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Brief Communication

Artificial intelligence in cardiology: a bibliometric study

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Abstract: Objectives: To perform a comprehensive bibliometric analysis of global publications on the applications of artificial intelligence (AI) in cardiology. Methods: Documents related to AI in cardiology published between 2002 and 2022 were retrieved from Web of Science Core Collection. R package "bibliometrix", VOSviewers and Microsoft Excel were applied to perform the bibliometric analysis. Results: A total of 4332 articles were included. United States topped the list of countries publishing articles, followed by China and United Kingdom. The Harvard University was the institution that contributed the most to this field, followed by University of California System and University of London. Disease risk prediction, diagnosis, treatment, disease detection, and prognosis assessment were the research hotspots for AI in cardiology. Conclusions: Enhancing cooperation between different countries and institutions is a critical step in leading to breakthroughs in the application of AI in cardiology. It is foreseeable that the application of machine learning and deep learning in various areas of cardiology will be a research priority in the coming years.

Keywords: Cardiology, artificial intelligence, hotspots, trends, machine learning, deep learning

Introduction

Artificial Intelligence (AI) is a highly complex system that incorporates logic, probability theory, mathematics, statistics, and other disciplines [1]. With the continuous progress of science and technology, AI has been applied to many fields such as program automation design, intelligent control, and image recognition [2, 3]. Since the 1950s, AI has been applied to aid in the diagnosis of diseases [4].

With powerful learning capabilities and algorithms, the application of AI in healthcare continues to expand, including disease diagnosis, disease monitoring, drug development and genetic engineering, which greatly promotes the innovation and development of healthcare [5, 6].

The use of AI techniques in cardiology has been emphasized since the invention of the electrocardiogram in the late 19th century [7]. In clinical practice, the diagnosis and treatment of cardiovascular disease often relies on a variety of formatted data [8-10]. Disease history, physical examination, laboratory data, diagnostic imaging and invasive angiography constitute a large amount of clinical data [11]. The constant evolution of medicine requires cardiologists to perform increasingly complex analyses, and the introduction of newer, data-rich technologies, including biometrics in electronic health records, wearable and implantable recording devices, mobile telemetry devices, and research and other patient-generated health data, can't be done without the support of AI technology [12-16].

With the surge of research interest in the application of AI in cardiology, a large number of related papers have been published. However, it is difficult for researchers to clarify the research frontiers and hotspot trends in this field [8, 9]. Bibliometric analysis is a method that uses mathematical statistics to quantitatively analyze the data characteristics of global literature in a certain field to understand the knowledge structure and identify the research frontiers and hotspots [17, 18]. Therefore, to

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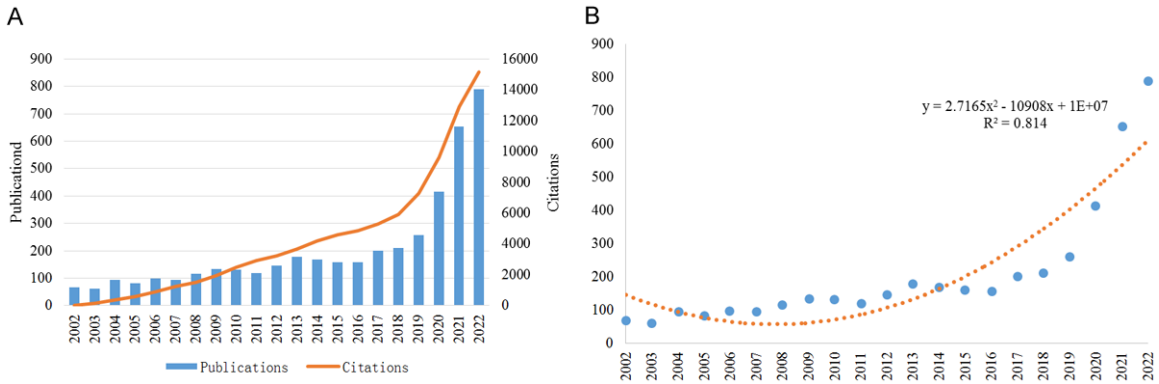

Figure 1. A. Number of times cited and publications over time. B. Curve fitting of the of the annual growth trend of publications.

provide a comprehensive overview of research trends in the use of AI in cardiology, we have highlighted the contributions of leading countries, leading institutions, and authoritative scholars, and provided insight into potential future collaborations and research directions.

Materials and methods

Data source

The most commonly used database for bibliometric analysis is Web of Science Core Collection, which has a huge selection of journal categories. Compared to other databases, the Web of Science Core Collection is considered to be the best source of data for bibliometric studies because it is the most detailed, transparent, and extensive [19-21]. The search formula for Web of Science Core Collection used in this study was as follows: TS = (cardiology OR cardiovascular OR heart OR cardiac) AND TS = (Artificial intelligence OR AI OR computational intelligence OR machine intelligence OR computer reasoning OR computer vision system OR knowledge acquisition OR knowledge representation). Retrieved on February 27, 2023, with a limited time frame of January 1, 2002 to December 31, 2022. Moreover, the document type was limited to 'article'.

Bibliometric analysis

VOSviewer (1.6.18), R software (4.0.2), and Microsoft Excel (2019) were used for data processing and result visualization. Using R software to analyze country, institutions, journals, authors, co-cited authors and keywords, the results were presented through a visual network map. Keyword analysis using R software helps to reflect the trend of high-frequency keywords on a timeline, thus helping researchers to understand hot topics and current trends. Using VOSviewer to map the co-citation and co-occurrence with the minimum number of references set to 25, and the keyword analysis set to 20. Furthermore, we used Microsoft Excel to analyze and predict publication trends in this field.

Results

Analysis of publications

A total of 4323 publications were included in this study. Trends in the number of publications are shown in **Figure 1A**. Despite fluctuations, the number of annual papers generally increased, from 67 in 2002 to 790 in 2022, and will continue to increase in the future (**Figure 1B**). Similarly, the number of citations of publications generally increased, from 28 in 2002 to 15,154 in 2022.

Analysis of countries

Countries with the top 10 publications are shown in Table S1. The United States had the largest number of publications (1400), followed by China (523), the United Kingdom (368), Germany (315) and Italy (259). Furthermore, United States (n = 38,596) topped the list in terms of total citations, while United Kingdom (n = 34.17) topped the list in terms of average citations. In addition, a close network of cooperation existed between the United States, China and United Kingdom (Figure S1).

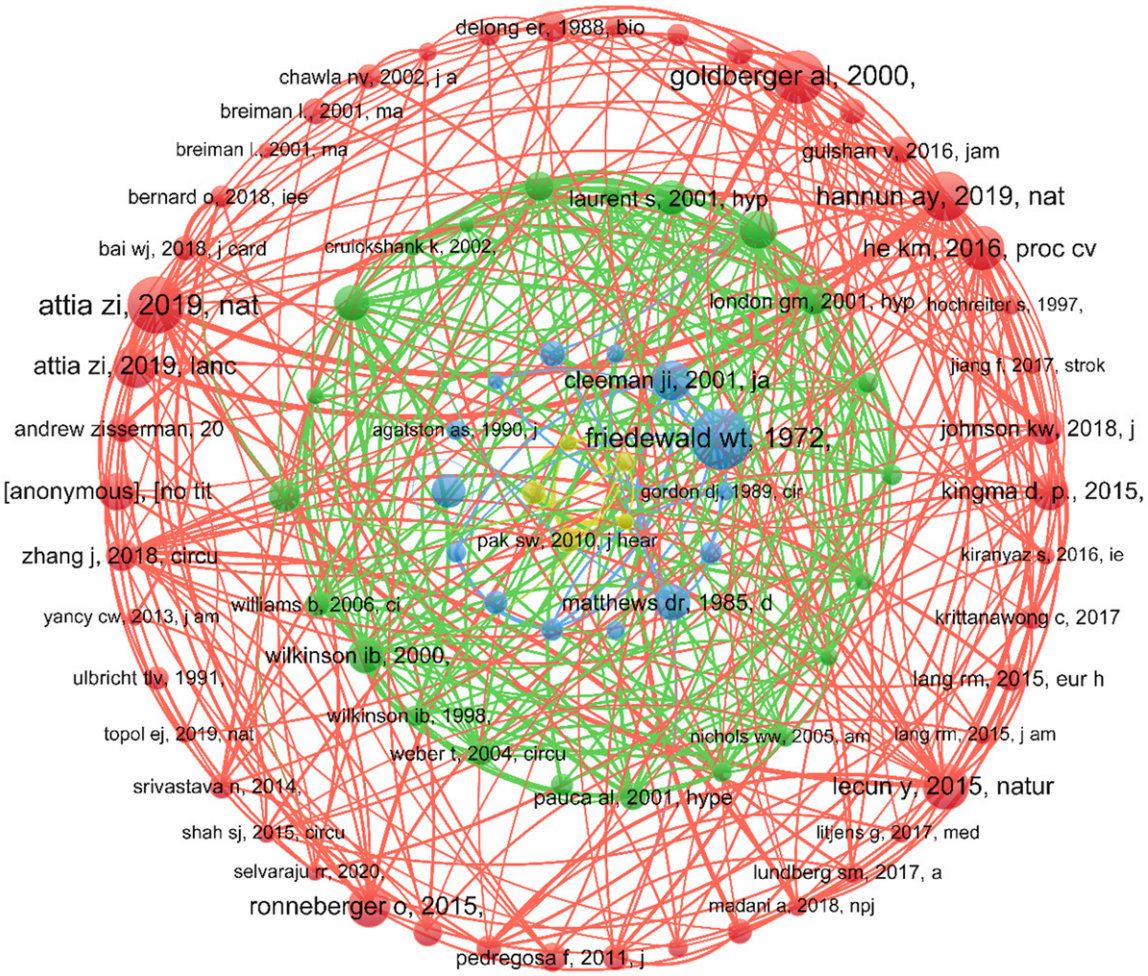

Figure 2. Network map of co-cited references.

Analysis of affiliations

Affiliations with the top 10 publications are shown in Table S2. Harvard University had the largest number of publications (n = 134), followed by University of California System (n = 121) and University of London (n = 115). In addition, Harvard University (n = 6,364) also topped the list in both total citations and average citations (n = 47.49). Furthermore, a close network of cooperation was identified between Mayo Clinic and Harvard Medical School (Figure S2).

Analysis of authors

Authors with the top 10 publications are shown in Table S3. Friedman PA had the largest number of publications (n = 29), followed by Noseworthy PA (n = 27), Zhang Y (n = 24), Attia ZI (n = 23), and Lopez-Jimenez F (n = 23). Furthermore, Friedman PA (n = 1,070) topped the list in terms of total citations, while Kapa S (n = 55.59) topped the list in terms of average citations. In addition, a close network of cooperation was identified between Friedman PA, Wang Y and Zhang Y (Figure S3).

Analysis of journals

Authors with the top 10 publications are shown in Table S4. *Sensors* had the largest number of publications (n = 62), followed by *IEEE Access* (n = 60), *PloS One* (n = 59), *Frontiers in Cardiovascular Medicine* (n = 54), and *Computers in Biology and Medicine* (n = 39). Furthermore, *PloS One* (n = 1,773) topped the list in terms of total citations, while *American Journal of Hypertensions* (n = 32.28) topped the list in terms of average citations. In addition, the number of publications in the top five most active journals had increased rapidly over the past five years (Figure S4).

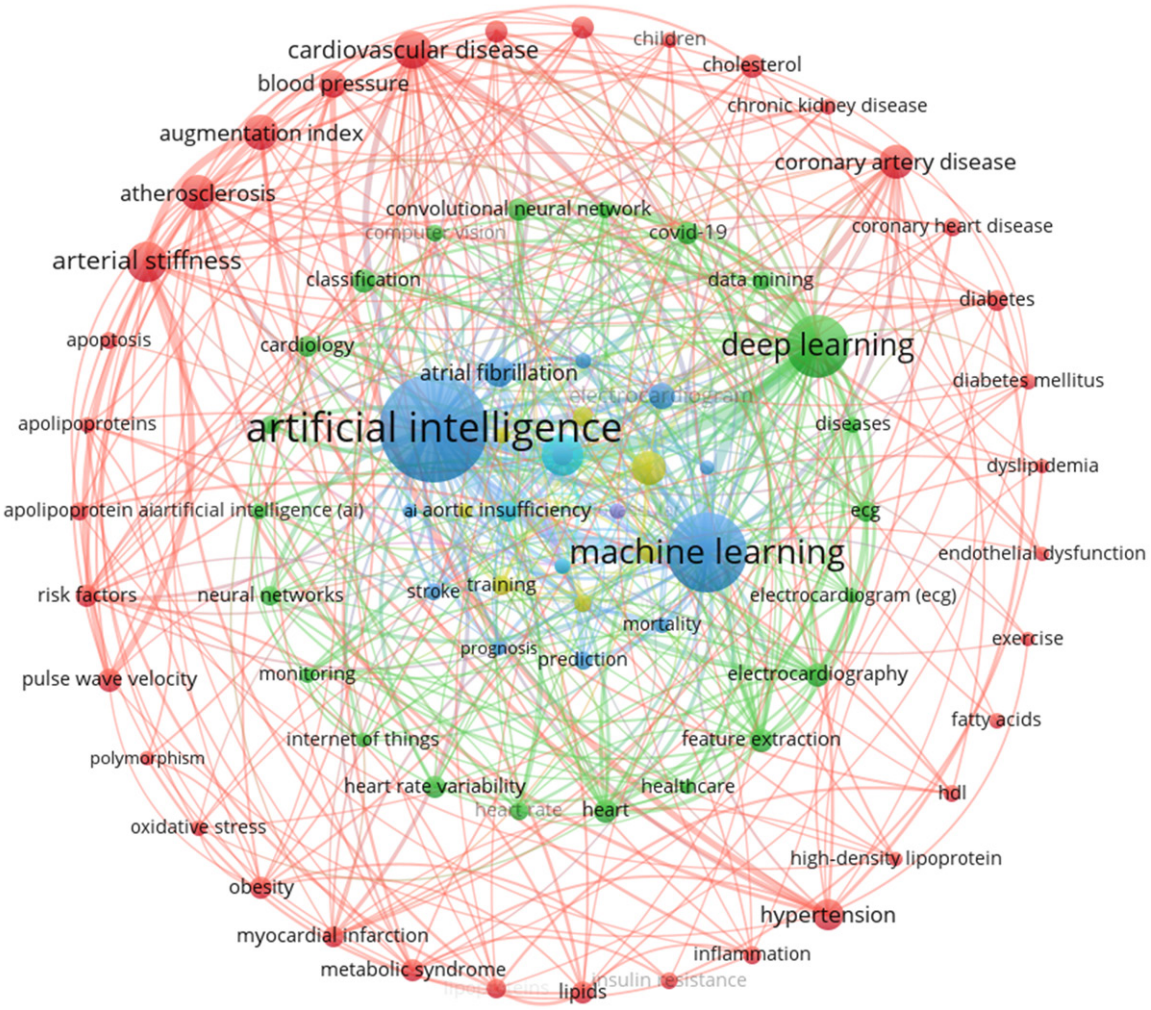

Figure 3. Network map of keywords from AI in cardiology.

Analysis of co-cited references

Co-citation analysis was conducted on the cited references. As showed in **Figure 2**, the red cluster represented the application of AI in healthcare, the green cluster represented the application of AI in cardiovascular diagnosis, the blue cluster represented the role of AI in risk factor identification and condition monitoring, and the yellow cluster represented the application of AI in the treatment of cardiovascular diseases.

Analysis of hotspots and trends in research

Co-occurrence analysis was performed for keywords that appeared more than 20 times. As showed in **Figure 3**, the red cluster represented the common cardiovascular diseases, the green and blue clusters represented the application of AI technologies in cardiovascular disease, and the yellow and purple clusters represented the application of AI in diagnostic tools for cardiovascular diseases. In addition to cardiology and AI, "machine learning" and "deep learning" appeared most frequently. Popular topics that had emerged recently were "machine learning", "convolutional neural networks", and "deep learning" (**Figure 4**).

Discussion

In this study, an upward trend in the annual number of publications was indicated by the polynomial-fitting curve. It is worth noting that a turning point emerged in 2018, with a clear increase in interest in the application of AI in cardiology. The number of publications account-

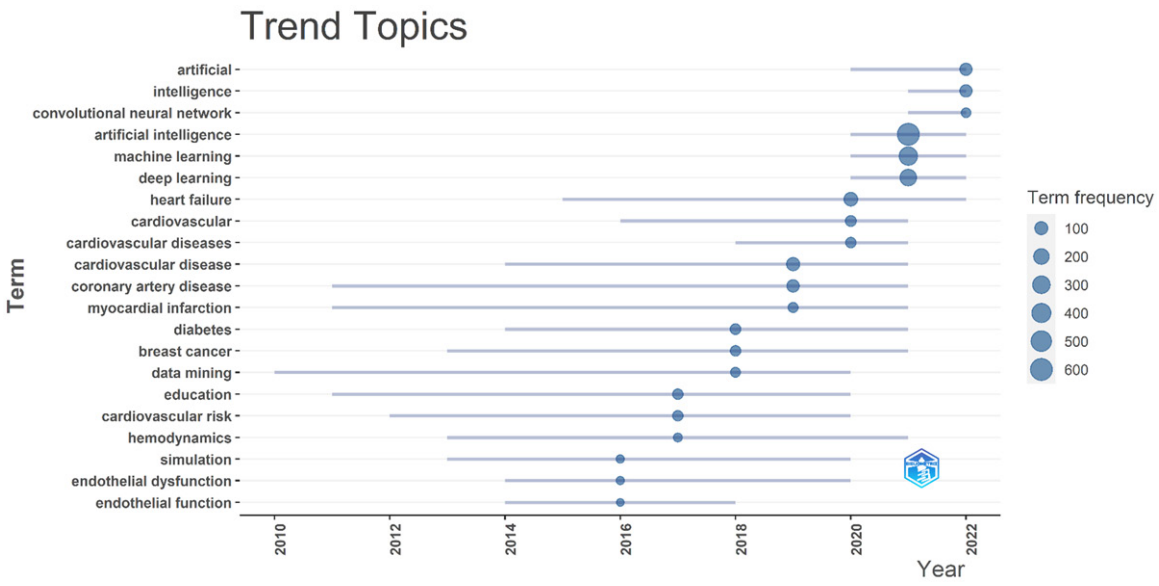

Figure 4. Trend of topics over time.

ed for 53.72% (2327/4332) of all included documents between 2018 and 2022. The explosion of AI application in the medical field has been largely attributed to its technological breakthroughs during this period [22]. The emergence of deep learning, machine learning, neural networks, speech recognition and autonomous robotics all offer unprecedented opportunities for disease diagnosis and management. Overall, the significant growth in annual publications is largely attributable to AI technology. Based on the current growth trend, it is reasonable to expect that there will be more annual publications in the future.

Researchers focusing on AI in cardiology are mainly from high-income countries, although people around the world are interested in this field. We found that United States, China, and United Kingdom published more than 50% of the total number of papers worldwide, suggesting that these countries are leaders in the field of AI in cardiology research. The United States has the highest number of publications, and six of the top 10 production units are from the United States. These findings suggest that United States has the largest number of elite institutions and professional researchers in the world. United Kingdom ranks first in the average citations of the publications, yet it has a lower number of publications compared to United States. These finding suggests that United States and United Kingdom have gone deeper into the field of AI in cardiology research. It is worth noting that close cooperation seems to be an important way to promote this research area. For example, the United States and China are the countries with the widest cooperation, and institutions in the United States also have cooperation relations with institutions in the United Kingdom. Therefore, the partnership may be beneficial to both sides and promote breakthroughs in this research area.

The top 10 most active journals are almost exclusively in cardiology and medical informatics. Most articles in this field were published in *Sensors*, *IEEE Access*, *PloS One*, and *Frontiers in Cardiovascular Medicine*, indicating that they are by far the most popular journals and that more future AI research on cardiology will be considered for publication in these journals. Among these journals, *Artificial Intelligence in Medicine* has the highest IF, followed by *Atherosclerosis*, *Computers in Biology and Medicine*, *Frontiers in Cardiovascular Medicine*, and *Scientific Reports*. Clearly, these journals are high-quality, authoritative journals that can provide the strongest support for AI research in cardiology.

AI-based algorithms are promising for promoting the development of the pharmaceutical field [23, 24]. The aim of co-citation analysis is to identify the recurring themes in different cat-

egories of research literature over time, and studies with high co-citation are usually regarded as the basis for research in a particular field [25]. We analyzed the co-cited references, and the results show that the current co-cited references mainly focus on the common technology of artificial intelligence, as well as the application of artificial intelligence in various aspects of cardiology. Keyword cluster analysis showed that the application of AI in cardiology has always been the hot focus of research. The trend topic analysis revealed that "machine learning" and "deep learning" have emerged frequently in recent years and therefore they were likely to be representative of current research hotspots and trends of AI in cardiology.

Some limitations must be acknowledged. First, despite the fact that Web of Science Core Collection has been rated as the most trustworthy database for bibliometric studies [19-21], it may add some source of bias to the current findings of this bibliometric study owing to the fact that PubMed, Embase, and Scopus databases are also available for scientific literature. In addition, other types of publications such as letters, comments and conference abstracts were excluded from this study, and this exclusion may have resulted in the omission of some hotspots.

Conclusion

Enhancing cooperation between different countries and institutions is a critical step in leading to breakthroughs in the application of AI in cardiology research. It is foreseeable that the application of machine learning and deep learning in various areas of cardiology will be a research priority in the coming years.

Acknowledgements

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Disclosure of conflict of interest

None.

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Table S1. The top 10 productive countries/regions

Ranking	Country/Region	Publications	% of (4332)	Total citations	Average citations
1	United States	1400	32.32	38,596	27.57
2	China	523	12.07	5,685	11.21
3	United Kingdom	368	8.49	12,576	34.17
4	Germany	315	7.27	9,814	31.16
5	Italy	259	5.98	6,283	24.26
6	Japan	234	5.40	5,788	24.74
7	Canada	217	5.00	5,414	24.95
8	Spain	195	4.50	4,276	21.93
9	Australia	189	4.36	5,953	31.50
10	India	187	4.32	2,263	12.10

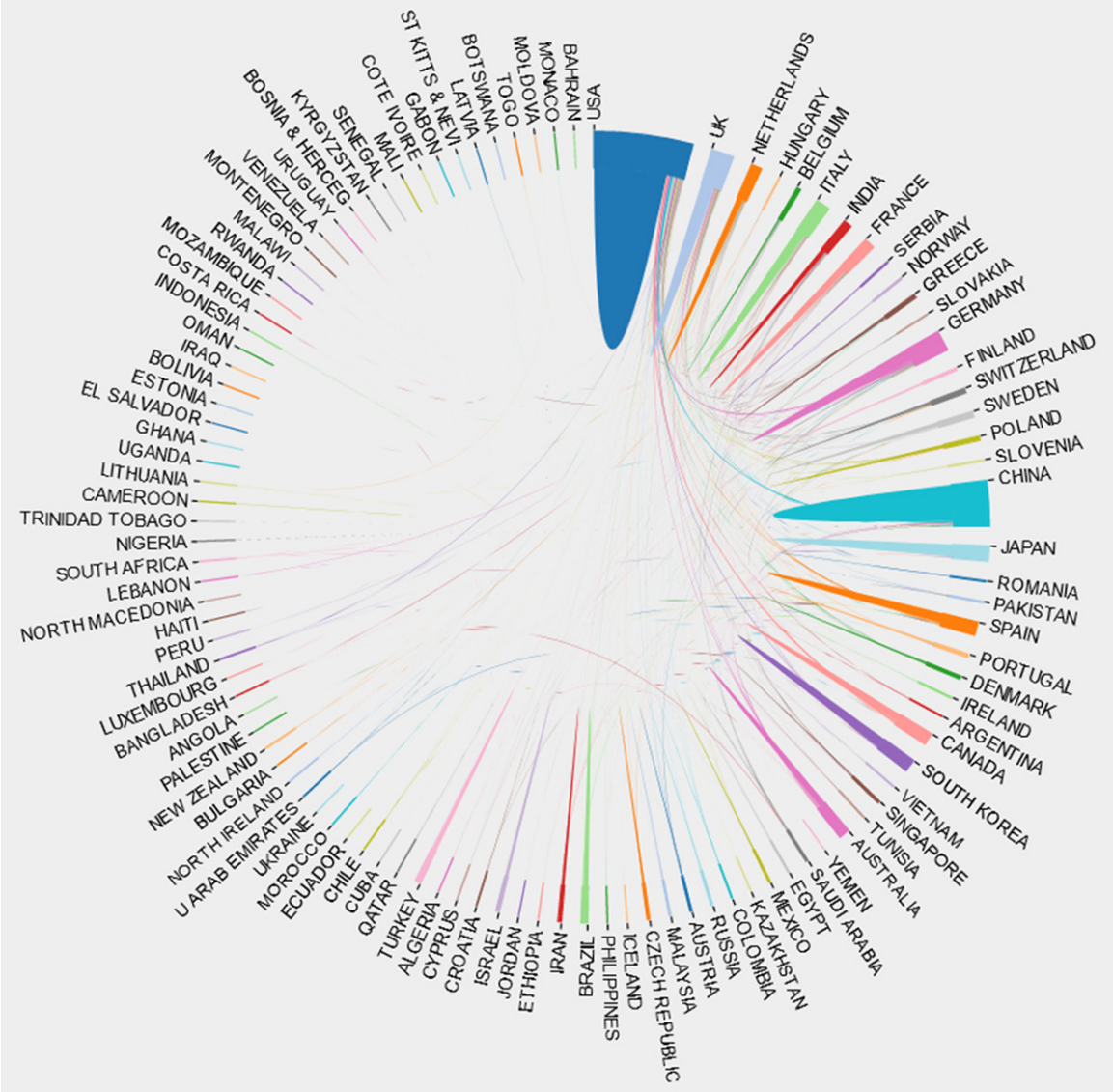

Figure S1. International collaboration between countries/regions.

Table S2. The top 10 productive affiliations

Ranking	Affiliation	Country	Publications	Total citations	Average citations
1	Harvard University	United States	134	6,364	47.49
2	University of California System	United States	121	4,824	39.87
3	University of London	United Kingdom	115	4,137	35.97
4	Udice French Research Universities	France	94	4,126	43.89
5	Mayo Clinic	United States	87	1,969	22.63
6	Harvard Medical School	United States	84	3,813	45.39
7	University College London	United Kingdom	59	2,780	47.12
8	Institut National de la Sante et de la Recherche Medicale	France	57	1,216	21.33
9	Johns Hopkins University	United States	55	2,083	37.87
10	Pennsylvania Commonwealth System of Higher Education	United States	55	1,542	28.04

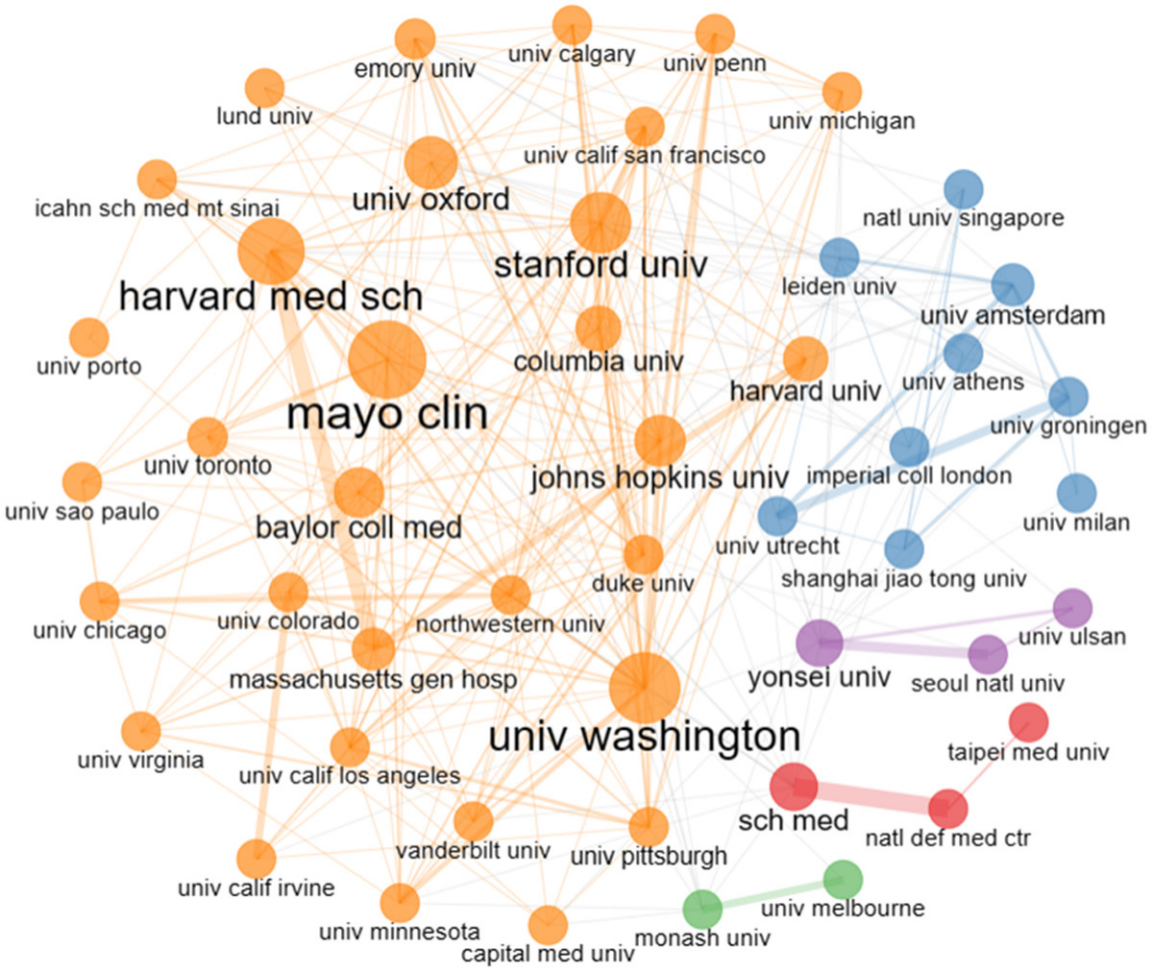

Figure S2. Collaboration between affiliations.

Table S3. The top 10 productive authors

Ranking	Author	Country	Publications	Total citations	Average citations	H-index
1	Friedman PA	United States	29	1,070	36.90	10
2	Noseworthy PA	United States	27	949	39.54	10
3	Zhang Y	China	24	949	39.54	10
4	Attia ZI	United States	23	997	43.35	9
5	Lopez-Jimenez F	United States	23	1,039	45.17	9
6	Kapa S	United States	17	945	55.59	8
7	Li Q	China	17	301	17.71	10
8	Lin CS	China	17	103	6.06	6
9	Zhang L	China	17	152	8.94	7
10	Paek J	Korea	16	441	27.56	9

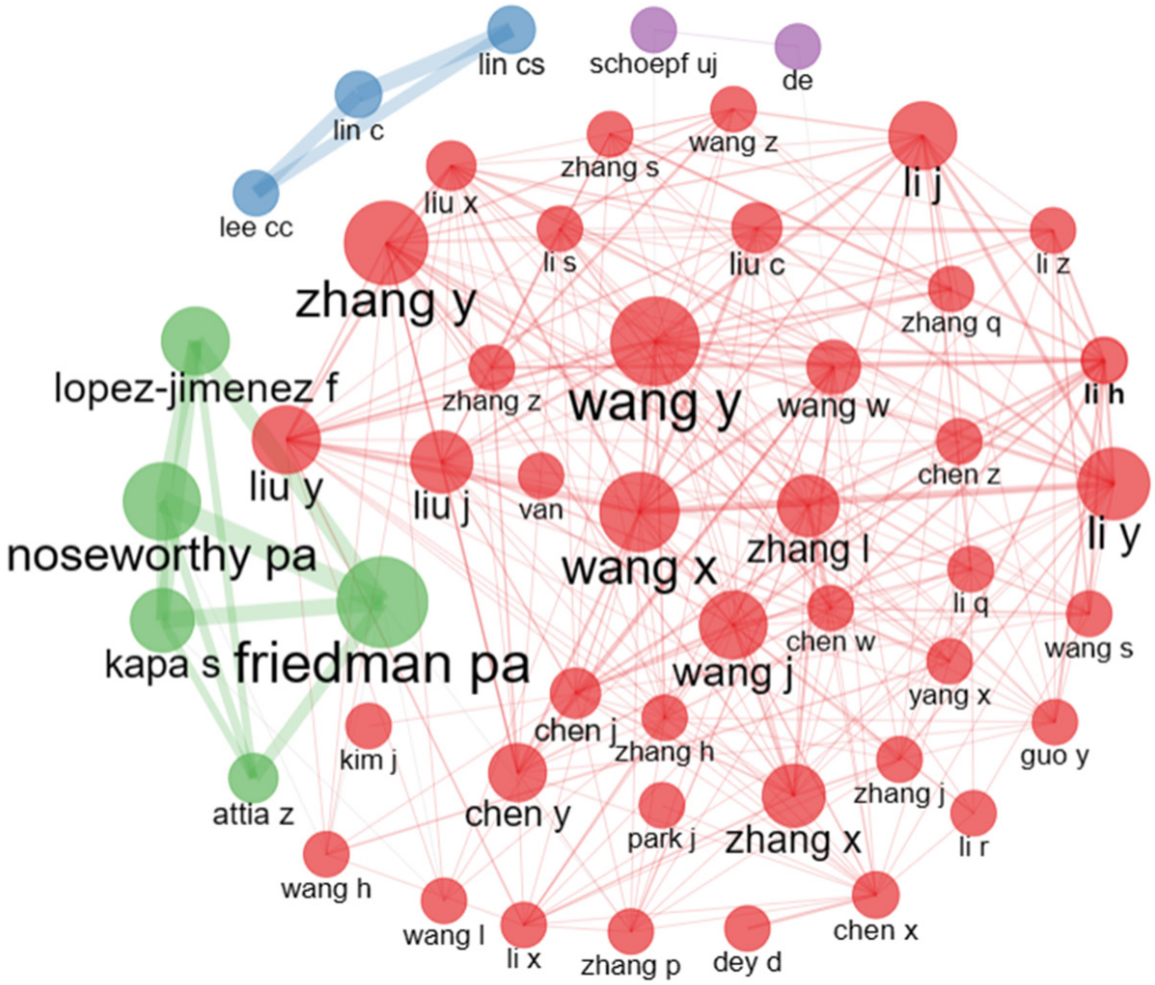

Figure S3. Collaboration between authors.

Table S4. The top 10 most active journals

Ranking	Journal	Publications	Total citations	Average citations	2021 IF
1	*Sensors*	62	537	8.66	3.847
2	*IEEE Access*	60	1,343	22.38	3.476
3	*PloS One*	59	1,773	30.05	3.752
4	*Frontiers in Cardiovascular Medicine*	54	123	2.30	5.848
5	*Computers in Biology and Medicine*	39	566	14.51	6.698
6	*Scientific Reports*	38	348	9.16	4.997
7	*Atherosclerosis*	36	1,129	31.36	6.851
8	*American Journal of Hypertensions*	29	936	32.28	3.076
9	*Applied Sciences-Basel*	29	128	4.41	2.838
10	*Artificial Intelligence in Medicine*	28	723	25.82	7.011

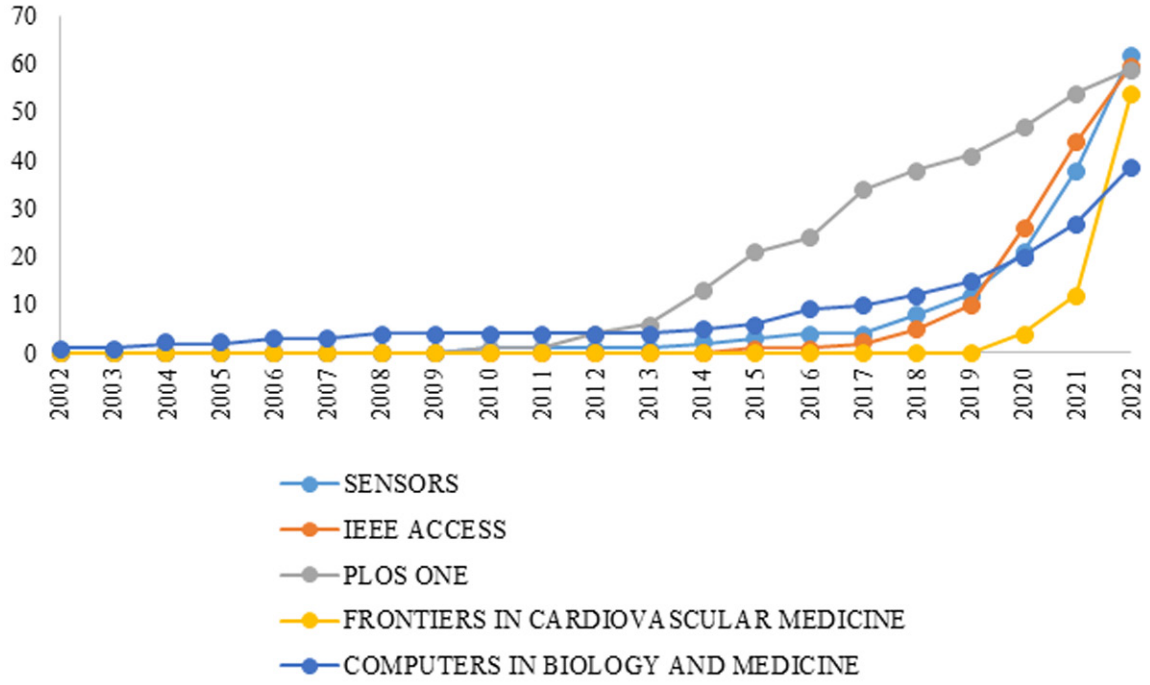

Figure S4. Publications of the top 5 most active journals over time.