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Advancing sick sinus syndrome research in an aging world: A comprehensive network analysis

Naruaki Ogasawara[1*]

[1]Editorial Department, The Japanese Society of Internal Medicine, 3-28-8 Hongo Bunkyo-Ward, Tokyo 113-8433, Japan. E-mail: n-ogasawara@naika.or.jp

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Abstract

Aim: This study investigates global collaboration networks in Sick Sinus Syndrome (SSS) research from 2000 to 2023, focusing on key contributors and trends. As SSS becomes more prevalent in aging populations, understanding these networks is crucial for advancing research in the field. **Method:** Using 1,693 SSS-related publications from the Web of Science (WoS) Core Collection, network analysis was performed in Python (Version 3.10.5) via PyCharm. Macro-level indicators-network density, clustering coefficient, number of components, and average path length-were analyzed. Micro-level indicators-degree centrality, closeness centrality, and betweenness centrality-were used to assess key figures and institutions. **Result:** Collaboration increased over time, with higher network density and stronger local clusters, though fragmentation persisted. Key researchers, including Giuseppe Boriani (Italy) and Michael Glikson (Israel), were identified as central figures. The analysis revealed consistent regional and institutional collaboration patterns, reflecting the growing importance of global partnerships. **Conclusion:** This study highlights the significance of international collaboration in SSS research. While efforts have increased, fragmentation remains, indicating room for greater integration. Identifying influential researchers and institutions can help foster further collaboration and advance SSS treatment, especially as global aging trends drive the need for more research.

Keywords: *Cardiovascular disease, Sick sinus syndrome, Co-authorship network analysis, Research collaboration, Research trend analysis, Research strategies, Internal medicine, Interdisciplinary approach*

1. Introduction

1.1. Background and objectives

Sick Sinus Syndrome (SSS), a group of heart rhythm disorders, represents a critical challenge in cardiology due

* *Corresponding author: Naruaki Ogasawara, Editorial Department, The Japanese Society of Internal Medicine, 3-28-8 Hongo Bunkyo-Ward, Tokyo 113-8433, Japan. E-mail: n-ogasawara@naika.or.jp*

to its complex pathology and the impact it has on the aging global population. The syndrome's prevalence, particularly in elderly patients, has made it a significant focus of research worldwide. Due to the aging of the population worldwide, this disease is expected to become very important in the future. In response to this growing health concern, substantial efforts have been directed towards understanding SSS, leading to advances in clinical management and basic scientific research. However, despite this progress, there remain significant gaps in understanding the underlying causes, optimal treatments, and long-term outcomes for SSS patients (Rodriguez and Schocken,1990; Semelka *et al.*, 2013).

Globally, the research landscape in SSS reflects different priorities and challenges across regions (Zhang *et al.*, 2022). In the United States and Europe, significant resources have been allocated to the development of innovative therapeutic approaches and the understanding of SSS mechanisms, such as pacemaker interventions and electrophysiological studies (Zhang *et al.*, 2022). Meanwhile, Asia, particularly Japan and China, has seen an increasing focus on the epidemiology of SSS due to the region's rapidly aging populations, leading to a rise in the number of studies aimed at improving diagnostic and therapeutic strategies tailored to local healthcare systems (Wong *et al.*, 2019). Japan has emerged as a key player in clinical research on SSS, leveraging its advanced healthcare infrastructure and strong tradition of cardiovascular research (Wong *et al.*, 2019).

Given the complexity of SSS, a comprehensive understanding of global research efforts, collaborations, and trends is essential for advancing the field. Network analysis offers a powerful approach to uncovering the relationships between researchers, institutions, and countries, facilitating a deeper understanding of how research in SSS evolves.

1.2. Scope of the study

This study examines publications related to SSS research indexed in the Web of Science (WoS) Core Collection database between 2000 and 2023. A total of 1,693 articles were selected for analysis, providing a comprehensive overview of the collaborative landscape within this specialized field over the past two decades. The dataset ensures the inclusion of the most recent publications (as of October 2024). The analysis will focus on constructing and evaluating co-authorship networks using macro-level indicators such as network density (the ratio of actual to possible connections), clustering coefficient (the degree to which nodes tend to cluster together), number of components (distinct connected subgroups within the network), and average path length (the average distance between nodes). At the micro-level, I will assess degree centrality (the number of direct connections each node has), closeness centrality (how close a node is to all other nodes), and betweenness centrality (the extent to which a node lies on the shortest path between other nodes). These metrics will help illuminate the structure and dynamics of researcher collaborations in this field.

1.3. Significance of the study

This study holds significant value in the context of SSS research by offering a detailed exploration of the collaborative landscape within this field. Identifying major researchers and institutions involved in SSS research can help highlight leading contributors and emerging leaders. Furthermore, evaluating the progression of international collaborative research and its impact is essential for understanding how global partnerships contribute to advancements in this area. The analysis of network structures and their evolution over time can reveal critical trends, such as shifts in research focus or the emergence of new collaborative clusters.

By providing a clear picture of the current state of research and collaboration in SSS, this study not only enhances our understanding of existing networks but also sheds light on future directions and potential areas for new partnerships. The findings underscore the importance of international collaboration in addressing the complex challenges associated with SSS, highlighting the role of network analysis as a powerful tool for guiding future research strategies and fostering global cooperation.

2. Material and methods

The present study investigates the co-authorship patterns in SSS research articles. I utilized the WoS Core Collection database, conducting a "Topic Search" with the keyword "Sick Sinus Syndrome" to analyze a total of 1,693 articles published between 2000 and 2023 (as of October 2024). In this analysis, I examined who collaborated with whom in co-authoring these articles. I conducted network analysis using the Python programming language (version 3.10.5) within the integrated development environment (IDE) PyCharm (software version 2022.1.3). This study employed methodology-established principles of social network analysis (Wasserman and Faust, 1994). I carried out the analysis in two main parts:

2.1. *Macro-level metrics*

Network density: Calculated as the ratio of the number of edges to the maximum possible edges between all nodes.

Clustering coefficient: Measured the extent to which nodes form clusters by considering the number of edges among neighboring nodes and calculating the average.

Components: Identified and counted the number of subgraphs (components) where nodes are mutually connected.

Average path length: Evaluated the average "distance" between nodes by calculating the overall average path length in the network.

2.2. *Micro-level metrics*

Degree centrality: Measured the importance of each node by counting the number of edges it has in the network.

Closeness centrality: Defined as the inverse of the sum of the shortest path lengths from a node to all other nodes, measuring how close each node is to others in the network.

Betweenness centrality: Assessed the extent to which a node lies on the shortest paths between other nodes, indicating its importance in information transmission within the network (Newman, 2001).

The significance of these macro-level metrics in understanding the structure of scientific collaboration networks and these micro-level centrality measures in scientific collaboration networks has been well documented and used (Newman, 2001). Through these analyses, I can identify collaborative relationships and influential researchers in SSS research. This information may be useful for understanding research trends and planning future collaborative studies.

3. Results

The study analyzed the co-authorship network of researchers in SSS research, focusing on the periods from 2000 to 2023. The analysis was conducted using data from the WoS Core Collection and utilized both macro and micro-level network metrics to understand the evolution of collaborative networks in this field.

3.1. *2000-2009 network analysis*

The network analysis of SSS research between 2000 and 2009 reveals a relatively sparse collaboration network with a network density of 0.0029 (Table 1), indicating that only a small fraction of possible collaborations between researchers were realized (Figure 1). The average clustering coefficient was 0.922, suggesting that most researchers were part of tight-knit clusters. However, the network remained fragmented, with 325 distinct components, which is indicative of many isolated groups of researchers working independently. The average distance between nodes was infinite, due to the disconnected nature of the network (Barabasi and Albert, 1999).

Table 1: Network metrics

Metric	2000 - 2009	2010 - 2019	2020 - 2023
Network Density	0.0029	0.0068	0.0048
Average Clustering Coefficient	0.922	0.937	0.963
Number of Components	325	363	274
Average Distance	Infinite	Infinite	Infinite

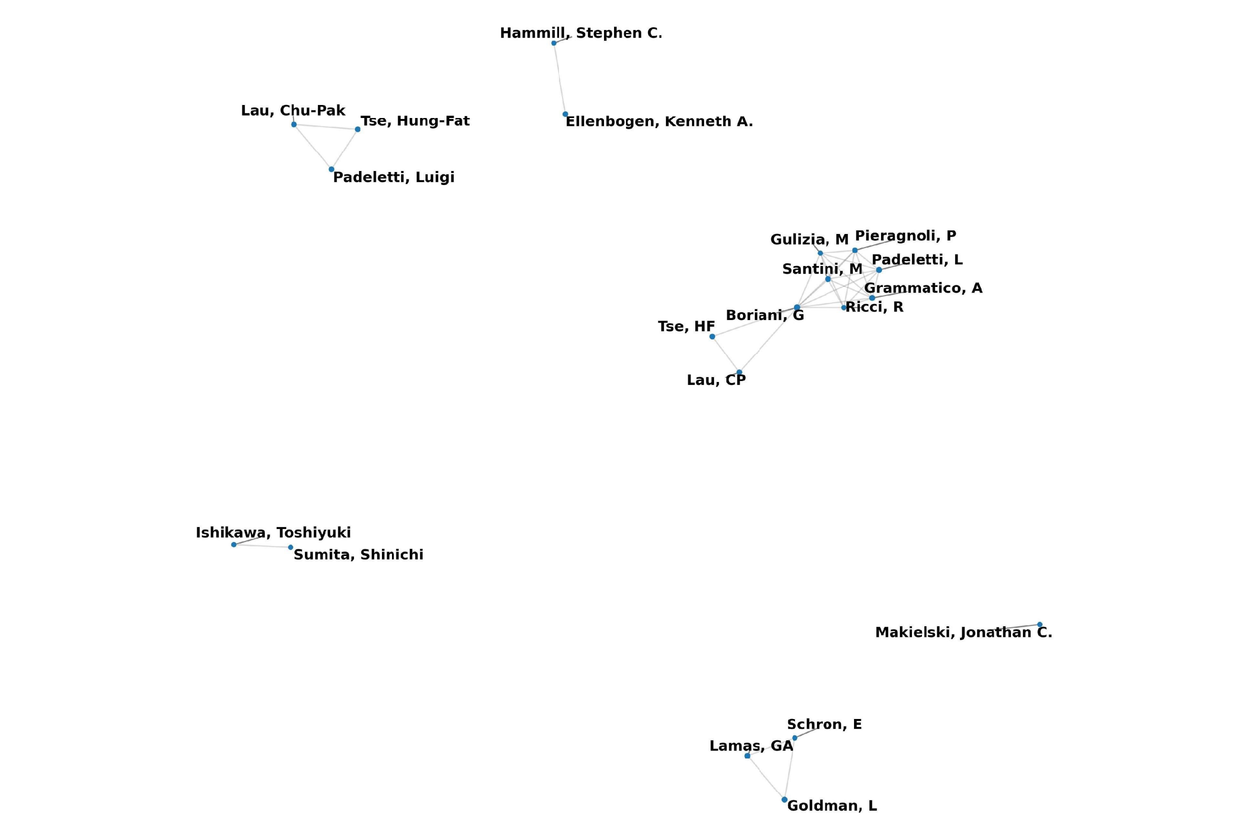

Figure 1: Top 20 sick sinus syndrome researcher network from 2000 to 2009

The top researchers by degree centrality included Boriani, G, Santini, M, and Lamas, GA, reflecting their significant collaborative roles (Table 2). By closeness centrality, Lau, CP, Boriani, G, and Tse, HF emerged as key figures, indicating their ability to quickly connect to others in the network (Table 3). In terms of betweenness centrality, Lau, CP and Boriani, G stood out, underlining their critical role in bridging different parts of the network (Table 4).

3.2. 2010-2019 network analysis

The second period (2010-2019) showed an increase in collaborative activity, with the network density rising to 0.0068 (Table 1), almost doubling the level of the previous decade (Figure 2). The average clustering coefficient increased slightly to 0.937, indicating stronger local collaboration within clusters. Despite this, the network remained highly fragmented, with 363 components. Again, the average distance was infinite, highlighting the disconnected nature of the broader research landscape (Barabasi and Albert, 1999).

During this period, Arnar, David O., Holm, Hilma, and Thorsteinsdottir, Unnur topped the list of degree centrality, suggesting their prominent collaborative roles (Table 2). For closeness centrality, Wang, Chun-Chieh and Abe, Haruhiko ranked highest, indicating their strategic positions in reaching others within the network (Table 3). Betweenness centrality revealed Abe, Haruhiko and Wang, Chun-Chieh as vital connectors who helped facilitate indirect collaboration across the network (Table 4).

3.3. 2020-2023 network analysis

The network in the final period (2020-2023) displayed a slight decline in network density, dropping to 0.0048 (Table 1), while the average clustering coefficient reached 0.963, the highest in the study, indicating exceptionally close collaborations within clusters (Figure 3). The number of components decreased to 274, suggesting some consolidation of research groups, though the network was still fragmented with disconnected segments (Barabasi and Albert, 1999).

Prominent researchers by degree centrality included Glikson, Michael, Boriani, Giuseppe, and Michowitz, Yoav, showing their leadership in collaborative efforts (Table 2). Boriani, Giuseppe also led in closeness

Table 2: Top 20 nodes by degree centrality

Node	2000 - 2009	Degree Centrality	2010 - 2019	Degree Centrality	2020 - 2023	Degree Centrality
1	Boriani, G	0.0187	Arnar, David O.	0.0771	Glikson, Michael	0.0346
2	Santini, M	0.0180	Holm, Hilma	0.0769	Boriani, Giuseppe	0.0342
3	Lamas, GA	0.0165	Thorsteinsdottir, Unnur	0.0769	Michowitz, Yoav	0.0322
4	Padeletti, L	0.0165	Stefansson, Kari	0.0769	Auricchio, Angelo	0.0293
5	Grammatico, A	0.0161	Darbar, Dawood	0.0766	Torp-Pedersen, Christian	0.0277
6	Goldman, L	0.0153	Heckbert, Susan R.	0.0718	Brunak, Soren	0.0252
7	Tse, Hung-Fat	0.0153	Alonso, Alvaro	0.0718	Westergaard, David	0.0252
8	Lau, Chu-Pak	0.0153	Psaty, Bruce M.	0.0710	Pedersen, Ole B.	0.0252
9	Tse, HF	0.0142	Kiemeney, Lambertus A.	0.0706	Sorensen, Erik	0.0252
10	Lau, CP	0.0142	Arking, Dan E.	0.0701	Banasik, Karina	0.0252
11	Padeletti, Luigi	0.0138	Bis, Joshua C.	0.0701	Oddsson, Asmundur	0.0252
12	Schron, E	0.0131	Morrison, Alanna C.	0.0701	Bundgaard, Henning	0.0252
13	Ellenbogen, Kenneth A.	0.0131	O'Donnell, Christopher J.	0.0701	Ullum, Henrik	0.0252
14	Pieragnoli, P	0.0131	Spector, Tim D.	0.0701	Thorsteinsdottir, Unnur	0.0252
15	Ricci, R	0.0116	Jamshidi, Yalda	0.0701	Holm, Hilma	0.0252
16	Gulizia, M	0.0116	Rotter, Jerome I.	0.0701	Stefansson, Kari	0.0252
17	Sumita, Shinichi	0.0116	Sotoodehnia, Nona	0.0701	Pavri, Behzad B.	0.0244
18	Ishikawa, Toshiyuki	0.0116	Newton-Cheh, Christopher	0.0701	Arnar, David O.	0.0208
19	Makielski, Jonathan C.	0.0112	Ellinor, Patrick T.	0.0701	Berul, Charles, I	0.0208
20	Hammill, Stephen C.	0.0108	den Hoed, Marcel	0.0647	Etheridge, Susan P.	0.0204

Table 3: Top 20 nodes by closeness centrality

Node	2000 - 2009	Closeness Centrality	2010 - 2019	Closeness Centrality	2020 - 2023	Closeness Centrality
1	Lau, CP	0.0398	Wang, Chun-Chieh	0.0974	Boriani, Giuseppe	0.0361
2	Boriani, G	0.0391	Abe, Haruhiko	0.0953	Glikson, Michael	0.0358
3	Tse, HF	0.0373	Ellenbogen, Kenneth A.	0.0941	Michowitz, Yoav	0.0343
4	Barold, SS	0.0371	Estes, N. A. Mark, III	0.0918	Auricchio, Angelo	0.0327
5	Hettrick, DA	0.0361	Zhang, Shu	0.0890	Pavri, Behzad B.	0.0302
6	Santini, M	0.0360	Padeletti, Luigi	0.0885	Tovia-Brodie, Oholi	0.0284
7	Padeletti, L	0.0359	Fauchier, Laurent	0.0877	Acha, Moshe Rav	0.0284
8	Pieragnoli, P	0.0353	Fenelon, Guilherme	0.0877	Belhassen, Bernard	0.0284
9	Lee, KL	0.0348	Al-Khatib, Sana M.	0.0870	Gasperetti, Alessio	0.0284
10	Vicentini, A	0.0347	Proclemer, Alessandro	0.0870	Schiavone, Marco	0.0284
11	Malinowski, K	0.0344	Munawar, Muhammad	0.0868	Forleo, Giovanni Battista	0.0284
12	Grammatico, A	0.0344	Russo, Andrea M.	0.0863	Guevara-Valdivia, Milton E.	0.0284
13	Yu, C	0.0344	Swerdlow, Charles D.	0.0863	Valdeolivar Ruiz, David	0.0284
14	Pignalberi, C	0.0343	Makita, Naomasa	0.0862	Lellouche, Nicolas	0.0284
15	Paul, VE	0.0343	Ishikawa, Taisuke	0.0860	Hamon, David	0.0284
16	Schuchert, A	0.0343	Chen, Mien-Cheng	0.0860	Castagno, Davide	0.0284
17	del Ojo, JL	0.0343	Kim, You-Ho	0.0858	Bellettini, Matteo	0.0284
18	Blanc, JJ	0.0343	Chen, Jan-Yow	0.0856	De Ferrari, Gaetano M.	0.0284
19	Ricci, R	0.0342	Lau, Chu-Pak	0.0856	Laredo, Mikael	0.0284
20	Capucci, A	0.0341	Li, Yi-Gang	0.0856	Carves, Jean-Baptiste	0.0284

Table 4: Top 20 nodes by betweenness centrality

Node	2000 - 2009	Betweenness Centrality	2010 - 2019	Betweenness Centrality	2020 - 2023	Betweenness Centrality
1	Lau, CP	0.0051	Abe, Haruhiko	0.0527	Boriani, Giuseppe	0.0005
2	Boriani, G	0.0044	Wang, Chun-Chieh	0.0438	Glikson, Michael	0.0004
3	Lee, KL	0.0043	Darbar, Dawood	0.0414	Pavri, Behzad B.	0.0003
4	Santini, M	0.0039	Ellenbogen, Kenneth A.	0.0268	Mohler, Peter J.	0.0003
5	Barold, SS	0.0028	Estes, N. A. Mark, III	0.0189	Dobrzynski, Halina	0.0002
6	Yee, R	0.0027	Makita, Naomasa	0.0155	Michowitz, Yoav	0.0002
7	Sweeney, MO	0.0025	Ishikawa, Taisuke	0.0144	Li, Ning	0.0002
8	Tse, HF	0.0023	Zhang, Shu	0.0130	Ohkubo, Kimie	0.0002
9	Lamas, GA	0.0013	Schulze-Bahr, Eric	0.0124	Arnar, David O.	0.0002
10	Carlson, MD	0.0013	Barc, Julien	0.0105	Fedorov, Vadim V.	0.0002
11	Ellenbogen, KA	0.0012	Redon, Richard	0.0105	Torp-Pedersen, Christian	0.0002
12	Prinzen, FW	0.0011	Padeletti, Luigi	0.0097	Boyett, Mark R.	0.0002
13	Vardas, P	0.0011	Nielsen, Jens Cosedis	0.0089	Berul, Charles, I	0.0001
14	Roda, J	0.0010	Verkerk, Arie O.	0.0084	Ren, Lu	0.0001
15	Goldman, L	0.0010	Nogami, Akihiko	0.0080	Etheridge, Susan P.	0.0001
16	Padeletti, Luigi	0.0009	Isbrandt, Dirk	0.0080	Brugada, Pedro	0.0001
17	Padeletti, L	0.0009	Makiyama, Takeru	0.0069	Auricchio, Angelo	0.0001
18	Gillis, AM	0.0008	Horie, Minoru	0.0067	Zhang, Henggui	0.0001
19	Raviele, A	0.0008	Ohno, Seiko	0.0057	Mesirca, Pietro	0.0001
20	Oto, A	0.0008	Bezzina, Connie R.	0.0056	Mangoni, Matteo E.	0.0001

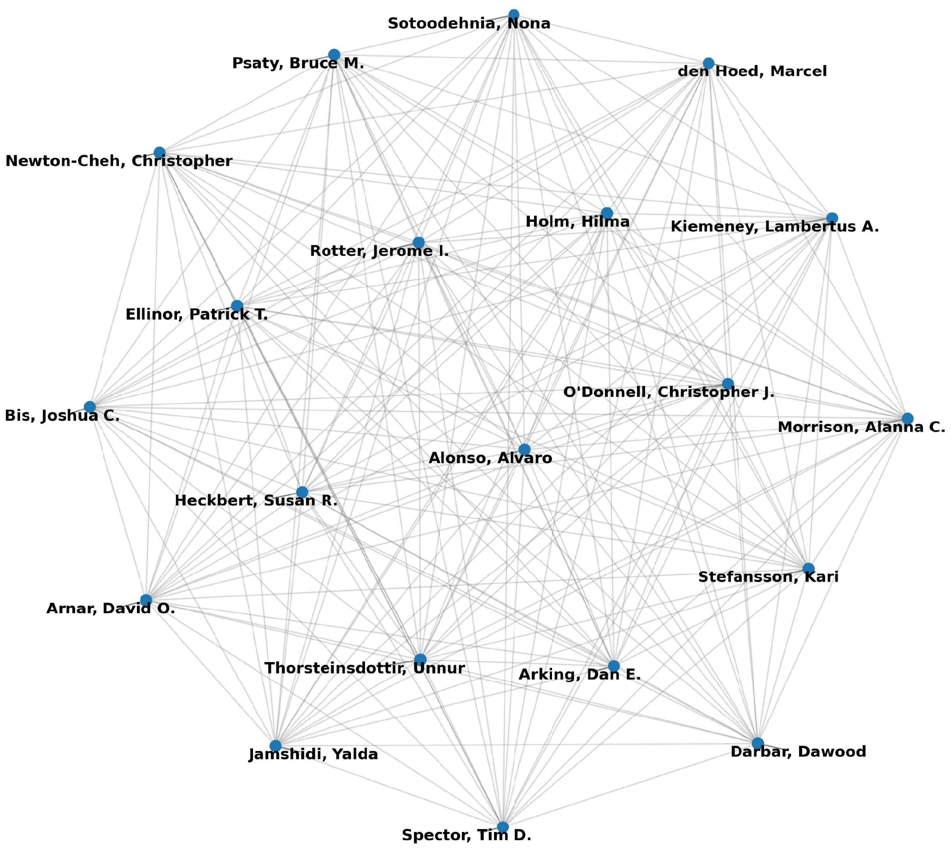

Figure 2: Top 20 sick sinus syndrome researcher network from 2010 to 2019

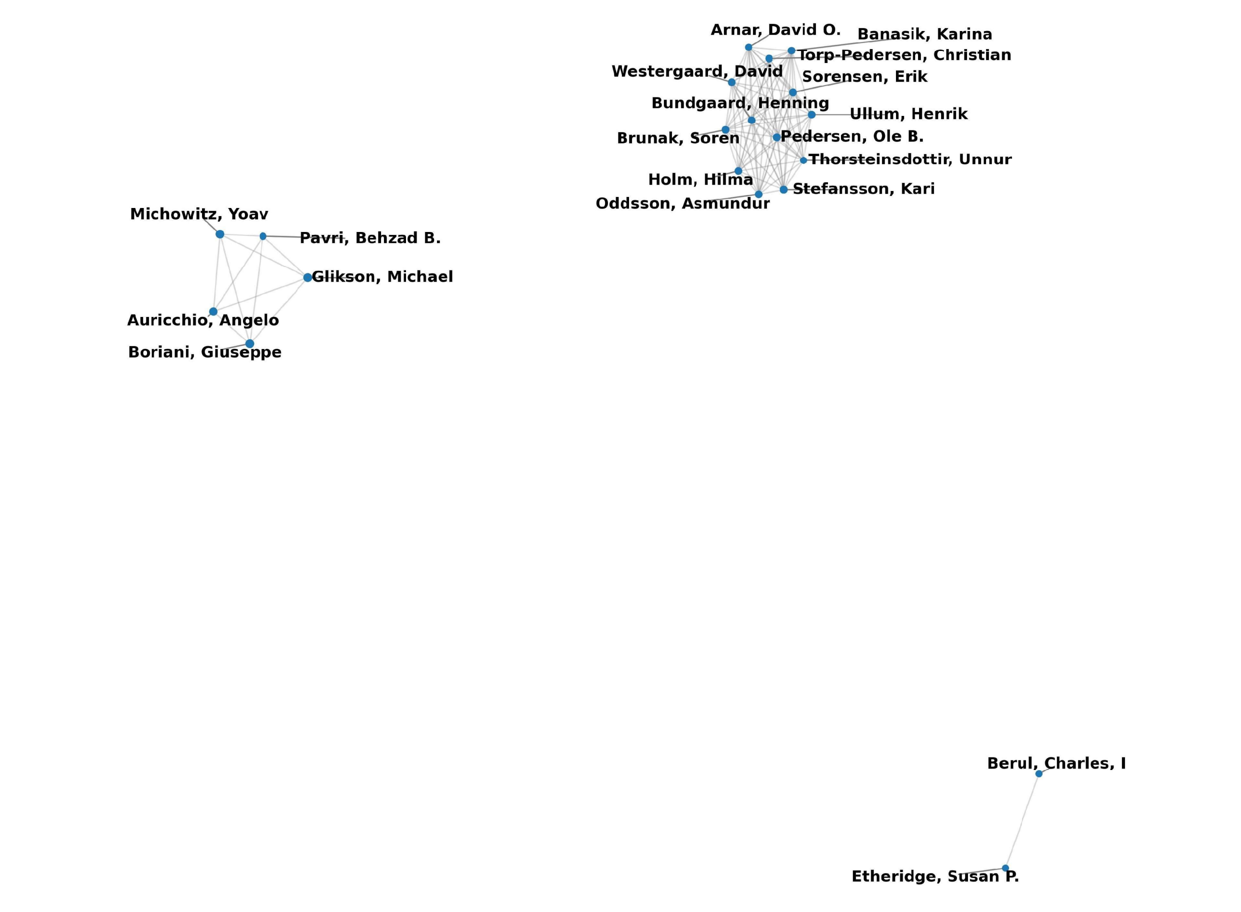

Figure 3: Top 20 sick sinus syndrome researcher network from 2020 to 2023

centrality, reflecting his central position within the network (Table 3). In terms of betweenness centrality, Glikson, Michael, and Boriani, Giuseppe continued to play crucial roles in linking otherwise unconnected parts of the network, facilitating broad collaboration (Table 4).

Overall, the network analysis over these three periods highlights increasing collaboration in SSS research, with certain researchers emerging as key figures in connecting the field across geographic and institutional boundaries. Despite the increased clustering, the network remains fragmented, suggesting potential for further integration and collaboration.

4. Discussion

The results of this study provide a comprehensive understanding of the collaborative landscape in SSS research from 2000 to 2023, revealing significant trends in how researchers, institutions, and geographic regions have connected over time. The evolving structure of co-authorship networks indicates both growth in collaborative efforts and persistent fragmentation within the field, offering critical insights into the dynamics of SSS research.

4.1. Increasing collaboration and key researchers

Over the three periods analyzed (2000-2009, 2010-2019, 2020-2023), a clear trend of increasing collaboration was observed. The rise in network density, particularly between 2000-2009 and 2010-2019, demonstrates an expansion in collaborative activity, as more researchers began to co-author papers on SSS. This increase aligns with the global rise in cardiovascular research, driven by the growing burden of heart diseases in aging populations, particularly in developed countries like the United States, Europe, and parts of Asia. However, despite this growth, the network remained highly fragmented, with numerous isolated components, which suggests that many researchers were working within specific groups without broader collaboration across the field. In anticipation of an aging society that will progress globally in the future, cooperative promotion of SSS research is required.

The identification of key researchers across different periods highlights the significant roles played by individuals such as Boriani, Giuseppe (Italy), and Glikson, Michael (Israel) in fostering collaboration. These researchers emerged as central figures, particularly in the later years, by maintaining high degree, closeness, and betweenness centrality scores. Their prominence indicates not only their productivity but also their ability to bridge different clusters of research, facilitating broader collaboration. The recurrent presence of these researchers across multiple periods underscores their influence in shaping SSS research, particularly in fostering international partnerships.

4.2. Fragmentation and cluster formation

Despite the rise in collaboration, the network remained fragmented, with many disconnected components throughout the study period. This fragmentation is common in niche research fields like SSS, where specialized expertise leads to the formation of tight-knit clusters. The high clustering coefficient observed in each period, particularly in the most recent years, indicates that while local collaboration within research groups was strong, there was a lack of integration across the broader network.

This pattern suggests that while researchers within specific institutions or geographic regions are working closely together, collaboration across regions and institutions remains limited. For instance, although Japan, China, and parts of Europe have made substantial contributions to SSS research, the lack of connectivity between these regions points to an opportunity for fostering more international collaborations. I believe that international research cooperation and collaboration have been promoted in the past, but it is very important to create an environment where researchers can work together to promote research and treatment across regions and countries. As diseases like SSS are expected to become more prevalent in aging populations globally, there is a need for greater cooperation across borders to share knowledge and resources more effectively.

4.3. Challenges and opportunities for future collaboration

The persistent fragmentation of the network presents both challenges and opportunities for future SSS research. On one hand, the existence of numerous isolated components indicates that valuable research may be conducted in silos, limiting the potential for cross-fertilization of ideas and breakthroughs that arise from interdisciplinary collaboration. On the other hand, this fragmentation also highlights potential areas for growth. Regarding the results of the analysis of this study, and by identifying the most influential researchers and clusters, stakeholders in the field of SSS can target these key figures to foster broader collaboration networks.

For example, researchers like Boriani, Giuseppe (Italy), and Glikson, Michael (Israel), who have demonstrated strong betweenness centrality, are well-positioned to act as connectors between otherwise unlinked groups. Facilitating collaborations through these central figures could help bridge gaps between isolated components, leading to a more integrated and cohesive global research effort. Additionally, institutions and funding agencies could play a role in incentivizing international partnerships, particularly between regions such as Asia and Europe, where research priorities and healthcare challenges are converging due to demographic shifts.

4.4. Implications for future research direction and collaboration

The findings of this study have important implications for research strategy and policy in the field of SSS. First, the identification of key collaborators and clusters offers a roadmap for fostering new partnerships, both within existing research groups and across different geographic regions. Funding agencies and academic institutions could leverage this information to design collaborative grant opportunities, workshops, and conferences that bring together researchers from previously disconnected clusters.

Second, the continued fragmentation of the network underscores the importance of encouraging interdisciplinary and international research. With the global burden of cardiovascular diseases, particularly those affecting aging populations, projected to rise, there is a pressing need for more integrated research efforts that transcend institutional and national boundaries. The creation of global consortia or collaborative research networks could facilitate knowledge exchange and accelerate advancements in understanding and treating SSS. Academic associations in each country also have the potential to contribute greatly to the creation of consortiums and collaborative research networks.

Lastly, this study highlights the value of network analysis as a tool for evaluating research collaboration and identifying areas for improvement. By regularly assessing the structure of co-authorship networks, stakeholders can monitor the effectiveness of policies aimed at fostering collaboration and adjust strategies accordingly.

5. Conclusion

This study provides a detailed analysis of the co-authorship network in SSS research from 2000 to 2023, shedding light on the evolution of collaborative structures in the field. The findings highlight several important trends. First, there has been a gradual increase in research collaboration over the two decades, with network density improving from the earlier period (2000-2009) to the more recent periods (2010-2019, 2020-2023). This growth in collaborative activity reflects the increasing recognition of the importance of SSS research, particularly in response to the aging global population.

Key researchers, such as Boriani, Giuseppe (Italy), and Glikson, Michael (Israel), have emerged as central figures in facilitating collaboration, connecting various research clusters, and advancing the field. These researchers played pivotal roles in linking otherwise fragmented groups, thereby fostering a more cohesive research network. Despite this progress, the network remains fragmented, with numerous isolated components, which indicate potential for further integration and collaboration among research groups.

The findings also underscore the importance of strong regional contributors, particularly from Europe, the United States, and Asia. In countries with rapidly aging populations, such as Japan and China, SSS has become an increasingly important research focus, necessitating further collaborative efforts to address the growing healthcare challenges posed by the disease.

Overall, this study provides a comprehensive understanding of the global research landscape in SSS. The application of network analysis has revealed key trends, collaborations, and gaps that can inform future research strategies. Further efforts to foster international collaboration and integrate isolated research groups will be critical for advancing our understanding of SSS and improving clinical outcomes for patients. I hope that the results of this research will help promote SSS research worldwide.

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