analysis and research hotspots

Based on keyword co-occurrence frequency, the evolution of research hotspots in strain imaging can be summarized. The most frequently occurring keyword was Speckle Tracking Echocardiography (664 occurrences), which first appeared around 2008, indicating that this core imaging technique began to attract wide attention in

the late 2000s. The next most frequent terms were Left Ventricular Function (485, appearing in 2002) and Heart Failure (385, 2004), reflecting the persistent focus of strain imaging on functional assessment and heart failure research. Other commonly used terms such as Echocardiography (350, 2003) and Dysfunction (315, 2002) demonstrated the close relationship between this field and cardiac function evaluation. The methodological concept of Strain (290, 2001) emerged early, while Global Longitudinal Strain (246, 2009) represented a newer parameter that has gained increasing importance in recent years. Of note, several high-frequency keywords, including American Society (294, 2009), European Association (271, 2012), and Recommendations (240, 2008), originated from the titles of guideline and consensus documents issued by the American Society of Echocardiography and the European Association of Cardiovascular Imaging, underscoring the significant influence of professional guidelines on research in this domain (**Table 4**).

Table 4. Top 10 keywords by co-occurrence frequency in strain imaging research for cardiac function assessment (2000–2025)

Rank	Frequency	Centrality	Time	Keyword
1	664	0.01	2008	Speckle Tracking Echocardiography
2	485	0.02	2002	Left Ventricular Function
3	385	0.03	2004	Heart Failure
4	350	0.05	2003	Echocardiography
5	315	0.04	2002	Dysfunction
6	294	0.01	2009	American Society
7	290	0.02	2001	Strain
8	271	0.02	2012	European Association
9	246	0.02	2009	Global Longitudinal Strain
10	240	0.02	2008	Recommendations

The keyword co-occurrence network further highlights the thematic clustering of research topics (**Figure 4**). The red cluster was dominated by methodological terms such as Myocardial Strain, Strain Rate, Two-Dimensional Strain, and Speckle Tracking, representing research on technical aspects and validation of strain imaging parameters. The green cluster centered on Left Ventricular Function, Heart Failure, Mortality, and Prognosis, reflecting clinical applications of strain imaging in cardiac function assessment and outcome prediction. The purple cluster encompassed terms such as American Society, European Association, Guidelines, and Consensus, corresponding to society-endorsed consensus statements and recommendations. The yellow cluster emphasized Right Ventricular Function and Pulmonary Hypertension, pointing to the use of strain imaging in right-heart assessment and disease-specific applications. Over time, the focus of research has evolved: early studies concentrated on methodological reliability and parameter development, followed by an increasing emphasis on the clinical significance of strain indices, and more recently on standardization and guideline implementation. This trajectory reflects a clear progression from technical development to clinical application and, ultimately, to normative standardization.

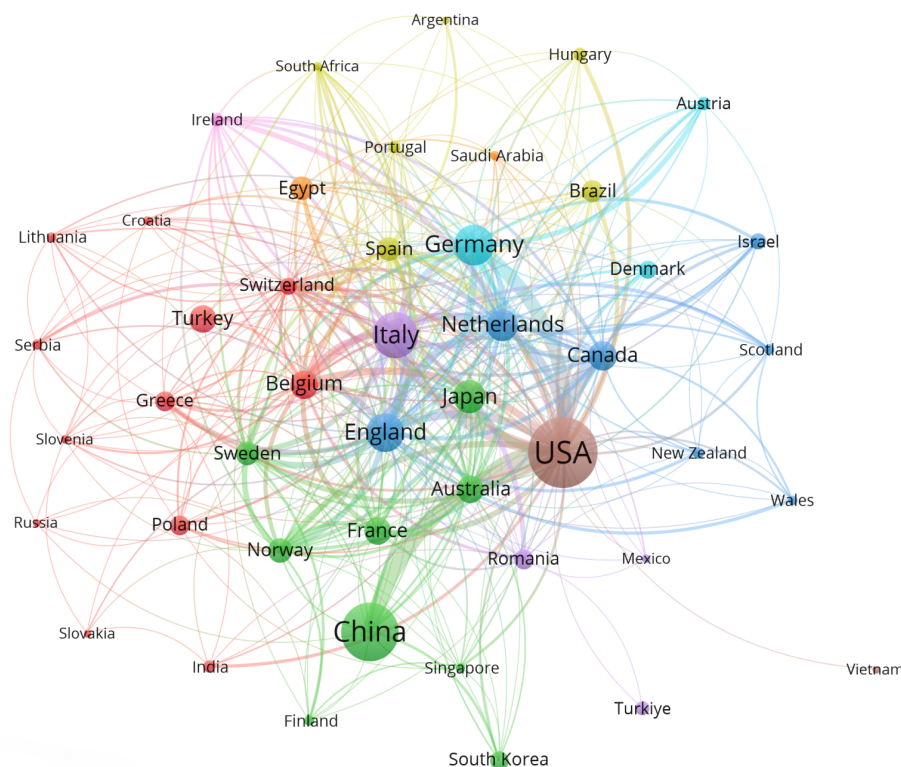


Figure 5. Global collaboration network in strain imaging research for cardiac function assessment (2000–2025).

3.7. Co-citation analysis

The co-citation network in strain imaging research revealed the core knowledge base of the field (**Figure 6**). In the network, nodes represent references (labeled by first author and publication year), with node size indicating citation frequency, link thickness reflecting co-citation strength, and node color denoting thematic clusters. Several major clusters were identified, each corresponding to different research themes. The red cluster included seminal methodological studies, such as the pioneering work by D’hooge *et al.* (2002), which first introduced speckle-tracking strain measurement. The green cluster encompassed numerous clinical application studies, evaluating the diagnostic and prognostic value of strain parameters in conditions such as heart failure. The purple cluster consisted mainly of guideline and consensus documents, notably those published around 2010 by the American Society of Echocardiography (ASE) and the European Association of Cardiovascular Imaging (EACVI).

The most frequently co-cited references represent key milestones across these domains. The foundational paper by D’hooge *et al.* (2002) established the methodological basis of speckle-tracking and occupies a central position in the network. Marwick *et al.* (2009) published a widely cited review highlighting the clinical applications of strain imaging, which has since become a landmark reference. Subsequent influential works include Sawaya *et al.* (2012), which investigated strain as a predictor of chemotherapy-induced cardiotoxicity, and Smiseth *et al.* (2016), which comprehensively reviewed the clinical value of myocardial strain. In addition, ASE/EACVI guideline papers published around 2015 also appeared prominently in the co-citation network, underscoring the importance of standardization and expert consensus in shaping the field.

Taken together, the co-citation analysis demonstrates that the development of strain imaging has been built upon three pillars: methodological innovation, clinical validation studies, and society-endorsed guidelines.

Collectively, these landmark publications have laid the academic foundation for the application of strain imaging in cardiac function assessment.

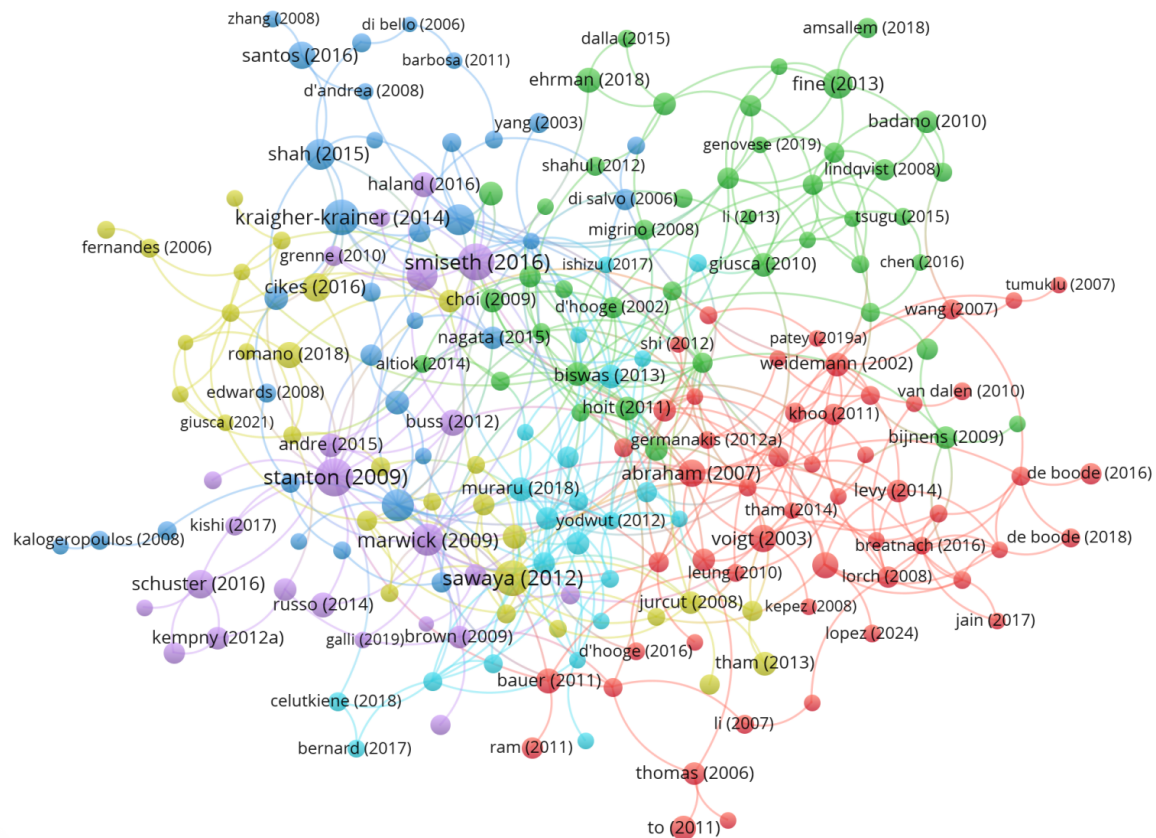


Figure 6. Co-citation network of references in strain imaging research for cardiac function assessment (2000–2025)

4. Discussion

Through a comprehensive bibliometric analysis, this study systematically summarized the developmental landscape of strain imaging research from 2000 to 2025, covering publication trends, key authors and institutions, collaboration networks, journal distribution, and research hotspots. Our findings revealed a steadily increasing publication output, with a rapid surge after 2010 and a peak in 2024. This trajectory indicates that strain imaging has transitioned from an experimental methodology into a widely adopted imaging tool for cardiac functional assessment, consistent with the increasing emphasis on its clinical standardization in recent years ^[4,5].

Analysis of authors and institutions demonstrated that Chinese scholars, such as Mingxing Xie and Li Zhang, led in publication output, reflecting strong research momentum from China. In contrast, European and North American scholars, including Thomas H. Marwick and Thor Edvardsen, produced papers with higher citation impact. This suggests a complementary pattern in the global advancement of strain imaging: while Chinese groups have expanded the breadth of research through high productivity, Western researchers have contributed highly influential publications and guideline development ^[6]. Institutional collaboration analysis further highlighted this pattern. Chinese institutions, led by Huazhong University of Science and Technology, formed tightly connected domestic clusters, whereas institutions such as the University of Oslo and Mayo Clinic acted as global

hubs, bridging collaborations across North America and Europe. Such collaborative networks underscore the increasingly internationalized nature of strain imaging research.

Journal distribution patterns revealed that strain imaging studies are concentrated in dedicated echocardiography journals but are also increasingly represented in high-impact cardiovascular journals. While the former ensured broad dissemination within the specialty, the latter provided platforms for high-impact publications, thereby amplifying the field's global visibility. The fact that highly cited studies often appear in leading journals highlights the need for future research to focus not only on volume but also on methodological rigor and clinical significance to achieve higher impact ^[7].

Keyword co-occurrence and burst analysis indicated a clear thematic evolution in the field. Early research focused on methodological innovation, such as speckle-tracking and two-dimensional strain, followed by clinical applications emphasizing left ventricular function, heart failure, and prognosis. More recently, guidelines and consensus statements from professional societies have emerged as research hotspots, reflecting the field's transition toward standardization and clinical implementation ^[4,7]. The increasing prominence of right ventricular and atrial strain further demonstrates the broadening applications of strain imaging in multidimensional cardiac functional assessment.

The national collaboration analysis revealed that the United States and China were the primary hubs, with Europe forming dense regional clusters. While China led in productivity, North American and European institutions achieved higher citation impact, likely reflecting differences in research infrastructure, leadership in guideline development, and accessibility to high-impact journals. Recent international surveys, however, highlight growing standardization of training and reporting, which may help reduce these disparities in the future ^[3].

5. Conclusion

Taken together, this study highlights the rapid growth and thematic evolution of strain imaging over the past two decades. The field has advanced along a trajectory from technological innovation to clinical application and, more recently, to guideline-based standardization. Future research should address several priorities: (1) establish disease-specific thresholds for GLS and other strain parameters; (2) conduct large-scale, prospective, multicenter trials to validate prognostic utility; (3) integrate multimodality imaging approaches such as echocardiography and CMR feature tracking; (4) leverage artificial intelligence to improve reproducibility and facilitate clinical translation; and (5) enhance international collaboration to harmonize practice standards. With these advancements, strain imaging is poised to play an increasingly central role in cardiac diagnosis, risk stratification, and therapeutic guidance.

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Disclosure statement

The authors declare no conflict of interest.

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