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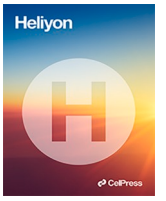

Research article

Research landscape of abdominal adhesions from 2004 to 2023: A bibliometric analysis

Kai Deng [a], Enmeng Li [a], Gan Li [a], Yiwei Ren [a], Tianli Shen [a], Zhengdong Jiang [a], Xuqi Li [a,c,*], Cancan Zhou [b,**]

[a] Department of General Surgery, The First Affiliated Hospital of Xi'an Jiaotong University, Xi'an 710061, Shaanxi, China
[b] Department of Hepatobiliary Surgery, The First Affiliated Hospital of Xi'an Jiaotong University, Xi'an 710061, Shaanxi, China
[c] Department of Talent Highland, The First Affiliated Hospital of Xi'an Jiaotong University, Xi'an 710061, Shaanxi, China

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ABSTRACT

Adhesions are the most common complication of abdominal or pelvic surgery and remain a challenging problem. To better understand the development tendency of abdominal adhesions, we performed a comprehensive bibliometric analysis of the field of abdominal adhesions. In total, 2219 articles regarding abdominal adhesions were screened and analyzed from 3410 manuscripts indexed in the Web of Science-indexed manuscripts regarding abdominal adhesion from 2004 to 2023. A bibliometric analysis was performed, and CiteSpace [version 6.2. R3 (64-bit)] and VOSviewer (version 1.6.19) were used to visualize the results. The number of annual publications showed slight growth before 2019, and the USA contributed the most publications. The most prolific author in this domain was Diamond, while the publications from Ten Broek had the strongest influence. The most popular journal in this field was the *Journal of Surgical Research,* and the most frequently co-cited journal was *Fertility and Sterility*. After analyzing the keywords, "prevention", "surgery" and "peritoneal adhesion" were the 3 most co-cited keywords, while "adhesive small bowel obstruction" was the strongest keyword in the citation burst. Here, for the first time, we used bibliometric methods to study abdominal adhesions over the past ten years. By summarizing the characteristics of publications and predicting future research prospects, we established a framework for researchers and provided a basis for subsequent research.

1. Introduction

The first case of abdominal adhesion was described in 1835 by Richard Bright [1]. By definition, peritoneal adhesions are pathological bands that connect adjacent structures. When the peritoneum is affected by injury or trauma, a series of biochemical/molecular biological cascades (tissue hypoxia, inflammation and mesothelial cell injury and loss) involving different factors are activated, inducing adhesion formation [2–4]. Abdominal adhesions occur after almost every abdominal operation; however, the severity of clinical symptoms and extent of adhesion are highly variable [5]. Problems related to adhesion, including infertility, abdominal pain and bowel obstruction, strongly impact the postoperative prognosis and quality of life of patients and thus affect the health care system [6,7]. Clinically, abdominal adhesion remains a challenge for the field; thus, further studies are urgently needed.

* Corresponding author.
** Corresponding author.
E-mail addresses: lixuqi@163.com (X. Li), czhou21@xjtu.edu.cn (C. Zhou).

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In recent decades, scholars have tried to find different ways to prevent adhesions or reduce their influence. The team under Ten Broek suggested that different surgical approaches may not impact the formation of adhesions, but the results are not clear [8]. Several scholars have found various pharmaceuticals that are helpful for preventing adhesions, such as agents targeting angiotensin, hypoxia-inducible factor inhibitors, and N-acetylcysteine and HMG-CoA reductase inhibitors [9–12]. Some researchers have focused on the use of inert polymers, such as natural polymers, synthetic polymer meshes, collagen sheets and composite polymers, to prevent or lessen adhesions [13–17]. Our team has been working on the mechanism of abdominal adhesion formation, and we tested both pharmaceuticals and barriers to prevent adhesion [18,19]. Although some advances have been made in surgical and preventive techniques, postoperative adhesions remain an inevitable concern in surgical practice [20].

Bibliometrics has become an important part of information science that can simplify cognitively demanding tasks in establishing an overview of the intellectual landscape and identifying research frontiers in certain fields [21]. Based on Java, CiteSpace is an application that can be used to analyze publications in a certain knowledge base or subject domain during a specific period and visualize research hotspots and frontiers via cluster analysis, co-cited analysis and metrology [22]. However, no bibliometric analysis has been conducted on the development of abdominal adhesions or on their prediction.

In this study, we collected articles on abdominal adhesions published in the past twenty years (from 2004 to 2023) via CiteSpace and analyzed the characteristics of the publications to determine the current research trends in the study of abdominal adhesions. The aim of this study was to provide a comprehensive understanding of abdominal adhesions, identify recent progress in research and determine the current and future directions of research.

2. Method

2.1. Inclusion criteria

The inclusion criteria were as follows: (1) basic and clinical research on abdominal adhesions; (2) reviews on abdominal adhesions; and (3) articles retrieved from the Web of Science from 2004 to 2023.

2.2. Exclusion criteria

The exclusion criteria were as follows: (1) articles that were not officially published; (2) proceedings, conference abstracts and corrigendum documents; (3) unrelated articles; and (4) duplicate articles.

2.3. Quality assessment

English-language articles that met the inclusion criteria were included in the analysis.

2.4. Search strategy

We searched for articles in the Web of Science Core Collection from inception to February 13th, 2024, using the following terms:

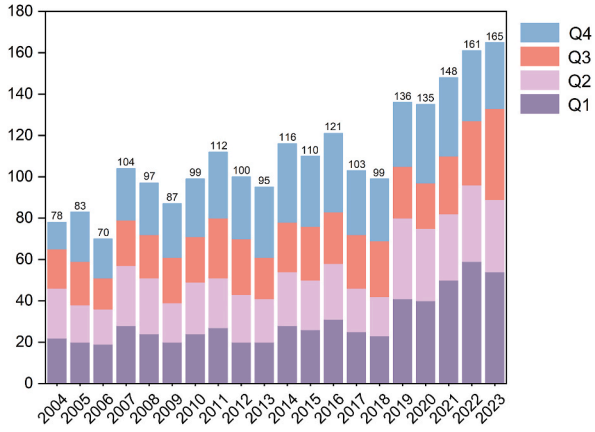

Fig. 1. The number of publications. The articles were exported from the Web of Science in plain text format with full records. The different colors represent the regions in the journal citation reports in certain years. Seventy-eight articles were published in 2004, 83 were published in 2005, 70 were published in 2006, 104 were published in 2007, 97 were published in 2008, 87 were published in 2009, 99 were published in 2010, 112 were published in 2011, 100 were published in 2012, 95 were published in 2013, 116 were published in 2014, 110 were published in 2015, 121 were published in 2016, 103 were published in 2017, 99 were published in 2018, 136 were published in 2019, 135 were published in 2020, 148 were published in 2021, 161 were published in 2022 and 165 were published in 2023. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

((TS=("bowel adhesion")) OR TS=("abdominal adhesion")) OR TS=("intestinal adhesion"). We added the following limiting strategies: Languages = English, Documents type = Article or Review Article. The details of the search strategy are shown in **Supplementary** Table 1.

2.5. Data arrangement and selection of information

After the data were downloaded from the Web of Science, 3410 manuscripts were imported to EndNote, and CiteSpace was used to remove duplicate articles. After removal, 2219 manuscripts were manually selected by two researchers. During the manual selection of manuscripts, a blinding method was adopted. After selection, the differences between the two researchers were discussed.

2.6. Analysis procedure

Supplementary Figure 1 shows the process of literature screening. A total of 987 articles were named "download_XXX.txt" and were imported into the Import folder for further analysis. CiteSpace [version 6.2. R3 (64-bit)] and VOSviewer (version 1.6.19) were used to analyze the data. We chose to select the top 50 most frequently cited or occurring items from each slice in CiteSpace and read

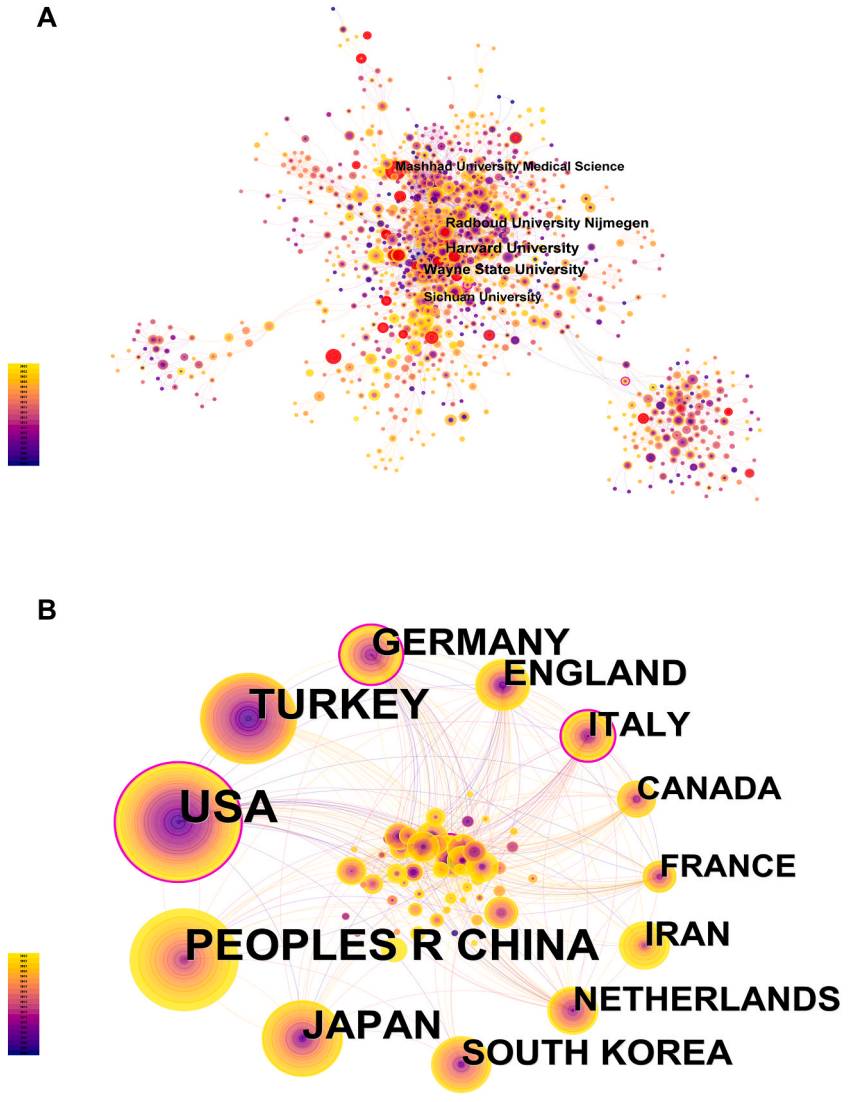

Fig. 2. The co-occurrence map of institutions and countries/regions. Cooperation among institutions or countries is indicated by lines between nodes, where the size of the lines represents the degree of cooperation, and the color illustrates the first year of cooperation. (A) The network map of co-occurrence institution. The red nodes illustrate that the institutions experienced a burst in publications. (B) Network map of co-countries/regions. The purple annulus represents high betweenness centrality. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

the data from the bibliographic database files in VOSviewer. The tree-ring history was chosen as the node display pattern.

3. Results

3.1. Trends in Quantity and Quality of Publications by Year

After manual screening, a total of 2219 publications were included. As shown in Fig. 1, the number of publications remained relatively stable. Before 2019, the annual number of publications fluctuated around 100, while it slightly increased over the past five years. Dividing publications by region according to the journal citation reports (JCR), there was a steady increase in the number of JCR Q1s, which reflects an improvement in the quality of publications. Even though people have realized that abdominal adhesion is a matter of concern, the variation in annual publication number is not growing as expected, which reveals that additional attention is needed in this field. It is gratifying that the quality of publications has improved, which implies good prospects for future research.

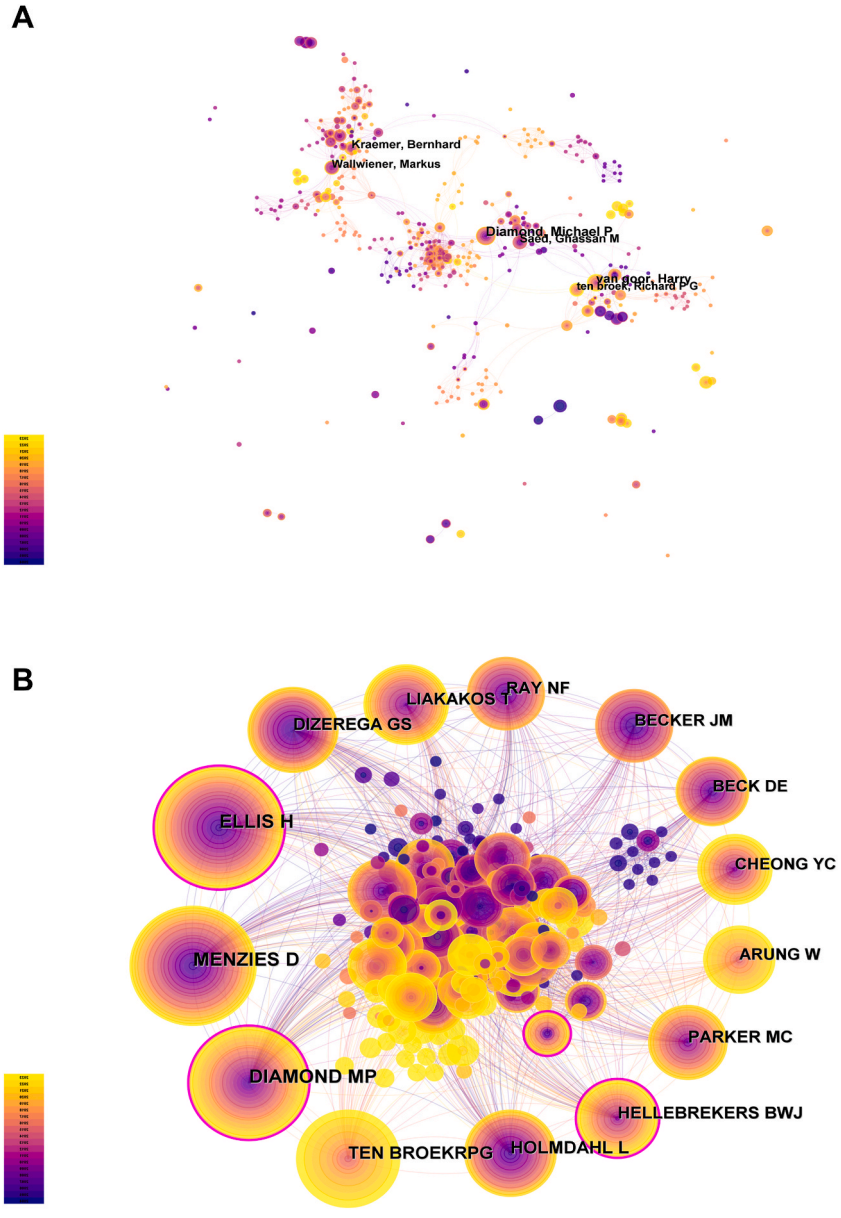

Fig. 3. CiteSpace visualization map of co-authors and co-cited authors. (A) The network map of authors. The color of the nodes represents the first year authors published articles. The red nodes represent authors with a burst in published articles. (B) The network map of co-cited authors. A purple annulus around a node represents high betweenness centrality, illustrating that the node plays an important role in certain fields. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

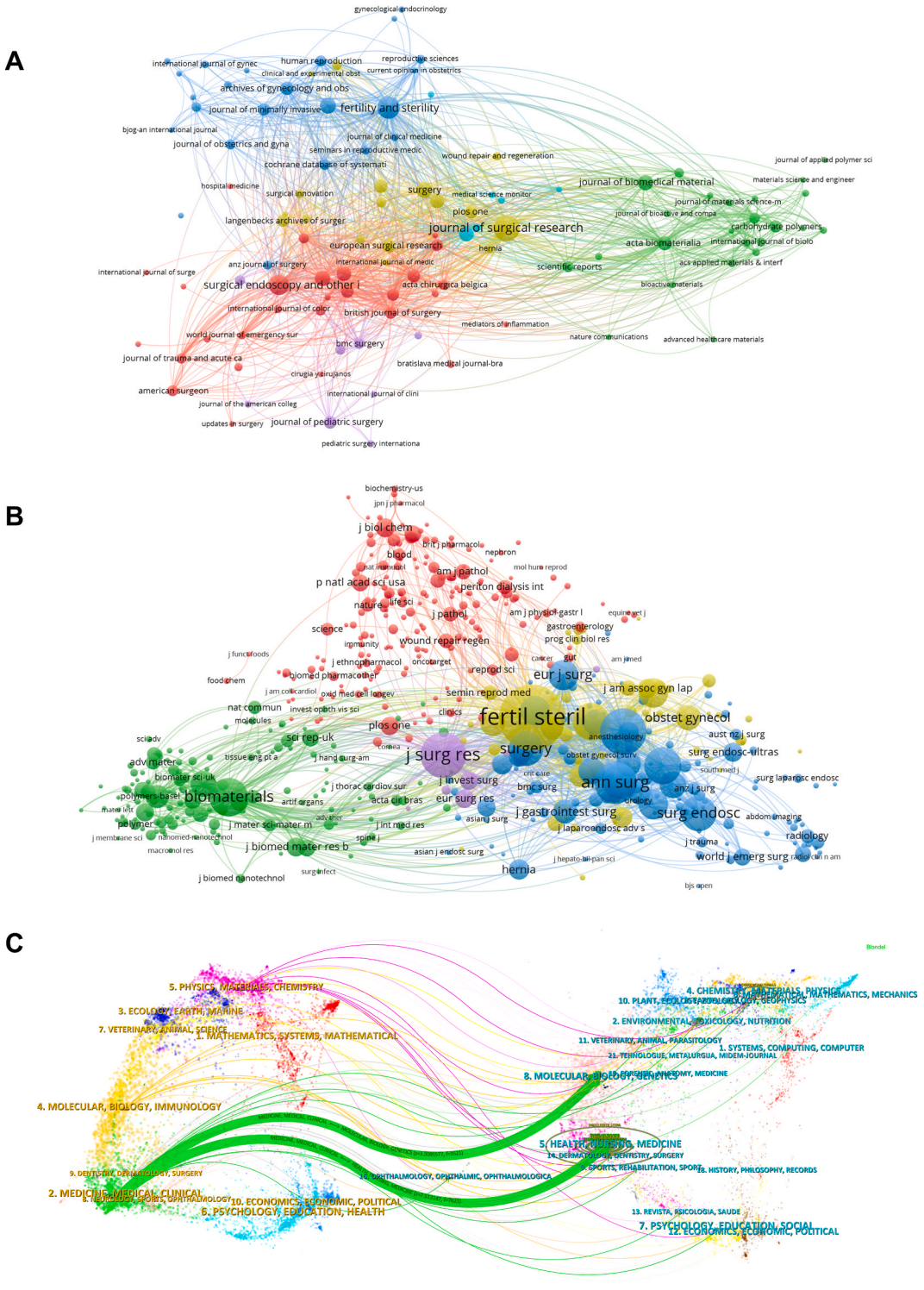

Fig. 4. The network map of journals, co-cited journals and dual-map overlay of journals. (A) The network map of journals. Nodes with the same color are related to each other. (B) Network map of co-cited journals. The minimum number of citations of a journal was 20. The size of the nodes represents the frequency of publications. (C) Dual-map overlay of journals. The map can display the distribution of the kinds of journals and the relationships between different journals and the journals they cite. The journals are on the left, while the cited journals are on the right. Source Circle Size: 40; Target Circle Size: 4; Snap to Centroids (<Radius): 0. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

3.2. Co-institution and Co-country analysis

The co-institution and co-country data were extracted from the individual literature and used to describe the cooperation between institutions and countries [23,24]. Only the top 50 institutions and countries publishing manuscripts in this area were included in the analysis. The red nodes indicate that a burst of publications occurred in a short time. The ten institutions that contributed the most to the study of abdominal adhesions are listed in **Supplementary** Table 2 The top five institutions were Harvard University (59 articles), Wayne State University (51 articles), Radboud University Nijmegen (47 articles), Sichuan University (32 articles) and Mashhad University Medical Science (31 articles). The co-institution network map is shown in Fig. 2A and included 1538 nodes and 5986 links. The centrality of institutions is low, which means that there is little direct cooperation between institutions in different countries. Among the institutions, Harvard University had the highest centrality, at 0.15. In addition, we found that Mashhad University of Medical Sciences entered this field in 2019 and published 27 articles in 5 years, which shows its potential for contributing to this field. The co-country network had 81 nodes and 513 links (Fig. 2B). Based on the total number of publications, the top five countries were the USA (451 articles), followed by the People's Republic of China (323 articles), Turkey (276 articles), Japan (199 articles) and Germany (137 articles). A purple ring indicates that the nodes have high centrality. Considering centrality and the number of publications, the USA was the country with the highest betweenness centrality (0.20) and a relatively large number of articles (451 articles), illustrating that it plays an important role in this area. These findings suggested that additional cooperation between institutions and countries should be encouraged.

3.3. Analysis of authors and Co-cited authors

A total of 4433 authors who published papers in this domain were included. The merged co-authorship network shows the collaboration among authors. As shown in Fig. 3A, there were 7571 nodes and 24,746 links, and we focused on visualizing the top authors (those who had published more than five articles). By ranking the authors based on their outputs, we can tell that the most prolific author was Diamond, who had 35 articles, followed by van Goor (29 articles), Kraemer (22 articles), Saed (22 articles) and Wallwiener (19 articles). Notably, van Goor not only produced a high output but also had the highest impact factor (*LANCET*, 2022 IF = 168.9), which was sufficient to reflect his pivotal role in this region of study. Although many researchers are working on abdominal adhesions, we found limited collaboration among them. Moreover, the authors showed low betweenness centrality, which reflected that further and continuous research is needed.

When authors have both high centrality and citation rates, they can be considered leading or influential scholars [25,26]. To identify the influential scholars in this field, we also analyzed the co-cited authors. As shown in Fig. 3B, the five most-cited authors were Ellis (610 citations) and Diamond (577 citations), followed by Menzies (568 citations), Ten Broek (377 citations) and Holmdahl (335 citations). In terms of betweenness centrality, the results were similar to those of the authors' analysis, which showed that the betweenness centrality of co-cited authors was low. However, there were 4 scholars with a relatively high betweenness centrality, greater than 0.1, which indicates that they are more influential than other scholars in this field. In addition, we considered both citations and centrality and found that Diamond (577 citations and centrality 0.19), Miller (82 citations and centrality 0.16) and Hellebrekers (287 citations and centrality 0.12) were the top three most influential scholars in the field of abdominal adhesions. By seeking leading scholars in this area, we provided a direction for researchers.

3.4. Analysis of journals and Co-cited journals

Over the past twenty years, 2219 papers related to abdominal adhesions have been published in 631 academic journals (Fig. 4A). **Supplementary** Tables 3 and 4 show the top five journals and co-cited journals. The *Journal of Surgical Research* published the most articles (n = 91), followed by *Fertility and Sterility* (n = 66), *Surgical Endoscopy and Other Interventional Techniques* (n = 54), *Surgery* (n = 35) and the *European Journal of Obstetrics & Gynecology and Reproductive Biology* (n = 34). Among the top 5 journals, all have published more than 15 articles in the past twenty years. Although the *Journal of Surgical Research* had a relatively low impact factor (2022, IF = 2.2; JCR Q2), it had the highest publication count. We further analyzed the co-cited journals, and the results are shown in Fig. 4B. By ranking journals according to citation count, we found that *Fertility and Sterility* was the most frequently co-cited journal, with 4733 citations, followed by the *British Journal of Surgery* (n = 2308), the *Journal of Surgical Research* (n = 2287), the *Annals of Surgery* (n = 1941) and *Biomaterials* (n = 1601). Among the top 5 co-cited journals, four are listed in the JCR Q1 region, and three are listed in the JCR Category of Surgery.

To further explore the interconnections between journals, a dual-map overlay of journals was drawn [27]. As shown in Fig. 4C, the citing journals are on the left, while the cited journals are on the right. The colored paths illustrate the relationships between citations. In this map, the green paths were the most notable and represented papers published in "health, nursing, and medicine" journals and "molecular, biology, and genetics" journals; additionally, they were often cited by papers published in "medicine, medical, and clinical" journals. The dual-map made the connections between journals visible, which made it easier for researchers to find possible points of cooperation and interdisciplinary directions.

3.5. Analysis of Co-citation and strongest citation references

The top co-cited references with both high centrality and frequency were analyzed, and these are visualized in Fig. 5A. The three most frequently co-cited references were published by Ten Broek. Specifically, in the most co-cited articles, Ten Broek made

recommendations that can be used by surgeons treating patients with adhesive small bowel obstruction (ASBO) and added scientific evidence for managing some aspects related to special patient groups [28]. The second-ranked reference was published in 2013, and this article provided detailed data and a systematic analysis of the disease burden of adhesions [29]. Ten Broek published the third co-citated reference, which evaluated the benefits and harms of four anti-adhesion barriers that have been validated for clinical use, including oxidized regenerated cellulose, icodextrin, polyethylene glycol, carboxymethylcellulose and hyaluronate [30]. The top 10 references with the most citations are shown in Table 1.

Clusters of citation references are shown in Fig. 5B. Fig. 5C shows a timeline of different clusters that formed from the network. Cluster #1 and Cluster #6 have a high concentration of citation bursts and include the top 3 co-citations. Cluster #1 emerged in 2012 and seems likely to persist in the future. Clusters #2, #3 and #5 have some highly co-cited manuscripts that are represented in a citation burst.

To better understand the most interesting research areas and research progress, we used CiteSpace to analyze the 299 references that showed the most citation bursts for abdominal adhesions. The top 30 most cited bursts are shown in Fig. 6. The short line on the right represents the timeline, the blue interval represents the period of citation, and the red represents the extent of the burst [31]. The 3 most common references with the most active citation bursts were "Bologna guidelines for diagnosis and management of adhesive small bowel obstruction (ASBO): 2017 update of the evidence-based guidelines from the world society of emergency surgery ASBO

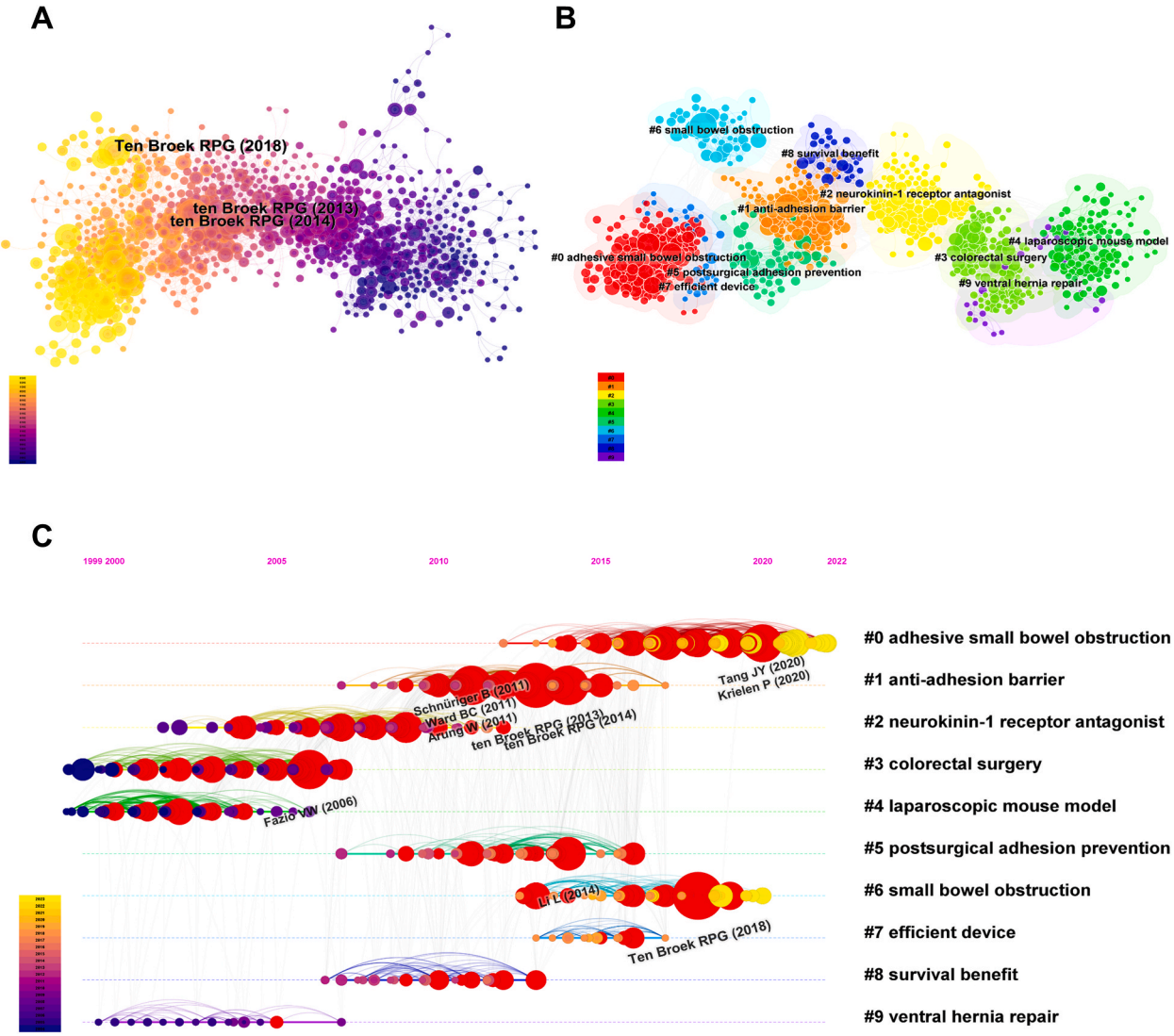

Fig. 5. The network of the top co-cited references. (A) The color of the nodes illustrates the years of publication. The purple annulus represents high betweenness centrality. (B) The clusters of cited references. Ten clusters were formed and are illustrated in different colors. The colors represent the clusters in a close-working network. Silhouette = 0.8873. Modularity Q = 0.7626. (C) The timeline diagram of the top 10 clusters of co-cited references. The red nodes represent references with a cited burst. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Table 1
The top 10 references with highest citation in abdominal adhesion research.

Rank	Document	Frequency
1	Ten Broek RPG(2018)	80
2	Ten Broek RPG(2013)	70
3	Ten Broek RPG(2014)	66
4	Arung W(2011)	54
5	Krielen P(2020)	53
6	Fazio VW(2006)	51
7	Schnüriger B(2011)	50
8	Ward BC(2011)	50
9	Tang JY(2020)	48
10	Li L(2014)	43

working group" (strength: 31.88; publication year: 2018), "Burden of adhesions in abdominal and pelvic surgery: systematic review and meta-analysis" (strength: 30.46; publication year: 2013), and "Benefits and harms of adhesion barriers for abdominal surgery: a systematic review and meta-analysis" (strength: 26.41; publication year: 2014). Since 2015, there were 15 references (accounting for 50 %) among the 30 most common citation bursts; 11 of these were in a citation burst until 2022, and this burst is likely to continue. These findings might provide a direction for future research.

3.6. Keyword analysis

Keywords are highly generalized summaries that can partly represent the content of articles, with terms that have high centrality and frequency often indicating hot spots in this field. To explore the research hotspots in the field of abdominal adhesions, we analyzed

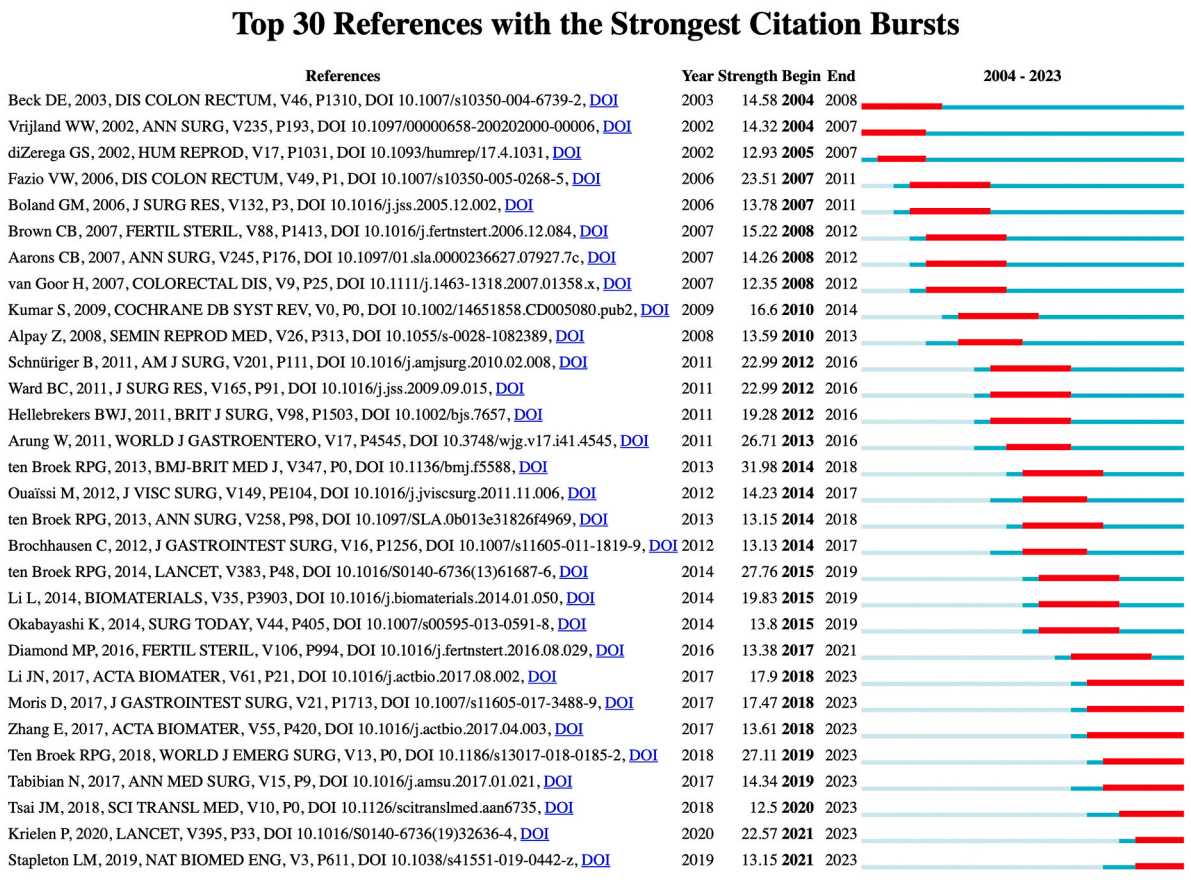

Fig. 6. The 30 references with the strongest citation bursts. The blue line represents the period when a reference was cited, while the red line represents the time interval when a reference burst occurred. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

these publications by keywords. We have cleaned and merged the keywords. The terms “abdominal adhesions”, “peritoneal adhesions”, “intraabdominal adhesions” and “postoperative abdominal adhesions” were deleted. “Small bowel obstruction” was merged with “intestinal obstruction”. As shown in Fig. 7A, the merged co-cited keyword network exhibited the top keywords, with 399 nodes and 681 links. The 3 most commonly co-cited keywords were “prevention”, “surgery” and “intestinal obstruction”. After eliminating the search terms, the 5 most common keywords with both high centrality and frequency (whose centrality and citation exceeded 0.1 and 20, respectively) are presented in **Supplementary** Table 5. Then, we used the log-likelihood ratio to produce 19 clusters, which included adhesion formation, multicenter, inflammation, morbidity, adhesion barrier, mesothelial, surgery, drug delivery, oxidative

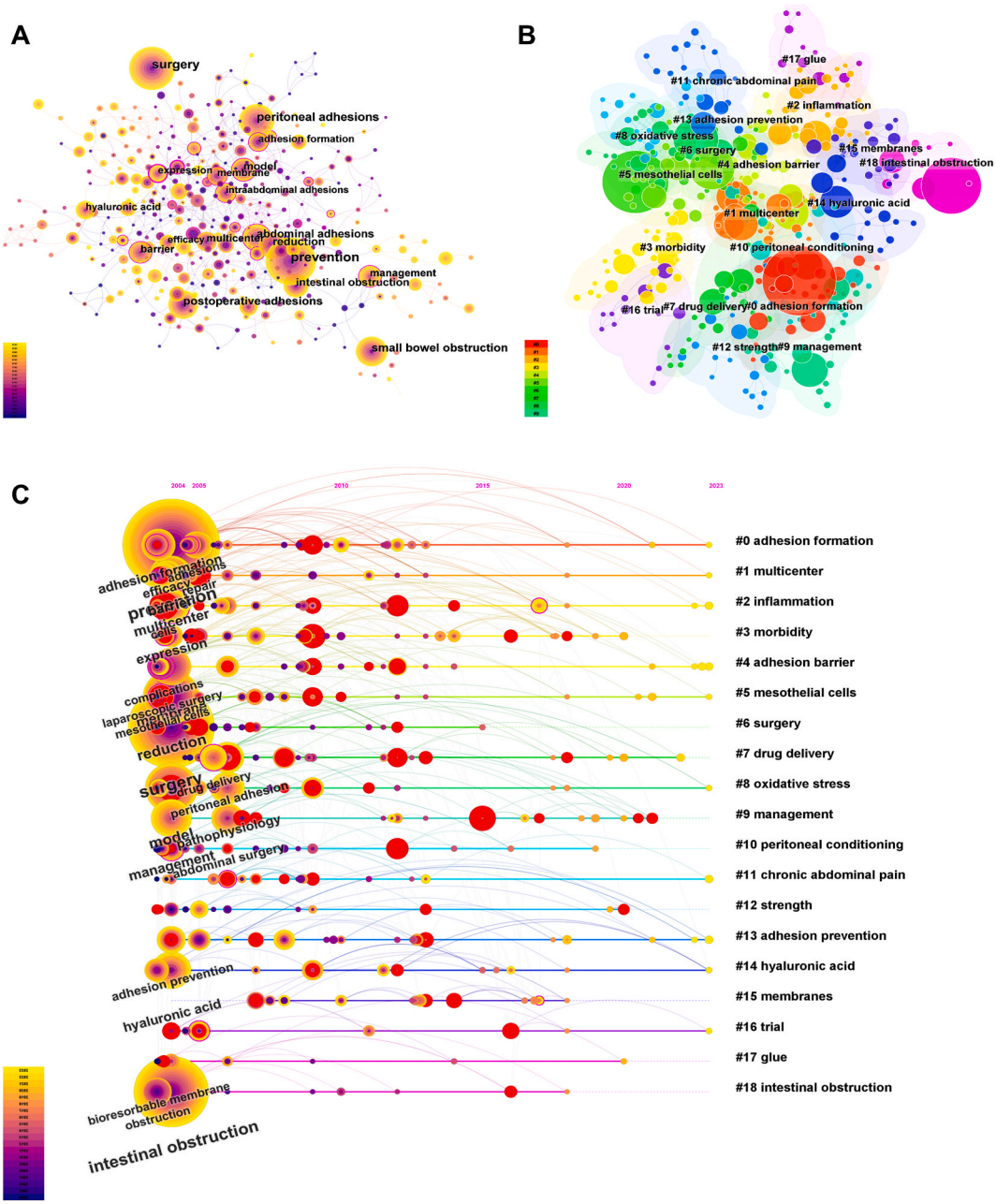

Fig. 7. The map of keywords Co-Citation, Clusters and Evolution. (A)The top co-cited keywords. (B) Nineteen clusters of keywords identified by LLR. Nineteen clusters were formed and are illustrated in different colors. The colors represent the clusters in a close-working network. Silhouette = 0.8855. Modularity Q = 0.7462. (C) CiteSpace visualization map of the timeline viewer. Recent studies have focused on five clusters: adhesion formation (cluster #0), multicenter (cluster #1), inflammation (cluster #2), adhesion barrier (cluster #4), mesothelial cells (cluster #5), oxidative stress (cluster #8), chronic abdominal pain (cluster #11), adhesion prevention (cluster #13) and hyaluronic acid (cluster #14). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

stress, management, peritoneal conditioning, chronic abdominal pain, strength, adhesion prevention, hyaluronic acid, membranes, trial, glue, and intestinal obstruction (Fig. 7B) clusters. These clusters mostly focused on the prevention of abdominal adhesion, which reflects the clinical desire for preventive methods. Next, we used CiteSpace to build a timeline viewer to show the development of each keyword in the clusters. The topics in this research field and the evolution of the field are intuitively visualized in Fig. 7C. The timeline showed that the study of most clusters started twenty years ago, and half of them are in continuation. There was a high proportion of keyword bursts in Cluster #2. Clusters #0, #6 and #18 include the top 3 co-citations. Cluster #0, Cluster #2, Cluster #5 and Cluster #8, which are related to adhesion formation, contribute to keyword bursts and are likely to persist in the future. Cluster #1, Cluster #4, Cluster #11, Cluster #13 and Cluster #14 are domains of clinical research and may continue to be of interest to clinicians. Not surprisingly, these clusters were correlated with studies of the formation of adhesions and adhesion prevention.

In addition, we studied keywords associated with citation bursts. A total of 91 keywords burst out at different time points, and the 15 keywords with the strongest bursts are shown in Fig. 8. The keyword "uterine horn model" (strength: 11.72) showed that the strongest citation burst started appearing in 2004. The bursts of the keywords "chitosan" and "seprafilm" lasted for 8 years (the longest). In addition, the bursts of the keywords "metaanalysis" and "inflammation" had strengths greater than 10 and continued to occur in 2023, suggesting that additional attention should be given to clinical aspects.

4. Discussion

Abdominal adhesions have been a challenge for surgeons since they were first described in 1835. Although many attempts have been made by surgeons and researchers to find preventive techniques and treatments, little progress has been made. With the development of computer science, many methods have been used to study clinical problems, one of which is bibliometric analysis. Bibliometrics can help individuals identify hidden associations, display these associations visually and facilitate understanding of associations at a broader level. Considering its strength, it is always used to summarize publications and analyze the evolution and progress in certain fields. Regrettably, there are no relevant bibliometric studies about abdominal adhesions. For this reason, we conducted this study using bibliometric methods to fill this gap. In total, 987 publications on abdominal adhesions were retrieved and analyzed from 2004 to 2023. By using CiteSpace [version 6.2. R3 (64-bit)] and VOSviewer (version 1.6.19), we analyzed the 2219 included publications, including quantity, institutions/countries, authors, journals, citations and keywords. This study provides the first overview of abdominal adhesion research using bibliometric methods.

In general, the research prospects for abdominal adhesions look bright. The number of publications showed a slight increase and seems to increase over the past five years; moreover, the quality of these papers showed signs of an uptrend. The most productive institution is Harvard University, one of the leading research universities located in the USA. In addition, Wayne State University, Radboud University Nijmegen, Sichuan University and Mashhad University Medical Science also made great contributions to the study of abdominal adhesions. In terms of country, the USA was the country with the most publications in this field, with 451 articles published in the past ten years, followed by the People's Republic of China (323 articles) and Turkey (276 articles). However, the total number of publications on this topic is less than that on other research areas, such as cancer and inflammation [32,33], which reminds us that additional attention should be given to abdominal adhesions. Moreover, we found that there were fewer connections between

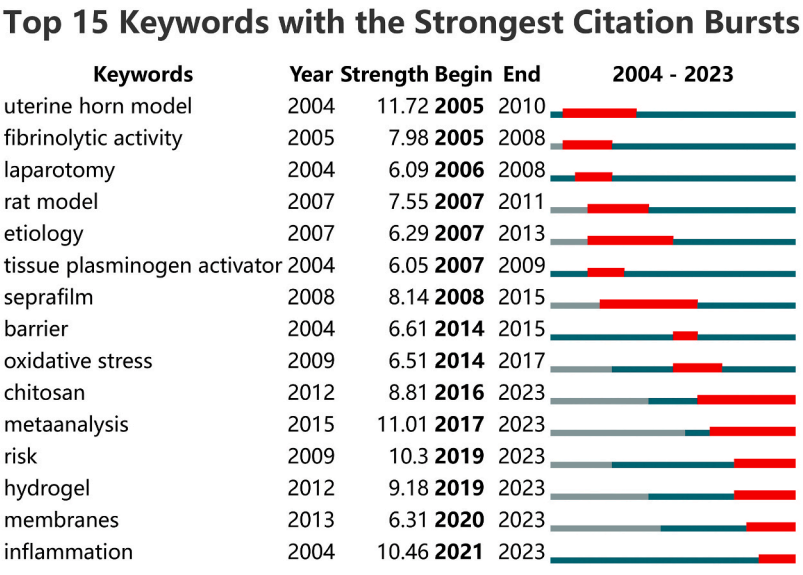

Fig. 8. The 30 keywords with the strongest citation bursts. The short line on the right represents the timeline, the blue interval represents the period of citation, and the red represents the extent of the burst. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

countries and institutions, revealing that abdominal adhesions have not received adequate attention and that more cooperation should be encouraged. As research progresses, the pathogenesis of this disease will be gradually elucidated, and effective preventive methods will be identified.

In the past 20 years, an increasing number of researchers, such as Diamond, van Goor, Kraemer, Saed and Wallwiener, have become interested in this field. Interestingly, Ten Broek, who has published some manuscripts in high-impact journals, worked with van Goor as a member of a team. Significantly, publications by Ten Broek not only are high in number but also have a high quality; not surprisingly, he has the highest number of citations. These factors make him one of the most influential scholars. The advantage of laparoscopic surgery has been discussed in his latest article with a high impact factor; laparoscopic surgery can lower the percentage of readmissions directly related to adhesions by approximately 30 % compared with open surgery [34]. Considering the centrality of authors and co-cited authors, poor cooperation between authors and the sustainability of related research have been revealed. More than six hundred journals have published articles about abdominal adhesions, and the *Journal of Surgical Research* ranks first with 91 publications. This journal is a JCR Q2 journal in the area of surgery and focuses on clinical and laboratory research aimed at providing surgical management for surgeons and researchers.

The top three co-cited references focus on clinical problems, which include prevention, mode of operation and the burden of adhesion; these can be considered the basis of related research and should be recommended for beginners. Recently, there have been several publications with strong citation bursts, which will last until 2023. By reading these publications, research hotspots can be easily identified. Clusters #0 and #6 have a strong co-citation relationship, which shows a close connection between adhesive small bowel obstruction and postsurgical adhesion prevention. Cluster #1 greatly contributed to the reference burst, showing that barriers were still an effective way to prevent adhesion. Anti-adhesion drugs, such as neurokinin-1 receptor antagonists, have been studied in recent years. However, there is still a lack of drugs that can effectively control adhesion formation in the clinic. Cluster #3 and Cluster #9 show that the field of general surgery-related diseases, such as colorectal surgery and hernia diseases, more heavily considers adhesions. The analysis of keywords revealed that the co-cited keywords were “prevention”, “surgery” and “intestinal obstruction”, while the 5 most common keywords that also had high centrality were “Drug delivery”, “Expression”, “Polypropylene mesh”, “Trial” and “Hernia repair”. It is clear that prevention methods were the keywords attracting the most interest in the past twenty years. Several keywords, such as “chitosan”, “metaanalysis”, “risk”, “hydrogel”, “membranes” and “inflammation”, started in recent years and lasted until 2023. The terms “uterine horn model”, “laparotomy”, “tissue plasminogen activator”, “barrier” and “inflammation” have lasted for twenty years. The study of adhesion formation has also shifted from “etiology” to “inflammation”. In recent years, “hydrogels”, “chitosan” and “membranes” have gradually replaced “seprafilm” as hot physical barrier materials. The keywords with citation bursts showed that researchers started taking an interest in clinical aspects [35,36].

Although more attention has been given to the field of abdominal adhesions and many related studies have been performed, there is still a long way to go. Abdominal adhesions are still a challenge in the clinical setting, and additional research should be carried out to elucidate the specific mechanism of how abdominal adhesions are formed, including what kinds of cells are involved, the roles of these cells, changes in metabolism, and variations in cytokines. By doing so, we can find relevant methods to prevent or treat abdominal adhesions.

Until now, the means by which abdominal adhesions develop have remained unclear. Recent studies suggest that the main physiological mechanisms of adhesion are apoptosis and proliferation, oxidative stress, coagulation and fibrinolysis, and inflammatory responses [37]. In these roles, different cells play different roles. Mesothelial cells can transdifferentiate into a subset of myofibroblasts via mesothelial-to-mesenchymal transition (MMT) to participate in the development of adhesions [38]. Neutrophils play an important role in inflammatory responses [39]. Macrophage function depends mainly on differentiation status, which plays an important role in determining the adhesion phenotype [40]. Mast cells and T lymphocytes are also important effector cells of inflammation [41,42]. The uncertainty around causation is also why adhesions cannot be completely prevented at present.

Currently, there are many different views on how to treat or prevent abdominal adhesions. Early operative intervention is one of the treatment options, but researchers hold different attitudes. Some researchers believe that early operative intervention for patients with adhesive small bowel obstruction may be associated with a lower incidence of local and systemic complications, a shorter hospitalization period and a notable survival benefit [43]. Others argue that delayed management of small bowel obstruction is associated with a prolonged postoperative hospital stay and death but not with complications or bowel resection [44]. The risk factors for adhesion-related readmissions have been widely studied in recent years. Surgical method, age, sex, malignancy as the primary indication for surgery, and type of surgery were all found to be associated with the risk of adhesion-related readmission [34]. In addition, laparoscopic surgery has been shown to cause less tissue trauma and less inflammatory cascade triggering than open surgery [45]. In the *Lancet*, Pepijn reported that laparoscopic surgery has advantages over open surgery, and the continued increase in laparoscopic surgery is expected to further reduce the incidence of adhesion-related diseases at the population level [34]. However, Liane found a few methodological limitations in this research, which may cause the conclusion to have some limitations [46]. Although some scholars remain skeptical about the effectiveness of laparoscopy, laparoscopic surgery has advantages, and more rigorous further research is needed [47,48]. Clinical trials should be designed and implemented to settle these disputes [49]. The most widely adopted means of prevention is the use of polymeric materials, such as sodium hyaluronate and carboxymethylcellulose [28,50]. In basic research, different drugs and materials have been used in animal models, and some have shown good preventive effects. Currently, sodium hyaluronate is the most popular material, and combination with antiadhesion drugs is a potential direction for future research [18,51–53]. Several researchers have endowed PLGA-g-PVP/I electrospun fibrous membranes with durable antibacterial properties to gain clinical significance [54]. The latest research reported the development of a biodegradable zwitterionic cream gel that presents several characteristics of an ideal antiadhesion material, including its unique yet malleable, injectable and self-supporting properties [55]. Emerging therapies, such as gene therapy and stem cell-based approaches, may disrupt the normal cascades of adhesion events

and offer new strategies for preventing adhesion formation [56]. Adenoviruses encoding the hepatocyte growth factor or sphingosine kinase 1 gene can reduce adhesion by stimulating mesothelial cells [57,58], and combination with a barrier can be an option in the future [59]. As the main carriers for mesenchymal stem cell activity, extracellular vesicles have been shown to inhibit the formation of adhesions [60]. Currently, physical barriers remain the best form of prevention, and further research is needed to optimize their safety and effectiveness [61,62]. Adhesive small bowel obstruction, the most common complication of abdominal adhesions, has also been the focus of related research [63]. In addition, the safety of therapeutic methods and barrier materials has attracted considerable interest in recent years [61,64], and additional research should be performed to demonstrate their safety.

Preventing the occurrence of abdominal adhesions is still a topic requiring further research, and there is no method for completely preventing the occurrence of abdominal adhesions. Reducing surgical trauma and placing barriers are still the mainstream methods of prevention. We believe that the combination of polymer materials and anti-adhesion drugs will continue to be the clinical standard in the future until a concrete understanding of the formation of adhesions has been obtained. In addition, different barrier synthesis methods have been developed. The identification of macrophage differentiation and the functions of various macrophage subpopulations may lead to the development of new prevention strategies and will become a research hotspot in the future. Moreover, the economic benefits of methods for preventing adhesions should also be considered in future research.

There are several limitations to our study. We aimed to include all search strategies to avoid missing articles and manually screened them for further analysis; although we did so with great care, some articles might have been omitted or excluded during the manual screening. Only English publications recorded in the Web of Science Core Collection were included, and analysis might have led to the exclusion of some good publications. In addition, it takes a few months for a paper to be cited, which might cause the most recent articles to have incomplete citations.

5. Conclusion

By summarizing the characteristics of these publications, we first established a framework for studying abdominal adhesions. Both the quantity and quality of the publications in this field show a stable upward trend. Harvard University ranks first among research institutions, and the USA ranks first among countries; moreover, we found that more collaboration should be encouraged. Diamond, with the most publications and significant impact, is considered one of the most influential authors in this field. The research findings have been welcomed by many journals, especially those related to surgery. Ten Broek published the three most frequently co-cited references with the most active citation bursts. Notably, the prevention of adhesion has been a research hotspot and will continue to be studied in the future. More *in vivo* experiments or even clinical trials should be performed to verify the use of new biological materials to solve this significant challenge as soon as possible. These findings help to visualize the research trends in the past two decades and provide a basis for subsequent research in the field of abdominal adhesions from a bibliometric perspective.

Data availability statement

Data included in article/supp. material/referenced in article.

Ethics statement

Review and/or approval by an ethics committee was not required for this study because this article did not involve any animal or human experiments.

CRediT authorship contribution statement

Kai Deng: Writing – original draft, Visualization, Software. **Enmeng Li:** Data curation. **Gan Li:** Data curation. **Yiwei Ren:** Investigation. **Tianli Shen:** Investigation. **Zhengdong Jiang:** Project administration. **Xuqi Li:** Project administration. **Cancan Zhou:** Writing – original draft.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.heliyon.2024.e30343.

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