RESEARCH ARTICLE

Global Cluster Analysis and Network Visualization in Prosthetic Joint Infection: A Scientometric Mapping

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Objective: Prosthetic joint infection (PJI) is the main reason of failure of total joint arthroplasty (TJA). This study aimed to investigate the global trends and network visualization in research of PJI.

Methods: Publications in PJI search during 1980–2022 were extracted from the Science Citation Index-Expanded of Web of Science Core Collection database (WoSCC). The source data was investigated and analyzed by bibliometric methodology. For network visualization, VOS viewer and R software was used to perform bibliographic coupling, co-citation, co-authorship and co-occurrence analysis and to predict the publication trends in PJI research.

Results: There were 7288 articles included. The number of publications and relative research interests increased gradually per year globally. The USA made the highest contributions in the world and with the highest H-index and the most citations. *Journal of Arthroplasty* published the highest number of articles in this area. The Mayo Clinic, Thomas Jefferson University (Rothman Institute), Hospital Special Surgery and the Rush University were the most contributive institutions by network visualization. Included studies were divided into four clusters: bacterial pathogenic mechanism and antibacterial drugs study, TJA complications, risk factors and epidemiology of PJI, diagnosis of PJI, and revision surgical management. More articles in PJI could be published over the next few years.

Conclusion: The number of publications about PJI will be increasing dramatically based on the global trends and network visualization. The USA made the highest contributions in PJI. Diagnosis and revision management may be the next hot spots in this field.

Key words: Bibliometrics; Global trend; Prosthetic joint infection; Total joint arthroplasty; Visualized study

Introduction

Total joint arthroplasty (TJA) is commonly recommended as the final line in treating end-stage degenerative joint disease, such as osteoarthritis or rheumatoid arthritis. TJA, typically in the knee or hip, are relatively cost-effective surgical procedures, which remove the source of joint pain and allow joint mobility and function to be restored for hundreds of millions of patients globally.[1–4] The total number of total knee arthroplasty (TKA) is expected to increase by 45% from 2016 to 2040 in Germany. During the same period, the number of total hip arthroplasty (THA) will be increased by 23%.[5] The projected percentage in annual US use for TKA and THA in 2040 will be 401% and 284%, respectively.[6] Over the past decades, major advances have been made in improving TJA surgical techniques, which resulted in increased implant longevity. Despite improvements in patient outcomes, however, more and more arthroplasty revisions are performed for infection, fracture, loosening

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and, in hips, dislocation.[7] Prosthetic joint infection (PJI) is the main reason of revision TJA, which constitute main cause of failure of THA and TKA in 15% and 25% of cases, respectively.[8,9] The prevalence of PJI has not reduced with advances in implant and surgical technology, and cases of PJI have continued to rise with an increasing rate of primary TJA. Currently, the incidence of PJI were reported between 1% and 3% in primary TJA and between 3% and 10% in revision TJA.[7,10,11] The number of PJI will be increased to 10,000 cases/year at 2030.[7]

PJI is a devastating and possibly life-threatening complication of TJA, which can often lead to implant failure and other problems. Even if treatable, PJI can have a variety of deleterious consequences including longer hospital stay, increased burden for the healthcare system, and high morbidity.[12–15] Thus, PJI has been a popular research area worldwide. Many research aspects in PJI are the focus of research, including risk factors,[16,17] pathogenesis and causative microorganisms,[18] diagnostic[19,20] and managements.[21–23] 23 However, the current state of research in this area and global trends have not yet been studied in detail.

As a primary outlet of research findings, publications indicate the contributions of global authors, countries, and academic institutions within most fields of research. Network visualization analysis is a quantitative method which uses statistical tools to investigate the relationships and impacts of publications in a certain research field.[24,25] This methodology has been utilized successfully to predict research focus and global trends in some fields, including knee surgery,[26] trauma,[27] COVID-19[28] and Parkinson's disease.[29] In this study, we constructed a network map using bibliometric tools to identify the relationships of authors, countries, and institutions for research on PJI. We also performed co-authorship, co-citation, co-occurrence and bibliographic coupling analyses, and made predictions of global research trends in this area including current areas of intense investigation.[30] Through these analyses, we provide a comprehensive evaluation into the current global trends and network relationship of PJI, which may provide scientists and clinicians with better understanding of the biggest players in the study fields.

Materials and Methods

Data Source

In this study, publications on PJI were extracted from Science Citation Index-Expanded of Web of Science Core Collection database (WoSCC). This database is considered the optimal database for network visualization, which covers over 12,000 international scientific journals of high impact and quality, and provides comprehensive data on the selected publications.

Search Strategy and Selection Criteria

Searches were conducted in the WoSCC database during 1 January 1980–31 March 2022. The query for items search was: (theme = prosthetic joint infection OR theme = periprosthetic infection NOT theme = fracture). All identified publications were in English.

Included articles were any article type and related to aspects of prosthetic joint infection, including epidemiology, risk factors, surgery, outcomes, complications, antibiotics, debridement, revision. Excluded articles were assessed to be not related to prosthetic joint infection (e.g., false positive data). Two reviewers independently read the title and abstracts of all searched publications, included the articles that met the selection criteria, and excluded the articles not related to prosthetic joint infection. Disagreements were reconciled by a third reviewer to reach consensus. We also excluded clinical studies or trials published only as abstracts, where no additional data was available from other sources.

Data Collection

Following a comprehensive search, publications were saved as "Plain Text" with "Full Record and Cited References." Publication information from all eligible documents was collected from the database, including title, author information, abstract, keywords, publication year, countries, affiliated institutions, and journal. Two authors screened and extracted the data independently.

Bibliometric Analysis

The characteristics of included studies were analyzed and summarized by bibliometrix package of R software (vision 4.0.3; https://cran.r-project.org).[31] This analysis displayed important bibliometric information about the bibliographic data, including annual scientific production, top cited manuscripts, top productive authors, top productive countries, total citations per country, top relevant journals, and top relevant keywords. The H-index is determined by the scholar/country's most cited papers, and the average number of citations that they have received in other publications.[32,33] The time trend of publications was plotted using the ggplot2 package of R software. The following three-parameter logistic model, $F(x) = a/[1 + b \times exp(-cx)]$, was utilized to fit and predict the cumulative number of publications.

Visualized Analysis

The network analysis of publications was conducted viaVoS viewer (Leiden University, Leiden, the Netherlands), which included co-authorship, co-citation, co-occurrence, and bibliographic coupling analysis.[34] A map of the number of publications in different countries was drawn using ggplot2 package of R software.

Results

Characteristics of Included Studies

There were 7288 included publications on PJI retrieved from WoSCC using the search terms, which were published between 1980 and 2022. These retrieved publications had a total of 164,708 citations, and 22.6 average citations per

document. There was a total of 6429 keywords contained within the publications, as well as 21,807 authors which appeared a total of 42,537 times.

Analysis of Global Publications

The rate of increase in global publications on PJI was low and steady from 1990 to 2005. After 2005, the field saw a rapidly rising trend in the number of publications annually, increasing from eight in 1990 to 879 in 2021. The highest number of research studies in this area occurred in 2021 (Fig. 1A).These results indicated increasing research interest in PJI over the last 3–4 decades. The three-parameter logistic model $F(year) = 1687/[1 + 2020 \times \exp(-4.85 \times year)]$ well fitted the annual number of studies on PJI (red points). The annual number of studies predicted to occur in the next 30 years was also indicated (blue points) (Fig. 1B). According to predictive plot, the cumulative number of publications will increase the fastest between 2015 and 2025. After 2035, there will be an increment plateau of annual number of publications (Fig. 1B).

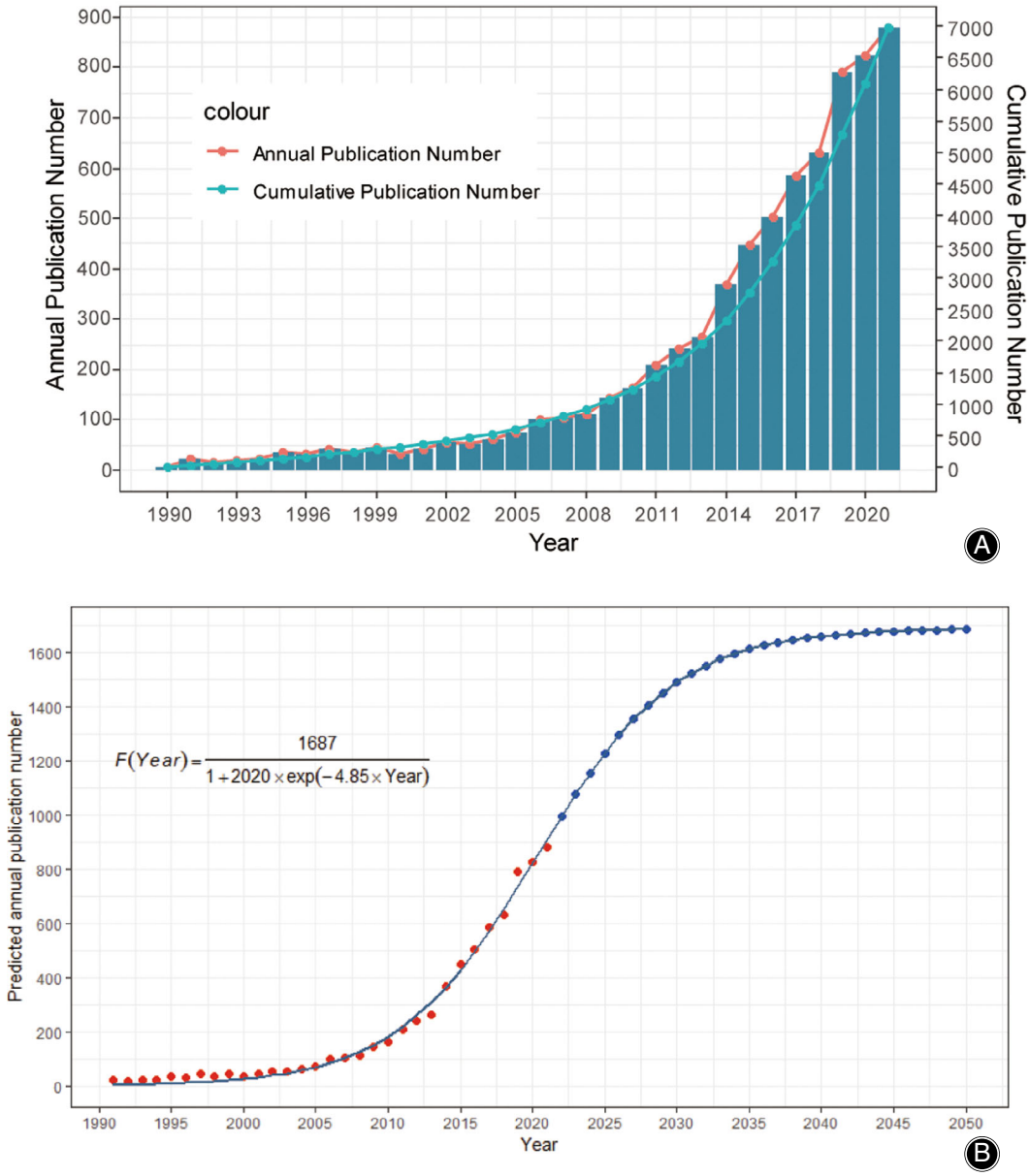

Fig. 1 Global trends of PJI research. (A) The global annual publication number and cumulative number of publications related to PJI research. The red line indicated the single-year publication numbers, and the blue line indicated cumulative number of publications. (B) Model fitting curves of growth trends in worldwide publications on applications to predict number of publications in the future. PJI, prosthetic joint infection

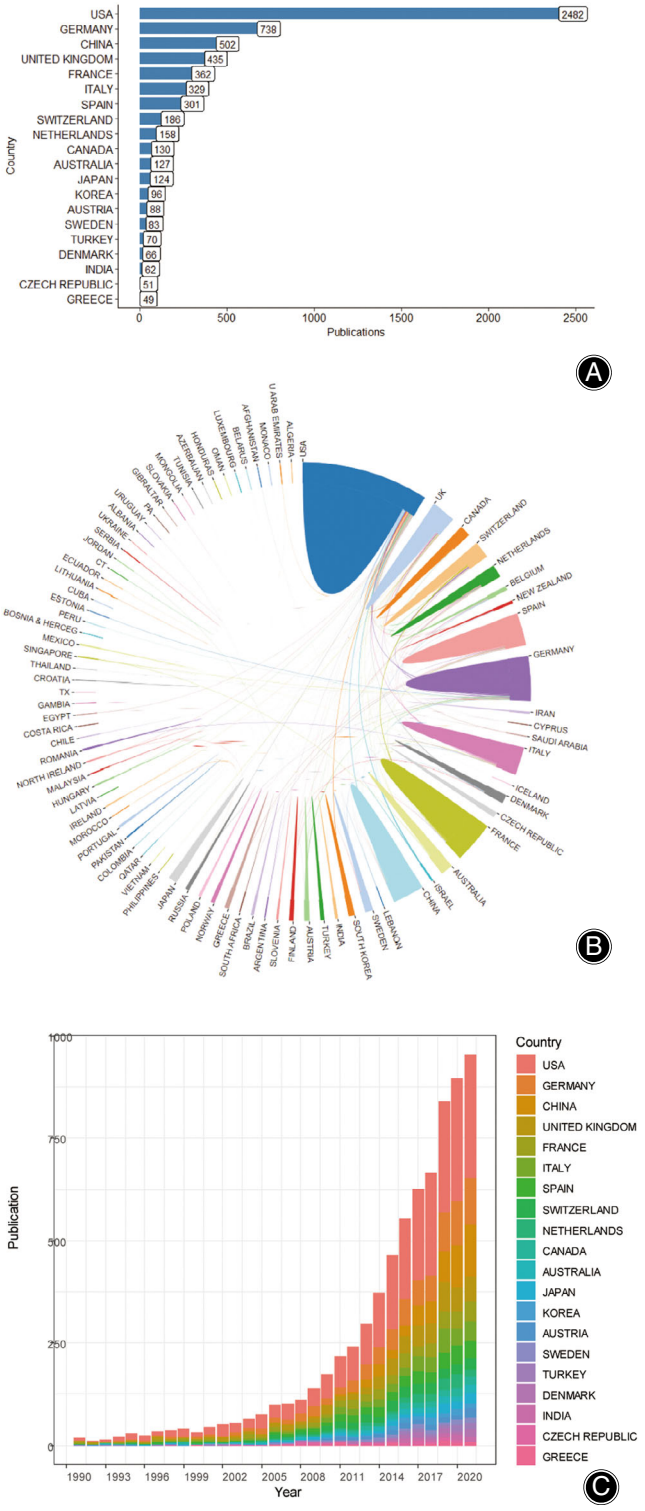

Fig. 2 Countries contributing to PJI research. (A) The sum of PJI research related articles from the top 20 countries. (B) Countries collaboration was the most significant between the USA and Germany, followed by that between the USA and France. (C) The publication proportion of top 20 countries for each year was demonstrated. PJI, prosthetic joint infection

Contributions of Countries

There were 71 countries or regions which published research on PJI worldwide, with the top 20 countries indicated in Fig. 2A. The US was the highest contributor (2031 publications, 33.7%), followed by Germany (634, 10.5%), China (413, 6.86%), and United Kingdom (366, 6.08%). Figure 2B shows that the collaboration between the US and Germany, followed by that between the US and France, occurred frequently. The publication numbers of top 20 countries were demonstrated by years (Fig. 2C).

Total Citation Number and H-index

As shown in Fig. 3A, The USA had the highest number of total citations (79,694), followed by the UK (11,838), Germany (11,762), Switzerland (8607), and France (6076). When ranked by H-index, the USA came first (125) followed by the UK (67), Germany (57), Switzerland (54) and France (43), which matched the ranking order based on total number of citations.

Institutions

Among the top 20 institutions publishing on PJI, Mayo Clinic produced the highest number of studies (537 papers), followed by the Thomas Jefferson University (Rothman Institute) (284 papers), Hospital Special Surgery (145 papers) and the Rush University (142 papers) (Fig. 3B).

Journals

The highest number of articles on PJI was published in *Journal of Arthroplasty* published (755), followed by *Clinical Orthopaedics and Related Research* (372), *Journal of Bone and Joint Surgery-American Volume* (263), *Bone & Joint Journal* (234), and *International Orthopedics* (153). The top journals publishing articles on PJI are shown in Fig. 3C. The cumulative number of studies published by the top 10 journals on PJI displayed a gradually rising trend for all journals particular after 2010. The *Journal of Arthroplasty* showed exponential growth in the number of studies in PJI (Fig. 3D).

Authors

As shown in Fig. 4A, top 20 authors with the highest number of studies on PJI had a total of 1710 articles among them, accounting for 23.5% of all included literature in this field. Of these, Parvizi had the largest number of published papers (302), followed by Trampuz (120), Patel (107), and Osmon (100). Parvizi also had the largest number of total citations (17,867), followed by Osmon (9427), and Zimmerli (7626). The number of publications and total citations per year (as reflected by size of circles) for each of the top 20 authors over time is shown in Fig. 4B.

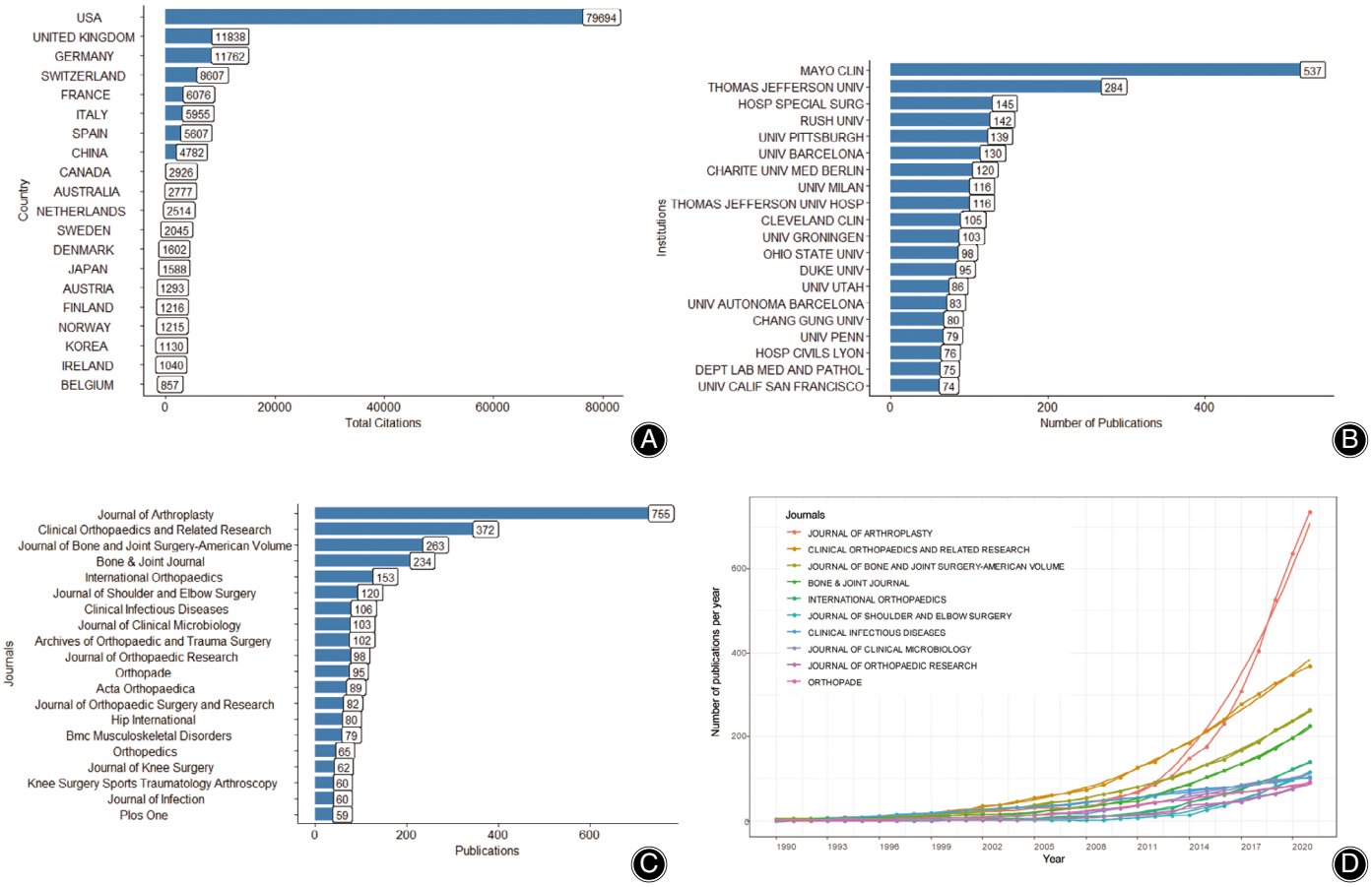

Fig. 3 Citation frequency of different countries, publication number of institutions and journals and trends of PJI research of journals. (A) The total citations for PJI research articles from different countries. (B) Publication number of top 20 institutions. (C) Publication number of top 20 journals. (D) The cumulative number of articles published by the top 10 journals on PJI per year indicated a rising trend for all journals after 2010. PJI, prosthetic joint infection

Bibliographic Coupling Analysis

Journals

Bibliographic coupling analysis, aiming to detect a similarity relationship between studies, was conducted based on the number of references they shared. Two studies will be bibliographically coupled, if they cite a set of the same sources. Bibliographic coupling analysis could be used to generate a knowledge relationship map of research institutions, journals and countries in a research area, demonstrating the collaboration network in that field.[31] As shown in Fig. 5A, there were 223 identified journals presented with their total link strength (TLS). The following top five journals with the largest TLS included *Journal of Arthroplasty* (TLS = 1,055,749 times), *Clinical Orthopedics and Related Research* (TLS = 466,816 times), *Journal of Bone and Joint Surgery-American Volume* (TLS = 356,809 times), *Bone & Joint Journal* (TLS = 288,702 times), and *International Orthopedics* (TLS =241,687 times).

Institutions

As shown in Fig. 5B, 671 institutions were identified which had published a minimum of five papers on PJI. The top five institutions with the largest TLS based on bibliographic coupling analysis were: Mayo Clinic (TLS = 859,437 times), Thomas Jefferson University (Rothman Institute) (TLS = 792,035 times), Rush University (TLS = 406,152 times), Thomas Jefferson University Hospital (TLS = 378,205 times), and Charité – Universitätsmediz in Berlin (TLS = 372,673 times).

Countries

A total of 57 countries were identified with a minimum five publications on PJI (Fig. 5C). The top five countries with the largest TLS were as follow, USA (TLS = 3,495,154 times), Germany (TLS = 1,720,611 times), the UK (TLS = 981,571 times), Spain (TLS = 896,637 times), and China (TLS = 897,601 times).

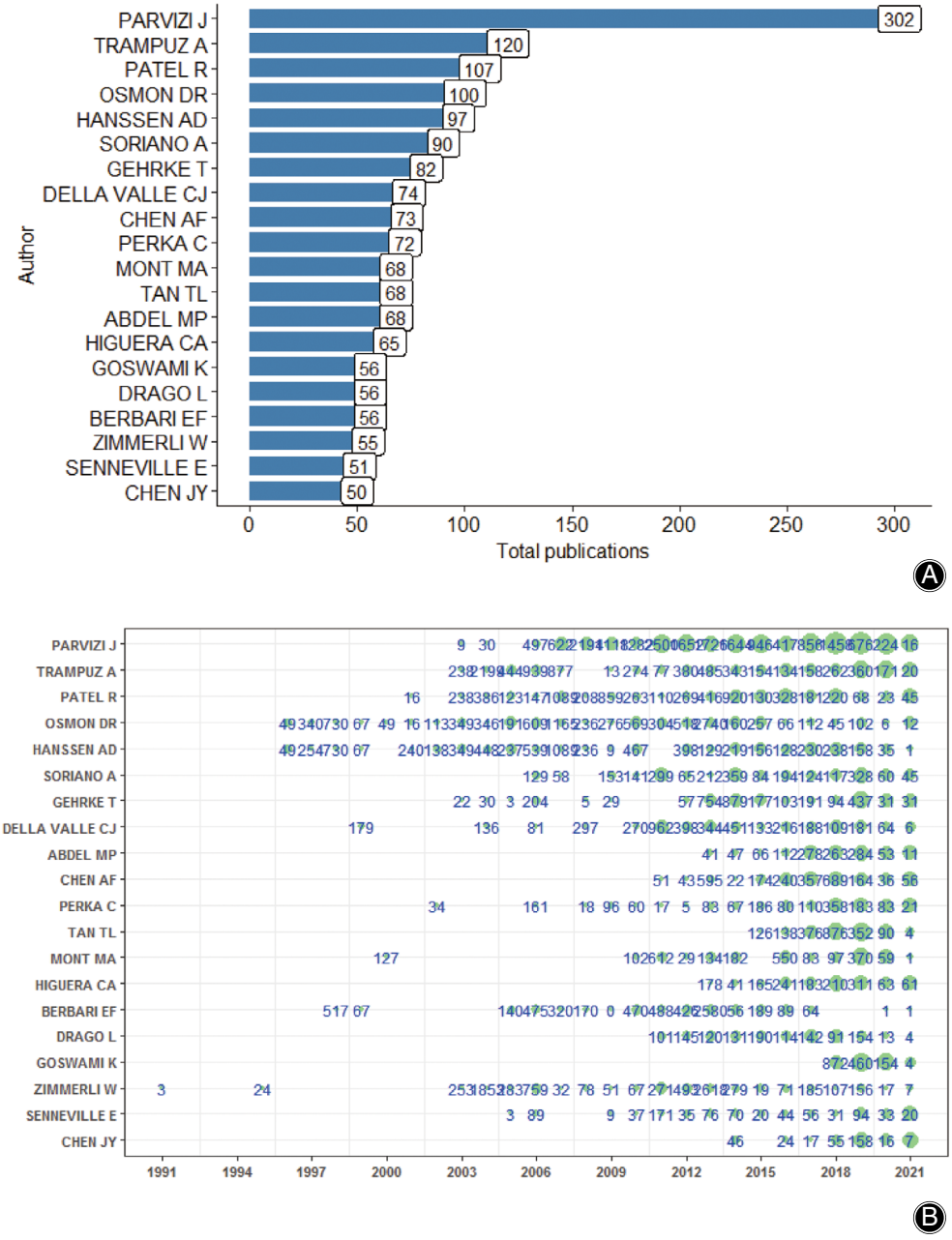

Fig. 4 High contribution authors of global research about PJI. (A) The high impact authors in the world. Parvizi also had the highest number of number of publications on PJI. (B) The number of publications and total citations per year for each of the top 20 authors over time. The total citations per year was reflected by size of circles. PJI, prosthetic joint infection

Co-authorship Analysis

Co-authorship analysis provided a vision of cooperation patterns among organizations, which was used to assess scientific collaboration patterns in a specific field. For investigating co-authorship, nodes (representing authors, countries or institutions) were connected, indicating they sharing the authorship the same study.[30]

Authors

There were 1095 authors contributed a minimum five publications on PJI were identified (Fig. 6A). The top five authors with the largest TLS were as following, Parvizi (TLS = 849 times), Osmon (TLS = 286 times), Patel (TLS = 271 times), Tan (TLS =268 times), and Soriano (TLS = 264 times).

Institutions

As shown in Fig. 6B, the 671 institutions which published at least five papers on PJI showed largest TLS based on co-authorship analysis for: Thomas Jefferson University (Rothman Institute) (TLS = 279 times), The Mayo Clinic (TLS = 252 times), Rush University (TLS = 229 times), Barcelona University (TLS = 206 times), and Charité – Universitätsmedizin Berlin (TLS = 200 times).

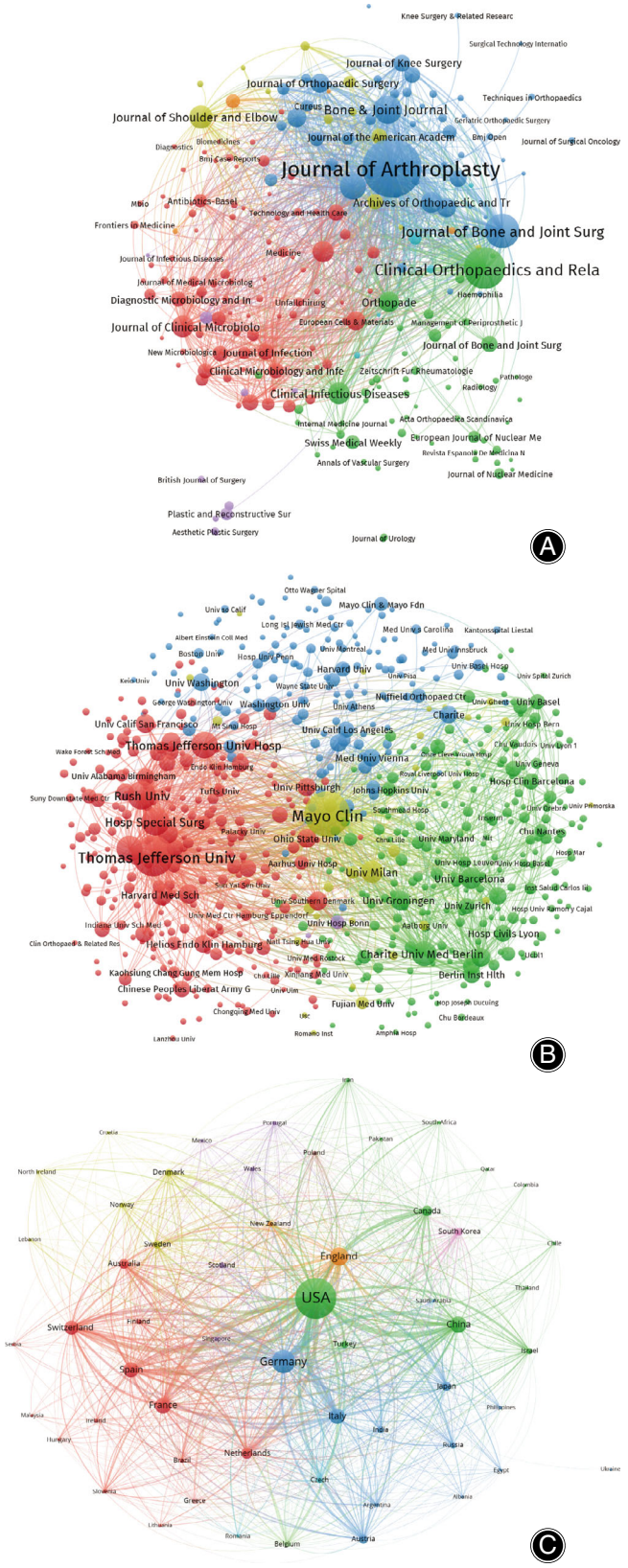

Fig. 5 Bibliographic coupling analysis of global research about PJI. (A) Mapping of the 223 identified journals on PJI. (B) Mapping of the 671 institutions on PJI. (C) Mapping of the 57 countries on PJI. The line between two points in the Figure represents that two journals/institutions/countries had establish a similarity relationship. The thicker the line, the closer the link between the two journals/institutions/countries. PJI, prosthetic joint infection

Countries

As shown in Fig. 6C, a total of 56 countries with at least five publications on PJI indicated the top countries with the largest TLS, namely USA (TLS = 715 times), Germany (TLS = 494 times), UK (TLS = 404 times), Switzerland (TLS = 312 times), and Italy (TLS = 302 times).

Co-citation Analysis

Co-citation is the frequency by which two documents are cited together by other documents. The more co-citations shared between two studies, the higher co-citation strength, and therefore the more likely that they are related.

Publications

As shown in Fig. 7A, a total of 1670 publications which have been cited a minimum of 20 times were identified for co-citation analysis. The top five publications with greatest TLS included Zimmerli *et al.* (TLS = 18,968 times), Osmon *et al.* (TLS = 16,479 times), Parvizi *et al.* (TLS = 12,847 times), Trampuz *et al.* (TLS = 12,456 times), and Kurtz *et al.* (TLS = 10,434 times).

Journals

As shown in Fig. 7B, a total of 951 journals were identified with references that were cited at least 20 times. The top five journals with the largest TLS by co-citation analysis were: *Clinical Orthopedics and Related Research* (TLS = 975,090 times), *Journal of Arthroplasty* (TLS = 839,818 times), *Journal of Bone & Joint Surgery-American Volume* (TLS = 813,161 times), *Clinical Infectious Diseases* (TLS = 415,596 times), and *Bone & Joint Journal* (TLS =362,090 times).

Co-occurrence Analysis

Co-occurrence analysis is conducted based on the relationship among some aspects, such as research fields. This study is performed according to the number of publications in which they occur together. The goal of this analysis is to track scientific development within particular fields and understand the most researched topic areas.

As shown in Fig. 8 A and B in different colors, the 1132 keywords arising from the included publications could be classified into four clusters: "bacterial pathogenic mechanism and antibacterial drugs study (red)," "TJA complications, risk factors and epidemiology of PJI (green),"

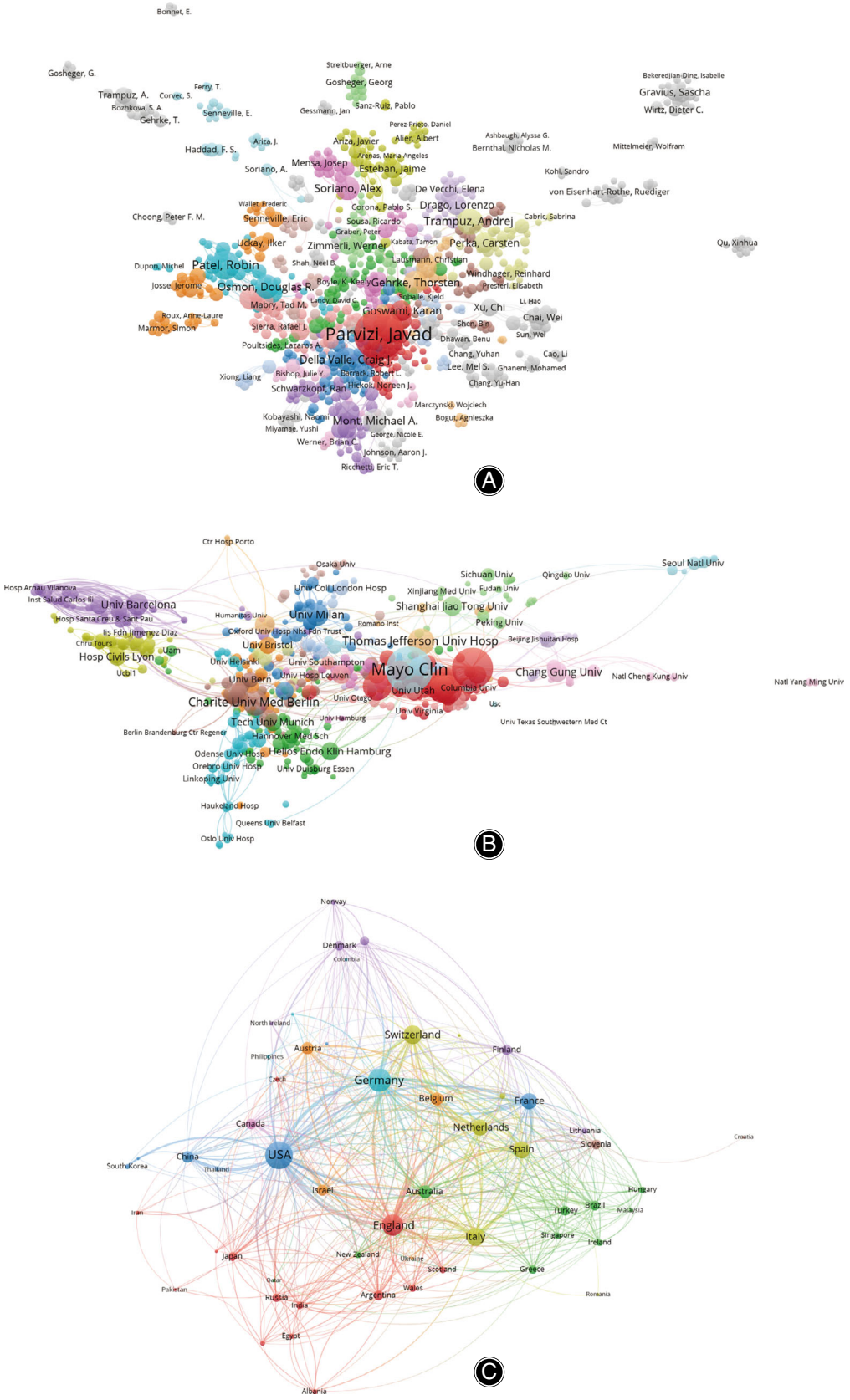

Fig. 6 Co-authorship analysis of global research about PJI.
(A) Mapping of the 1095 authors co-authorship analysis on PJI.
(B) Mapping of the 671 institutions co-authorship analysis on PJI.
(C) Mapping of the 56 countries co-authorship analysis on PJI. The size of the points represents the co-authorship frequency. The line between two points in the Figure represents that two authors/institutions/countries had establish collaboration. The thicker the line, the closer the collaboration between the two authors/institutions/countries. PJI, prosthetic joint infection

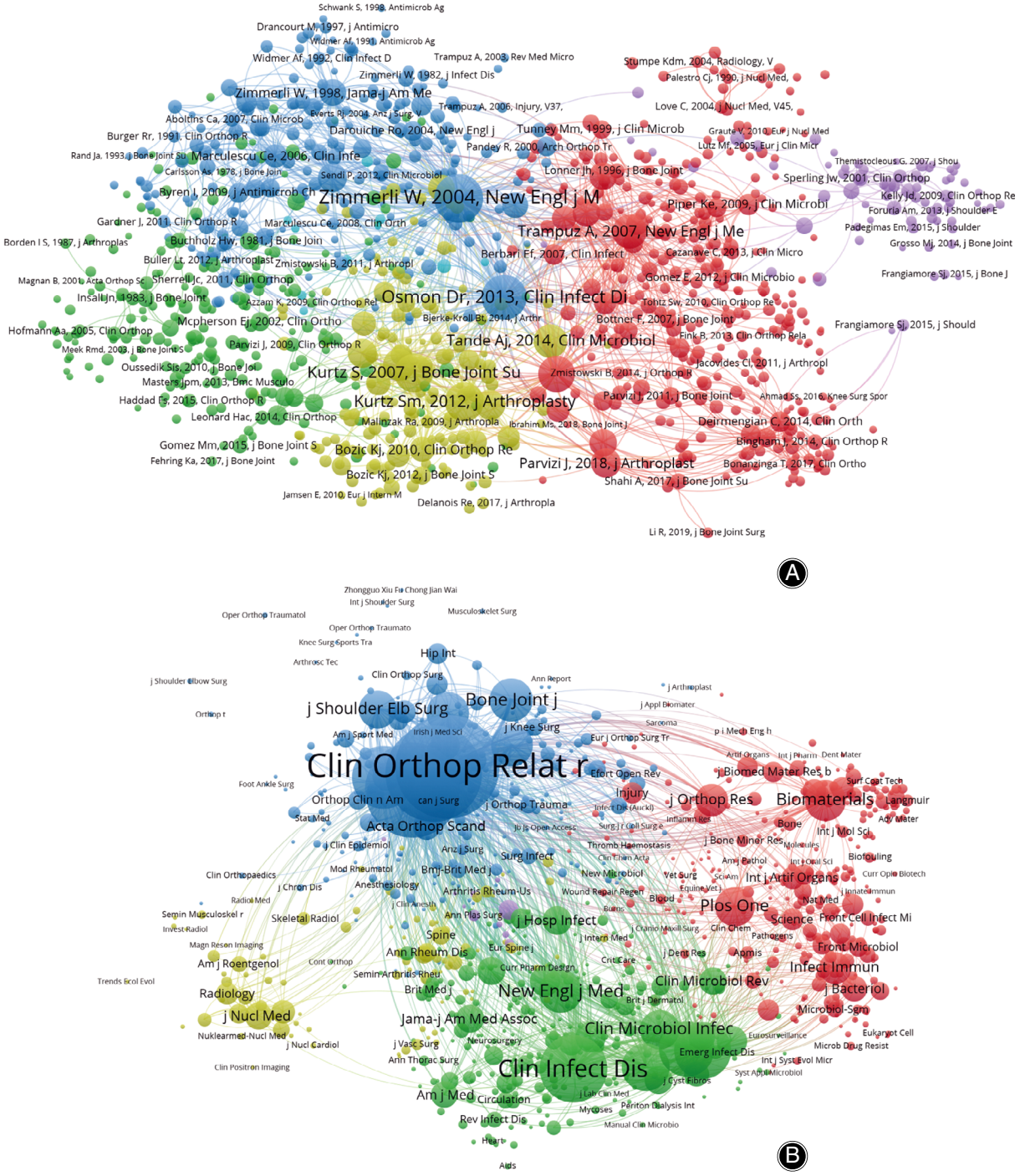

Fig. 7 Mapping of co-citation related to PJI. (A) Mapping of co-cited references related to the field. (The different colors represent the 1670 cited references. The size of the points represents the citation frequency. A line between two points means that both were cited in one paper. A shorter line indicates a closer link between two papers. Points in the same color belong to the same research direction.) (B) Mapping of co-cited journals related to the field. (The different colors represent the 951 identified journals. The size of the points represents the citation frequency. A line between two points means that both were cited in one journal. A shorter line indicates a closer link between two journals. Points in the same color belong to the same research direction.) PJI, prosthetic joint infection

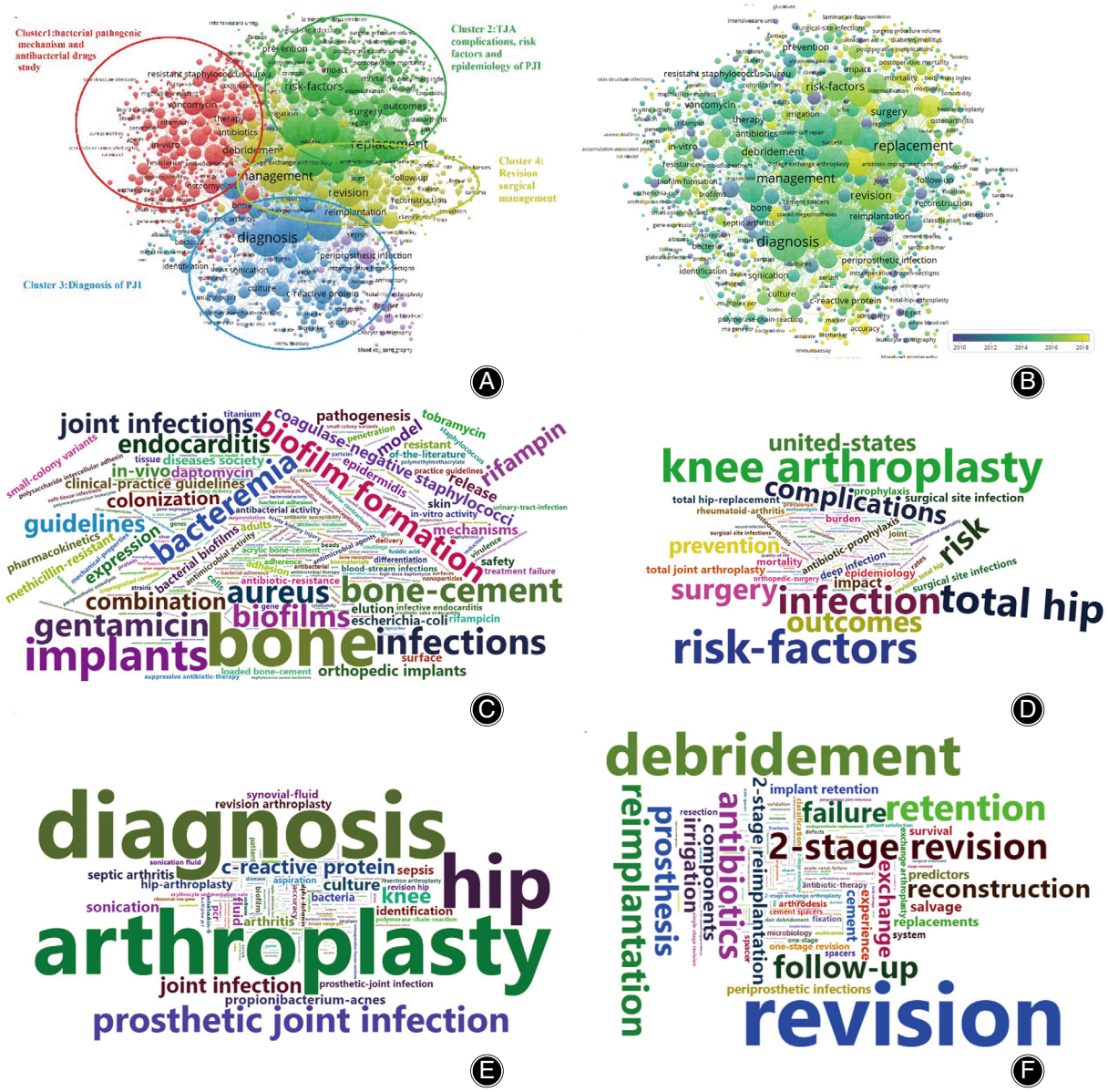

Fig. 8 Co-occurrence analysis of global research about PJI. (A) Mapping of keywords in the research on PJI; the size of the points represents the frequency, and the keywords are divided into four clusters: bacterial pathogenic mechanism and antibacterial drugs study (red), TJA complications, risk factors and epidemiology of PJI (green), diagnosis of PJI (blue), and revision surgical management (yellow). (B) Distribution of keywords according to the mean frequency of appearance; keywords in blue appeared earlier than those in yellow and red colored keywords appeared later. (C) The frequency of individual keywords in bacterial pathogenic mechanism and antibacterial drugs study. (D) The frequency of individual keywords in TJA complications, risk factors and epidemiology of PJI. (E) The frequency of individual keywords in diagnostic of PJI. (F) The frequency of individual keywords in revision surgical management. These keyword clusters demonstrated the most popular areas of research on PJI to date in four clusters. TJA, total joint arthroplasty, PJI, prosthetic joint infection

"diagnosis of PJI (blue)," and "revision surgical management (yellow)."

The frequency of individual keywords in each cluster were organized by the year of appearance instead of topic area. In the "bacterial etiology and antibacterial drugs study" cluster, the main keywords were biofilms, staphylococcus-aureus, resistance staphylococcus-aureus, rifampin, therapy, and bacteremia (Fig. 8C). In the "TJA complications, risk factors and epidemiology of PJI" cluster, the main keywords were risk-factors, complications, outcomes, surgery, infection, and epidemiology (Fig. 8D).In the "diagnostic of PJI" cluster, the main keywords were C-reactive protein,

sonication, culture, fluid, identification, and PCR (Fig. 8E). In the "revision surgical management" cluster, the main keywords were management, antibiotics, debridement, revision, 2-stage revision, retention, reimplantation, components, and irrigation (Fig. 8F).These keyword clusters demonstrate the most popular areas of research on PJI to date.

Discussion

Global Trends in PJI Research

This study presented the global status of a research field, as well as making predictions for future developments in related areas. In this study, we evaluated PJI research using these tools and illustrated the current global trends according to the publications, contributing countries/regions, institutions, journals, authors, and topic areas. Significant progress has been made in this field over the last 40 years, with contributing publications from a total of 71 countries and increasing publication and citation trends. Based on the predication data, this field should see a continued increase in publications over the next 30 years.

Quality and Status of Global Publications in PJI

In present study, the US made the largest sum of contributions to PJI globally. This was commonly followed by the UK, Germany and Switzerland in various orders. Other countries which also made significant contributions to the field and ranked within the top 10 included France, Spain, Italy, and China. In general, countries/regions with publications on PJI which attracted a high number of citations were from North America, Europe, and some areas of the Asia-Pacific such as China and Australia.

The top journals demonstrated the strongest link strength through various analyses were *Journal of Arthroplasty*, *Clinical Orthopedics and Related Research*, *Journal of Bone and Joint Surgery-American Volume*, *Bone & Joint Journal*, and *International Orthopedics*, which may represent the most relevant publication outlets in this field. The top 20 journals in this field with the greatest contribution accounted for 41.7% of all studies included in the present study. These high-quality journals might be the main routes for publishing new findings on PJI.

Among the top 20 contributing institutions to PJI research, almost all were from the top 10 countries. Over 50% of these institutions were in the US. These leading research institutions in PJI research are perceived to improve their country's academic reputation in the field. Among the top contributing authors, Parvizi, Trampuz, and Patel were consistently highlighted from various types of analyses, who may represent the major figures in PJI research and whose work may be seen to lead the latest developments in the field.

The results of visualized network analyses corroborated each other. The top contributors as indicated by bibliometric analyses were mostly replicated through the visualized analyses. For instance, the USA, *The Journal of Arthroplasty*, Parvizi, and Mayo Clinic were indicated by both bibliometric and visualized analyses as the highest contributing country, journal, author, and institution respectively to PJI research.

Areas of Research Focus

The co-occurrence analysis conducted using keywords arising out of the included publications was useful in identifying common research directions and tracking hotspots in PJI research, which could be broadly classified into several topic areas including pathogenetic mechanism, diagnostics, TJA complications, risk factors, revision surgery, and infection control. These results along with associated keywords may be used to determine future research trends in the field. The most popular research areas are likely to remain connected to the keywords with the biggest size circles, such as diagnosis, management, revision, risk factors, debridement, and outcomes.

It is crucial to understand the knowledge of the microbiology of PJI, including microorganism distribution and properties, pathogenesis, biofilm formation, antibiotic-resistance, and choice of the antimicrobial agents. Microbiological spectrum is essential for determining the antibiotic choice, which could help to avoid the toxicity from combinations of broad-spectrum empiric antimicrobial agents, such as acute kidney injury caused by vancomycin combined with a β-lactam agent.[35] There were significant differences in the microbial etiology, which depended on the different regions, time to occurrence of PJI, type of arthroplasty.[18,36] *Staphylococcus aureus* complex and coagulase-negative *Staphylococcus* species were the most common pathogens causing PJI,[18] which was consistent with the conclusions of a cohort study from France.[36] However, a study reported that coagulase-negative *Staphylococci* might be more common than the *S. aureus* complex in PJI.[35] Further studies should update the knowledge about microbial etiology.

The discovery of biofilm is a great breakthrough in the field of PJI. Bacterial biofilm is associated with some infections, namely catheters or prosthetic joints.[37] They are recalcitrant to antibiotic treatment owing to multiple tolerance mechanisms[38] and increasedβ-lactamase and efflux pump activity.[39,40] Therefore, this problem often remains in a dormant state without significant elicitation of the host response.[41] Additionally, biofilm had been found on the surface of cement spacers in revision TJA.[42,43] Therefore, how to eradicate bacteria in the biofilm has become a research hotpot, including antibiotic combination therapy (rifampin combined with flucloxacillin),[44] bacteriophage therapy,[45] and immunological therapy (monoclonal antibodies).[46]

The correct preoperative diagnosis of PJI is crucial to choosing the proper management.[47] The determination of PJI depends on clinical symptoms, laboratory tests, imaging findings, and histopathological tests of tissues. Musculoskeletal Infection Society (MSIS) and the Infectious Disease Society of America (IDSA) developed criteria in 2011 and 2013.[48,49] Further, the evidence-based PJI modified definition was developed by International Consensus Meeting (ICM) in

2018.[50] European Bone and Joint Infection Society (EBJIS) reported a latest definition of PJI in 2020.[51] C-reactive protein (CRP) and Erythrocyte sedimentation rate have variable sensitivities and specificities, as reported in difference publications.[19] Joint synovial fluid analysis has developed substantially such as leucocyte counts, percentage of polymorphonucleocytes (PMN%), and CRP, which show sensitivities of 0.89, 0.89 and 0.85, respectively.[52] Recently novel biomarkers such as leucocyte-esterase test and α-Defensin test revealed a sufficient diagnostic accuracy, especially α-Defensin test with an extremely accuracy.[53,54] The gold standard is still based on bacterial culture, which has to be conducted for 3–14 days for fastidious organisms.[55] Currently, about three to five distinct intraoperative tissue samples has to be collected.[56] The frequency of culture-negative PJI might be caused by several factors, such as prior antibiotics administration, a biofilm formation on the implants, and culture conditions.[57] Some novel techniques, such as synovial fluid culture in blood bottles, could improve the sensitivity.[58,59] Other techniques included sonication of removed prosthetic components[60,61] and optimum incubation conditions. In addition, polymerase-chain-reaction (PCR) and next-generation sequencing (NGS) could provide an evidence on causative organisms as well as antimicrobial susceptibility, which could potentially enable rapid diagnosis of PJI.[62–64]

In particular, in the overlay visualization map which displays the appearance frequency of keywords over time in the included publications, terms surrounding "diagnosis" and "revision" accounted for the majority of keywords with a high frequency of appearance in recent years (>2014). This observation is consistent with the greatest challenges currently faced by surgeons in PJI management, and suggests that strategies to improve diagnostic accuracy and the success rate of revision surgery will remain the primary focus areas in PJI research. Nevertheless, it is interesting to note that some new research areas have been developed which do not have a strong representation in the field at the current moment, but have great potential to develop strong links in future years and offer novel perspectives to PJI research. These include aspects relating to disease conditions (chronic kidney disease, diabetes mellitus), diagnostic techniques (flight mass spectrometry, multiplex PCR), treatment technologies (nanoparticles, beads, drug delivery), and policy development (international consensus, registry, resource utilization).

According to our results in this study, the number of studies in PJI has been gradually increasing since 2010. Based on the S-shape growth pattern, more articles will be published over the next 10 years. More investigators could devote themselves to PJI research in the future. The network visualized analyses could give researchers a comprehensive understanding in PJI. Meanwhile, the present study described the hotspots and global trends in PJI, which may direct future research in this field. In the future, researchers will more likely to see an increase in basic science studies (e.g., understanding infection mechanisms, developing new diagnostic/treatment technologies) or in clinical studies (e.g., patient studies looking at prevalence of PJI in different cohorts and testing treatments).

Strength and Limitations

This study is performed detailed bibliometric and visualized analysis on PJI research. Through these analyses, we have provided a comprehensive insight into the current status and research trends in the field worldwide. Most importantly, we have identified an S-shape growth pattern for PJI research which is likely to continue into the years ahead, as well as leading countries, institutions, authors, and journals making the most significant contributions to developments in the field. In addition to analyzing the academic impact, partnership, and links among these entities, we have also presented the imminent topic areas underpinning PJI research and discussed our predictions for future advances.

Some limitations have to be considered when interpreting the findings. First, only studies published in English were included for analysis, which may have skewed the results toward countries, authors, institutions, and journals which use English as their primary language. Second, we only retrieved publications from the WoSCC database due to the complete publication information provided by this source. Searches were not performed in other commonly used scientific databases such as Scopus and Embase, which might have resulted in some retrieval bias. Third, there may be intrinsic differences between the findings as indicated by bibliometric analyses and the real-world situation. For example, recently published articles might not have had sufficient time to receive significant attention or citation frequency proportionate to its quality or impact, and in addition to the five most cited articles, other highly cited articles with great quality or impact were not analyzed. Finally, this paper only briefly retrieved and explained keywords in the related hotspots, further research on these hotspots (e.g., common bacteria and their effective treatment methods) needed in the future. Despite these limitations, our study has presented a detailed and structured overview of the field of PJI research at this current point in time, which well portrays the status of research outputs and publication trends in this field on a global level.

Conclusion

This study shows the current status and trends in Prosthetic joint infection worldwide. The United States is the leading country in number of publications and total citation frequency. *Journal of Arthroplasty* published the highest number of papers on this topic. It can be predicted that the number of papers will continue to rise in the next decade. In particular, studies on diagnosis and revision management of prosthetic joint infection will likely be the next subject areas to receive more research attention.

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Author Contributions

Project conceptualization: Dong, S.J., Mei, F.Y. &Xing, D. Study design: Dong, S.J., Mei, F.Y.& Xing, D. Data collection/validation: Dong, S.J., Mei, F.Y. & Xing, D. Data analysis: Dong, S.J.& Mei, F.Y. Result interpretation: Dong, S.J., Mei, F.Y., Li, J.J. & Xing, D. Reporting &and editing: Dong, S.J., Mei, F.Y., Li, J.J.& Xing, D. Final approval of the version to be submitted: Dong, S.J., Mei, F.Y., Li, J.J. & Xing, D. Project guarantor: Dong, S.J. & Xing, D. All authors have read and approved the manuscript.

Data Availability Statement

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

References

1. Ji HM, Ha YC, Baek JH, Ko YB. Advantage of minimal anterior knee pain and long-term survivorship of cemented single radius posterior-stabilized total knee arthroplasty without patella resurfacing. Clin Orthop Surg. 2015;7:54–61.
2. Steinberg ME. Determining the cost of total hip and knee arthroplasty: commentary on an article by John a. Palsis, MD, et al.: "the cost of joint replacement. Comparing two approaches to evaluating costs of total hip and knee arthroplasty". J Bone Jt Surg Am. 2018;100:e24.
3. Palsis JA, Brehmer TS, Pellegrini VD, Drew JM, Sachs BL. The cost of joint replacement: comparing two approaches to evaluating costs of total hip and knee arthroplasty. J Bone Jt Surg Am. 2018;100:326–33.
4. Bumpass DB, Nunley RM. Assessing the value of a total joint replacement. Curr Rev Musculoskelet Med. 2012;5:274–82.
5. Rupp M, Lau E, Kurtz SM, Alt V. Projections of primary TKA and THA in Germany from 2016 through 2040. Clin Orthop Relat Res. 2020;478:1622–33.
6. Singh JA, Yu S, Chen L, Cleveland JD. Rates of total joint replacement in the United States: future projections to 2020-2040 using the National inpatient sample. J Rheumatol. 2019;46:1134–40.
7. Kurtz S, Ong K, Lau E, Mowat F, Halpern M. Projections of primary and revision hip and knee arthroplasty in the United States from 2005 to 2030. J Bone Jt Surg Am. 2007;89:780–5.
8. Bozic KJ, Kurtz SM, Lau E, Ong K, Chiu V, Vail TP, et al. The epidemiology of revision total knee arthroplasty in the United States. Clin Orthop Relat Res. 2010; 468:45–51.
9. Bozic KJ, Kurtz SM, Lau E, Ong K, Vail TP, Berry DJ. The epidemiology of revision total hip arthroplasty in the United States. J Bone Jt Surg Am. 2009;91: 128–33.
10. Konigsberg BS, Hartman CW, Hewlett AL, Garvin KL. Current and future trends in the diagnosis of periprosthetic hip infection. Orthop Clin North Am. 2014;45:287–93.
11. Kurtz SM, Ong KL, Schmier J, Mowat F, Saleh K, Dybvik E, et al. Future clinical and economic impact of revision total hip and knee arthroplasty. J Bone Jt Surg Am. 2007;89(Suppl 3):144–51.
12. Natsuhara KM, Shelton TJ, Meehan JP, Lum ZC. Mortality during total hip periprosthetic joint infection. J Arthroplasty. 2019;34:S337–42.
13. Lum ZC, Natsuhara KM, Shelton TJ, Giordani M, Pereira GC, Meehan JP. Mortality during total knee periprosthetic joint infection. J Arthroplasty. 2018;33: 3783–8.
14. Boddapati V, Fu MC, Mayman DJ, Su EP, Sculco PK, McLawhorn AS. Revision total knee arthroplasty for periprosthetic joint infection is associated with increased postoperative morbidity and mortality relative to noninfectious revisions. J Arthroplasty. 2018;33:521–6.
15. Sabah SA, Alvand A, Price AJ. Revision knee replacement for prosthetic joint infection: epidemiology, clinical outcomes and health-economic considerations. Knee. 2021;28:417–21.
16. Namba RS, Inacio MC, Paxton EW. Risk factors associated with surgical site infection in 30,491 primary total hip replacements. J Bone Jt Surg Br. 2012;94: 1330–8.
17. Namba RS, Inacio MC, Paxton EW. Risk factors associated with deep surgical site infections after primary total knee arthroplasty: an analysis of 56,216 knees. J Bone Jt Surg Am. 2013;95:775–82.
18. Tai DBG, Patel R, Abdel MP, Berbari EF, Tande AJ. Microbiology of hip and knee periprosthetic joint infections: a database study. Clin Microbiol Infect. 2022; 28:255–9.
19. Carli AV, Abdelbary H, Ahmadzai N, Cheng W, Shea B, Hutton B, et al. Diagnostic accuracy of serum, synovial, and tissue testing for chronic periprosthetic joint infection after hip and knee replacements: a systematic review. J Bone Jt Surg Am. 2019;101:635–49.
20. Kheir MM, Tan TL, Shohat N, Foltz C, Parvizi J. Routine diagnostic tests for periprosthetic joint infection demonstrate a high false-negative rate and are influenced by the infecting organism. J Bone Jt Surg Am. 2018;100: 2057–65.
21. Kildow BJ, Della-Valle CJ, Springer BD. Single vs 2-stage revision for the treatment of Periprosthetic joint infection. J Arthroplasty. 2020;35:S24–30.
22. Whiteside LA, Roy ME. One-stage revision with catheter infusion of intraarticular antibiotics successfully treats infected THA. Clin Orthop Relat Res. 2017;475:419–29.
23. Rodriguez-Pardo D, Pigrau C, Corona PS, Almirante B. An update on surgical and antimicrobial therapy for acute periprosthetic joint infection: new challenges for the present and the future. Expert Rev Anti Infect Ther. 2015;13:249–65.
24. Synnestvedt MB, Chen C, Holmes JH. Visual exploration of landmarks and trends in the medical informatics literature. AMIA Annu Symp Proc. 2005; 2005:1129.
25. Broadus RN. Toward a definition of "bibliometrics". Scientometrics. 1987; 12:373–9.
26. Gao J, Xing D, Dong S, Lin J. The primary total knee arthroplasty: a global analysis. J Orthop Surg Res. 2020;15:190.
27. Peng G, Guan Z, Hou Y, Gao J, Rao W, Yuan X, et al. Depicting developing trend and core knowledge of hip fracture research: a bibliometric and visualised analysis. J Orthop Surg Res. 2021;16:174.
28. Liao KY, Wang YH, Li HC, Chen TJ, Hwang SJ. COVID-19 Publications in family medicine journals in 2020: a PubMed-based bibliometric analysis. Int J Environ Res Public Health. 2021;18:7748.
29. You Y, Min L, Tang M, Chen Y, Ma X. Bibliometric evaluation of global Tai chi research from 1980-2020. Int J Environ Res Public Health. 2021;18:6150.
30. Fonseca Bde P, Sampaio RB, Fonseca MV, Zicker F. Co-authorship network analysis in health research: method and potential use. Health Res Policy Syst. 2016;14:34.
31. Aria M, Cuccurullo C. Bibliometrix: an R-tool for comprehensive science mapping analysis. J Informetr. 2017;11:959–75.
32. Bertoli-Barsotti L, Lando T. The h-index as an almost-exact function of some basic statistics. Scientometrics. 2017;113:1209–28.
33. Bertoli-Barsotti L, Lando T. A theoretical model of the relationship between the h-index and other simple citation indicators. Scientometrics. 2017;111: 1415–48.
34. van Eck NJ, Waltman L. Citation-based clustering of publications using CitNetExplorer and VOSviewer. Scientometrics. 2017;111:1053–70.
35. Benito N, Mur I, Ribera A, Soriano A, Rodriguez-Pardo D, Sorli L, et al. The different microbial etiology of prosthetic joint infections according to route of acquisition and time after prosthesis implantation, including the role of multidrug-resistant organisms. J Clin Med. 2019;8:673.
36. Triffault-Fillit C, Ferry T, Laurent F, Pradat P, Dupieux C, Conrad A, et al. Microbiologic epidemiology depending on time to occurrence of prosthetic joint infection: a prospective cohort study. Clin Microbiol Infect. 2019;25: 353–8.
37. Gbejuade HO, Lovering AM, Webb JC. The role of microbial biofilms in prosthetic joint infections. Acta Orthop. 2015;86:147–58.
38. Driffield K, Miller K, Bostock JM, O'Neill AJ, Chopra I. Increased mutability of Pseudomonas aeruginosa in biofilms. J Antimicrob Chemother. 2008;61:1053–6.
39. Ciofu O. Pseudomonas aeruginosa chromosomal beta-lactamase in patients with cystic fibrosis and chronic lung infection. Mechanism of antibiotic resistance and target of the humoral immune response. APMIS Suppl. 2003;1–47.
40. Pamp SJ, Gjermansen M, Johansen HK, Tolker-Nielsen T. Tolerance to the antimicrobial peptide colistin in Pseudomonas aeruginosa biofilms is linked to metabolically active cells, and depends on the pmr and mexAB-oprM genes. Mol Microbiol. 2008;68:223–40.
41. Shoji MM, Chen AF. Biofilms in periprosthetic joint infections: a review of diagnostic modalities, current treatments, and future directions. J Knee Surg. 2020;33:119–31.

42. Nelson CL, Jones RB, Wingert NC, Foltzer M, Bowen TR. Sonication of antibiotic spacers predicts failure during two-stage revision for prosthetic knee and hip infections. Clin Orthop Relat Res. 2014;472:2208–14.
43. Schmolders J, Hischebeth GT, Friedrich MJ, Randau TM, Wimmer MD, Kohlhof H, et al. Evidence of MRSE on a gentamicin and vancomycin impregnated polymethyl-methacrylate (PMMA) bone cement spacer after two-stage exchange arthroplasty due to periprosthetic joint infection of the knee. BMC Infect Dis. 2014;14:144.
44. Greimel F, Scheuerer C, Gessner A, Simon M, Kalteis T, Grifka J, et al. Efficacy of antibiotic treatment of implant-associated Staphylococcus aureus infections with moxifloxacin, flucloxacillin, rifampin, and combination therapy: an animal study. Drug Des Dev Ther. 2017;11:1729–36.
45. Chegini Z, Khoshbayan A, Taati Moghadam M, Farahani I, Jazireian P, Shariati A. Bacteriophage therapy against Pseudomonas aeruginosa biofilms: a review. Ann Clin Microbiol Antimicrob. 2020;19:45.
46. Raafat D, Otto M, Reppschlager K, Iqbal J, Holtfreter S. Fighting Staphylococcus aureus biofilms with monoclonal antibodies. Trends Microbiol. 2019;27:303–22.
47. Tande AJ, Patel R. Prosthetic joint infection. Clin Microbiol Rev. 2014;27: 302–45.
48. Parvizi J, Zmistowski B, Berbari EF, Bauer TW, Springer BD, Della Valle CJ, et al. New definition for periprosthetic joint infection: from the workgroup of the musculoskeletal infection society. Clin Orthop Relat Res. 2011;469:2992–4.
49. Osmon DR, Berbari EF, Berendt AR, Lew D, Zimmerli W, Steckelberg JM, et al. Executive summary: diagnosis and management of prosthetic joint infection: clinical practice guidelines by the Infectious Diseases Society of America. Clin Infect Dis. 2013;56:1–10.
50. Parvizi J, Tan TL, Goswami K, Higuera C, Della Valle C, Chen AF, et al. The 2018 definition of periprosthetic hip and knee infection: an evidence-based and validated criteria. J Arthroplasty. 2018;33(1309–1314):e1302.
51. McNally M, Sousa R, Wouthuyzen-Bakker M, Chen AF, Soriano A, Vogely HC, et al. The EBJIS definition of periprosthetic joint infection. Bone Jt J. 2021;103: 18–25.
52. Lee YS, Koo KH, Kim HJ, Tian S, Kim TY, Maltenfort MG, et al. Synovial fluid biomarkers for the diagnosis of periprosthetic joint infection: a systematic review and meta-analysis. J Bone Jt Surg Am. 2017;99:2077–84.
53. Yu BZ, Li R, Fu J, Chai W, Hao LB, Chen JY. Leukocyte esterase test and alpha-defensin test have similar accuracy for the diagnosis of periprosthetic joint infection. Int Orthop. 2021;45:1677–82.
54. Zahar A, Sarungi M. Diagnosis and management of the infected total knee replacement: a practical surgical guide. J Exp Orthop. 2021;8:14.
55. Kheir MM, Tan TL, Ackerman CT, Modi R, Foltz C, Parvizi J. Culturing periprosthetic joint infesction: number of samples, growth duration, and organisms. J Arthroplasty. 2018;33(3531–3536):e3531.
56. Mikkelsen DB, Pedersen C, Hojbjerg T, Schonheyder HC. Culture of multiple peroperative biopsies and diagnosis of infected knee arthroplasties. APMIS. 2006;114:449–52.
57. Watanabe S, Kobayashi N, Tomoyama A, Choe H, Yamazaki E, Inaba Y. Clinical characteristics and risk factors for culture-negative periprosthetic joint infections. J Orthop Surg Res. 2021;16:292.
58. Yan Q, Karau MJ, Greenwood-Quaintance KE, Mandrekar JN, Osmon DR, Abdel MP, et al. Comparison of diagnostic accuracy of periprosthetic tissue culture in blood culture bottles to that of prosthesis sonication fluid culture for diagnosis of prosthetic joint infection (PJI) by use of Bayesian latent class modeling and IDSA PJI criteria for classification. J Clin Microbiol. 2018; 56:e00319-18.
59. Peel TN, Dylla BL, Hughes JG, Lynch DT, Greenwood-Quaintance KE, Cheng AC, et al. Improved diagnosis of prosthetic joint infection by culturing periprosthetic tissue specimens in blood culture bottles. mBio. 2016;7: e01776–15.
60. Padolino A, Cataldo G, Tarallo L, Fabbri E, Merolla G, Micheloni GM, et al. Implant sonication versus intraoperative tissue sample cultures for periprosthetic joint infection (PJI) of shoulder arthroplasty. Acta Biomed. 2021; 92:e2021009.
61. Dudek P, Grajek A, Kowalczewski J, Madycki G, Marczak D. Ultrasound frequency of sonication applied in microbiological diagnostics has a major impact on viability of bacteria causing PJI. Int J Infect Dis. 2020;100:158–63.
62. Luftinger L, Ferreira I, Frank BJH, Beisken S, Weinberger J, von Haeseler A, et al. Predictive antibiotic susceptibility testing by next-generation sequencing for periprosthetic joint infections: potential and limitations. Biomedicine. 2021; 9:910.
63. Bourbour S, Emaneini M, Jabalameli M, Mortazavi SMJ, Tahmasebi MN, Taghizadeh A, et al. Efficacy of 16 S rRNA variable regions high-resolution melt analysis for bacterial pathogens identification in periprosthetic joint infections. BMC Microbiol. 2021;21:112.
64. Tarabichi M, Shohat N, Goswami K, Alvand A, Silibovsky R, Belden K, et al. Diagnosis of periprosthetic joint infection: the potential of next-generation sequencing. J Bone Jt Surg Am. 2018;100:147–54.