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Exploring the development and trends of prostate cancer radiotherapy research: a bibliometric analysis

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Abstract

Background: Prostate cancer (PC) is one of the most common malignant tumors in men globally, with its incidence increasing annually due to lifestyle changes and an aging population. Radiotherapy, which has been a curative treatment for PC, has undergone continuous development and refinement since its introduction. However, few comprehensive reviews have been conducted on the hotspots and trends in this field. Therefore, this study employs bibliometric analysis to evaluate the key research domains, current research landscape, and future development patterns in PC radiotherapy over the last 30 years. **Methods**: Relevant literature on PC radiotherapy from 1994 to 2023 was retrieved using appropriate keywords from the Web of Science Core Collection database. A bibliometric analysis and visualization of annual production, countries, institutions, authors, journals, keywords and references were performed using CiteSpace and Bibliometrix. CiteSpace was used for systematic mapping to understand the structural evolution of this field over time. **Results**: A total of 4923 articles were included, and the annual number of publications showed a growing trend. The United States and the University of California System were the leading countries and institutions. International Journal of Radiation Oncology Biology Physics had the highest number of publications in terms of publication output. Alongi F was the most prolific author. The main study domains focused on technological innovations, assessment of treatment efficacy, and initiatives to reduce the risk associated with PC radiation. Stereotactic body radiation therapy is currently a major research focus, with potential advancements in PC radiotherapy emphasizing adaptive radiotherapy, proton and heavy ion therapy, and multimodal imaging approaches. **Conclusions**: It is evident from the analysis that the field of PC radiotherapy holds promising research prospects.

Keywords

Prostate cancer; Radiotherapy; Stereotactic body radiation therapy; Bibliometrics; Visualization

1. Introduction

Prostate cancer (PC) is the most prevalent malignant neoplasm of the male genitourinary system, ranking as the second leading cause of cancer mortality and the fifth most common cancer globally among males. Over 50% of countries, PC is identified as the predominant malignancy among men [1]. In the United States, PC as a common cancer accounts for 29% of cancer diagnoses [2]. The survey revealed that the quality of life of prostate cancer patients declined after radical prostatectomy, with 61.40% of them suffering from impotence and 26.31% experiencing urinary incontinence after the operation [3]. Radiotherapy is a curative treatment option for PC, offering therapeutic efficacy comparable to surgical resection, with a lower incidence of adverse events [4]. It is appropriate for patients at all phases, supported by a broad range of evidence, reduced complications and positive outcomes. Therefore, a comprehensive review of radiotherapy for PC is imperative.

The advancement of radiotherapy techniques, including Stereotactic Body Radiotherapy (SBRT) and complex tumor localization methods using multimodal imaging technologies such as Computed Tomography (CT), Magnetic Resonance Imaging (MRI) and Positron Emission Tomography (PET), has the potential to significantly improve curative outcomes for PC [5]. Hypofractionated radiotherapy is particularly effective for PC as it can achieve an effective dose comparable to that of traditional fractionated radiotherapy while shortening the treatment time [6]. It may also demonstrate greater efficacy in certain scenarios [7, 8]. The efficacy of radiotherapy for PC can be further improved by combining multimodal imaging methods, such as CT-MRI fusion. MRI provides enhanced soft tissue contrast, which helps the identification of tumors and surrounding normal tissues, whereas CT provides detailed anatomical information. CT-MRI fusion in

radiotherapy significantly increases the accuracy of PC target volume delineation, reduces the side effects on organs at risk (OAR), including the rectum and bladder [9–11]. Therefore, a comprehensive analysis of the current status, key areas, and emerging trends in prostate cancer radiotherapy is expected to provide valuable insights.

Although there is extensive research and abundant literature on PC, a bibliometric analysis exclusively focusing on PC radiotherapy has yet to be conducted. Therefore, this study aims to address this gap using bibliometric techniques by examining the literature addressing PC radiotherapy. It systematically evaluates the research status, hotspots and trends in this field over the past three decades, thereby providing a comprehensive understanding of its development and potential future directions.

2. Materials and methods

2.1 Data collection

This study conducted a comprehensive literature search within the Web of Science Core Collection (WoSCC) to examine the use of radiotherapy for PC over the past 30 years, specifically from January 1994 to December 2023 (Note: This choice may exclude significant contributions from other databases, such as Scopus and PubMed, which could affect the comprehensiveness of the review). The search formula was formulated as follows: Topics (TS) = ("prostate cancer" OR "prostatic neoplasms") and TS = (radiotherapy OR radiation therapy) AND TS = (SBRT or "Intensity Modulated Radiation Therapy (IMRT)" or Volumetric Modulated Arc Therapy (VMAT) or Image Guided Radiation Therapy (IGRT) or dosimetry or dose distribution or dose-volume histogram or fractionation). The article was composed in English, and to confirm the accuracy of the data updates, all previously specified tasks were finalized within one day, particularly on 10 July 2024.

The study exclusively included articles and reviews as document formats, while meeting abstracts, editorial content, proceedings papers, and similar items were excluded. Duplicate studies were manually removed. All relevant information was collected for bibliometric analysis, including the number of papers and citations, titles, authors, affiliations, countries of origin, keywords, journals, publication years and references.

2.2 Data arrangement and analysis

This study used CiteSpace (version 6.2. R6) and the Bibliometrix 4.1.4 Package, using the R programming language, to conduct the bibliometric analysis. The knowledge domain was visually examined, and trends were identified using CiteSpace [12–14]. This tool includes cluster analysis, timelines and citation bursts of references and keywords. Cluster analysis can group authors, keywords and publications with similar topics together, allowing us to identify key research areas in prostate cancer radiotherapy and clearly see the mainstream directions, hot issues, and emerging trends in this field [14, 15]. Burst refers to the phenomenon where a specific keyword or citation experiences a sharp increase in frequency over a short period of time. The burst of keywords is often closely related to research hotspots during a particular period, reflecting changes in research trends within the field of prostate cancer radiotherapy. Citation bursts, on the other hand, validate the academic influence and recognition of certain publications in the field of prostate cancer radiotherapy. The ideas and methods contained in these publications have made significant contributions to the development of the field. In cluster analysis, the modularity score (Q score) measures how well a network can be divided into separate groups or clusters, while the silhouette score (S score) helps to judge the quality of clustering [16]. The clustering structure was considered statistically significant when the Q score was >0.3, with higher values potentially indicating a well-structured network. When the S value is greater than 0.5, the clustering is generally considered reasonable. When the S value exceeds 0.7, the clustering is considered highly reliable. The Bibliometrix Package [17], a well-established tool grounded in the R language, was used for bibliometric analysis. This study used the Bibliometrix Package to conduct a thematic evolution analysis to classify the changes in PC radiotherapy research into distinct periods.

3. Results

3.1 Analysis of publication outputs

Approximately 4923 publications on PC radiotherapy were retrieved from the WoSCC, including 4474 (90.88%) research and 449 (9.12%) review articles. The annual publication trend, illustrated in Fig. 1, demonstrates an increase from 3 publications in 1994 to 297 in 2023, reflecting an annual growth rate of 17.16%. This trend highlights a substantial rise in research output over the past three decades. Currently, these publications have collectively received 150,236 citations (excluding 113,451 self-citations), yielding an average of 30.51 citations.

All articles related to PC radiotherapy were published in 484 journals, with the top 10 journals by publication volume listed in Table 1. The journal with the highest number of publications in this field was the International Journal of Radiation Oncology Biology Physics (published by Elsevier Science with 629 articles and 45,654 citations), followed by Radiotherapy and Oncology (Elsevier Ireland with 390 articles and 16,502 citations), Medical Physics (Wiley, with 292 articles and 9295 citations), Radiation Oncology (BioMed Central (BMC), with 229 articles and 6185 citations), Physics in Medicine and Biology (IOP Publishing Ltd., with 190 articles and 5110 citations), Strahlentherapie und Onkologie (Springer Heidelberg, with 166 articles and 3701 citations), Journal of Applied Clinical Medical Physics (Wiley, with 152 articles and 1818 citations), Frontiers in Oncology (Frontiers Media SA, with 131 articles and 1035 citations), Brachytherapy (Elsevier Science, with 114 articles and 2204 citations), and Medical Dosimetry (Elsevier Science, with 99 articles and 1719 citations).

Among the top 10 journals by publishing volume, the International Journal of Radiation Oncology Biology Physics possesses the highest impact factor (IF) at 6.4. Of the 10 journals with the most publications, the average impact factor was 2.8, with 6 journals above an impact factor of 3. The domain of PC radiation was intensely competitive, characterized by strong academic research and considerable impact, and it indicates a

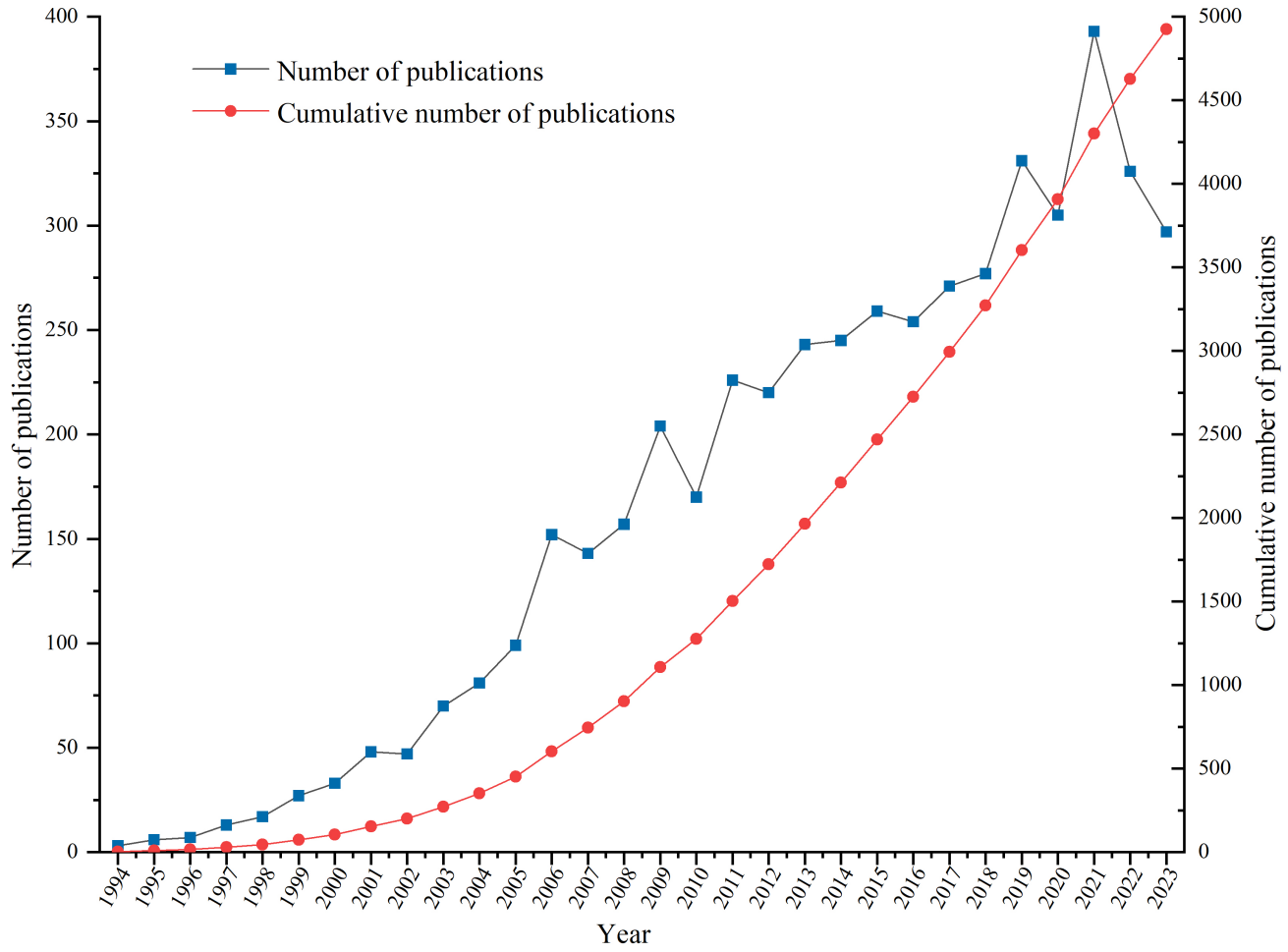


FIGURE 1. Annual publications on the topic of prostate cancer radiotherapy. The image showing the dynamic change in the number of publications on PC radiotherapy from 1994 to 2023 is illustrated with a dual Y-axis. The left Y-axis (blue line with square markers) shows the annual publication numbers, while the right Y-axis (red line with dot markers) displays cumulative publication numbers. Data was retrieved from the Web of Science. The representative graph reveals a steady rise in annual publications, with indications of accelerated growth throughout the period.

TABLE 1. A list of the top 10 journals most actively publishing research on radiotherapy for prostate cancer.

Rank	Sources title	Counts	TLCS	TGCS	IF (2023)	H-index	Category Quartile
1	International Journal of Radiation Oncology Biology Physics	629	45,654	43,327	6.4	112	Q1
2	Radiotherapy and Oncology	390	16,502	15,842	4.9	65	Q1
3	Medical Physics	292	9295	8978	3.2	53	Q1
4	Radiation Oncology	229	6185	5954	3.3	41	Q2
5	Physics in Medicine and Biology	190	5110	4995	3.3	41	Q2
6	Strahlentherapie und Onkologie	166	3701	3306	2.7	32	Q3
7	Journal of Applied Clinical Medical Physics	152	1818	1774	2.0	22	Q3
8	Frontiers in Oncology	131	1035	990	3.5	16	Q2
9	Brachytherapy	114	2204	2086	1.7	22	Q4
10	Medical Dosimetry	99	1719	1682	0.33	20	Q4

TLCS: Total Local Citation Score; TGCS: Total Global Citation Score; IF: impact factor.

promising future.

3.2 Analysis of countries and institutes

A total of 88 countries were identified as having published research articles on radiotherapy for PC from 1994 to the end of 2023. The geographical distribution of the global collaboration network is illustrated in Fig. 2A. Fig. 2B displays the countries and institutions with the highest citation counts. The network was organized using betweenness centrality, where nodes with high betweenness centrality scores typically connect two or more large node groups and significantly influence the network. Purple nodes indicate hotspots, and bright lines represent key pathway connections. The analysis showed that the US had the highest number of publications (n = 1847) and the greatest centrality score (0.44), followed by Italy (n = 490) and Germany (n = 447). Furthermore, the findings demonstrated that the US was the most cited country, with a total of 61,733 citations, while Germany ranked second (n = 15,386), followed by Canada (n = 13,843), England (n = 13,409), Italy (n = 12,501), Belgium (n = 6079) and France (n = 5276).

This study identified 3471 different institutions (Fig. 2C). The top five most cited institutions were the University of California System (n = 244), the University of Texas System (n = 236), the University of Toronto (n = 153), University of Texas MD (UTMD) Anderson Cancer Center (n = 153), and United Against Cancer (UNICANCER) (n = 143). The top three institutions in terms of centrality were UNICANCER (n = 0.13), Johns Hopkins University (n = 0.12), and the University of London (n = 0.10), indicating that collaboration between institutions was not particularly close.

3.3 Analysis of authors

The co-citation network clustering map of authors was developed in the current study using CiteSpace (Fig. 3A). The clustering labels and the collaborative associations among authors over the past 30 years were illustrated in the figure, with the names within clusters representing prominent figures in the field. Alongi F was identified as the most cited author and prolific radiotherapy contributor over the past three decades in the most recent and significant cluster, "following stereotactic body radiation therapy (SBRT)". His 2009 publication, "IMRT substantially decreases the acute toxicity of whole-pelvis irradiation in patients treated with post-operative adjuvant or

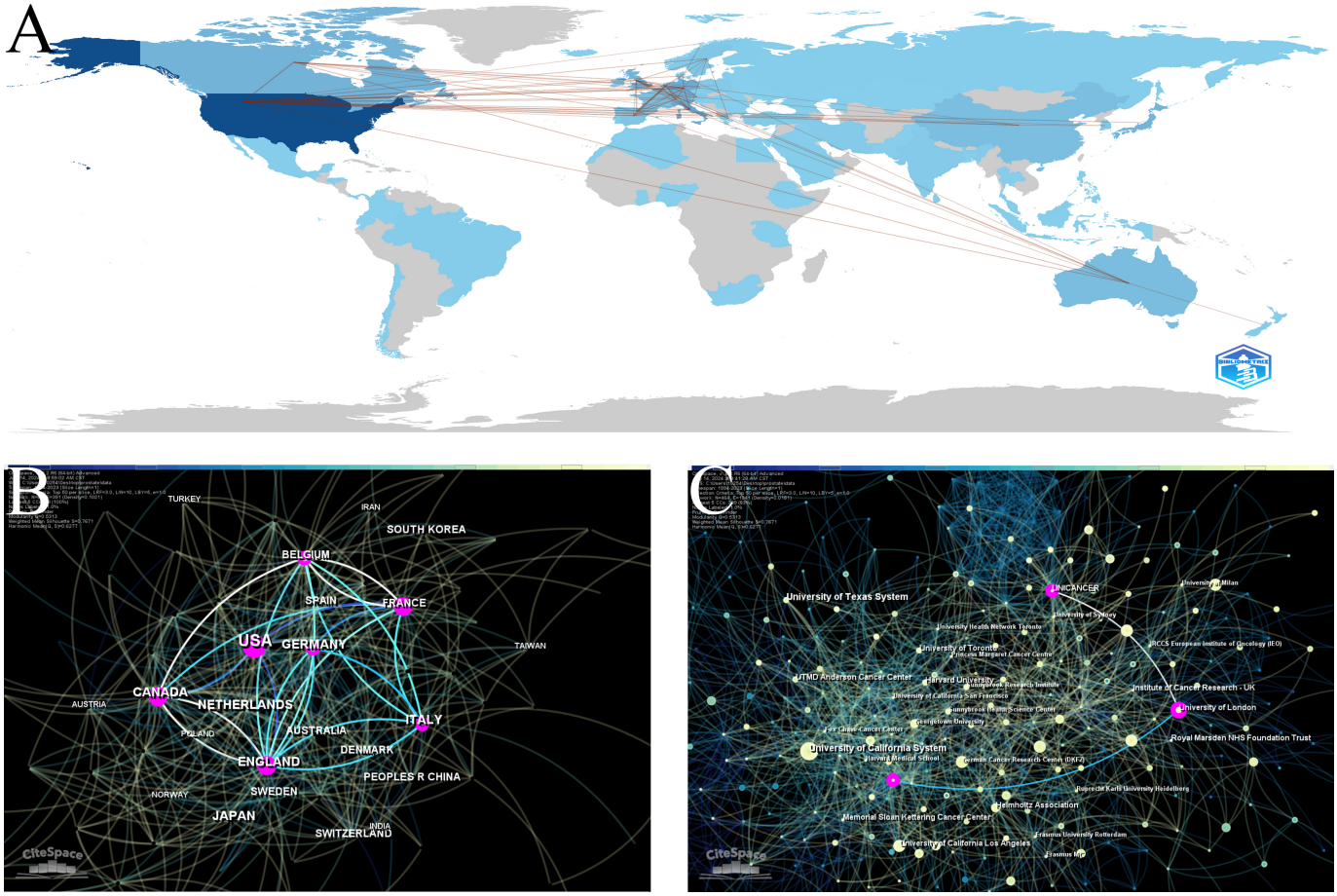


FIGURE 2. Representative cooperative network among countries and institutions focusing on radiotherapy for prostate cancer. (A) Global research output by geography, (B) Cooperation network of multiple countries, and (C) Institutional cooperation network. Note: Networks (B) and (C) were visualized using CiteSpace, limited to the top 50 countries. Node size reflects each entity's contribution, with larger nodes indicating greater importance (Q = 0.5313, S = 0.7671). Purple rings highlight nodes with high betweenness centrality, indicating crucial connections within the network. Brighter lines between nodes denote stronger co-occurrence and association within the dataset.

salvage radiotherapy after radical prostatectomy", was determined to have made a substantial contribution to the field of PC radiotherapy.

According to Fig. 3B, the top ten most prolific authors were listed.

Three authors with the highest publication counts were Alongi F from Istituto di Ricovero e Cura a Carattere Scientifico (IRCCS) Sacro Cuore Don Calabria (n = 66), Collins SP from Vanderbilt University (n = 60), and Jereczek-Fossa BA from the IRCCS European Institute of Oncology (IEO) (n = 57). Furthermore, Zelefsky MJ was recognized as an early researcher in radiotherapy for PC, having been active in this area for nearly 30 years. In 2011, he published his influential paper titled "High-dose intensity modulated radiation therapy for PC: early toxicity and biochemical outcome in 772 patients", which significantly contributed to the advancement of intensity-modulated radiation therapy (IMRT).

3.4 Analysis of keywords

This study used CiteSpace to construct a timeline of the keyword network from 1994 to 2023 (Fig. 4A). Eight groups of keywords were identified (Q = 0.5641; S = 0.8228), with the most significant being "stereotactic body radiation therapy", followed by "megavoltage cone-beam CT", treatment plan evaluation, "planning organ", external beam irradiation, "conformal radiotherapy", volumetric modulated arc therapy, and "prostate brachytherapy". The study additionally outlined the same network, constricting the temporal scope to 2019–2023 (Fig. 4B), and identifying seven clusters (Q = 0.5313; S = 0.7671). The foremost cluster was "knowledge-based planning", followed by "adaptive radiotherapy", "brachytherapy boost", "rectal retractor application", "targeted alpha therapy", "oligometastatic prostate cancer", "oligorecurrent prostate cancer" and "radiation proctitis".

Moreover, the keyword burst analysis (Fig. 4C) revealed the top five keywords with the highest burst strength: "outcome" (45.61), "organ motion" (41.6), "carcinoma" (38.99), "conformal radiation therapy" (38), and "stereotactic body radiotherapy" (36.58). The top five keywords with the longest burst duration were "carcinoma" (16), "complications" (16), "escalation" (15), "morbidity" (13), and "conformal radiation therapy" (13). The values in parentheses reflect the burst strength.

3.5 Analysis of reference co-citation

Co-citation analysis of the literature is a crucial method for detecting the structure and evolution of a specific field. Constructing a co-citation analysis network enables the tracing of academic knowledge distribution paths, comprehension of the knowledge network and disciplinary communication within the field, and identification of current research hotspots and core topics. This study constructed a visual network of co-cited literature (Fig. 5A) using a visual network and cluster analysis. This network identified 20 distinct clusters within the co-citation network. Three distinct main research trends emerged from the various clusters in this field (Fig. 5B). The first and most significant trend relates to the advancement of radiotherapy techniques.

These clusters were characterized by their labels, size, silhouette scores, average publication year, and most representative references: cluster #5 ("conventional v", 76, S = 0.975, 1993) [18], cluster #2 ("conformal radiotherapy", 51, S = 0.869, 1999) [19], cluster #0 (SBRT, 174, S = 0.948, 2006) [20], and cluster #1 ("intensity-modulated radiotherapy", 151, S = 0.869, 2014) [21]. However, PC radiotherapy has also advanced in the field of brachytherapy: cluster #4 ("select patient", 76, S = 0.973, 1995) [22] and cluster #11 ("permanent prostate brachytherapy", 55, S = 0.945, 1998). This research trend highlighted the progression of PC radiotherapy techniques, which have evolved from 3D conformal radiotherapy to intensity-modulated radiotherapy (IMRT) and hypofractionated treatments like CyberKnife and SBRT. Further, the precision and efficiency of brachytherapy have been enhanced by technological advancements.

The second significant trend was the precision of radiotherapy and the evaluation of treatment outcomes, which have been continuous with the advancement of radiotherapy techniques. Representative clusters in this trend include cluster #19 ("accuracy", 16, S = 1, 1993) [23], cluster #10 ("using dose-volume histogram", 56, S = 0.964, 1993) [24], cluster #8 ("planning delivery", 59, S = 0.98, 1995) [19], cluster #9 ("internal organ motion", 58, S = 0.961, 1995) [25], and cluster #7 ("intrafraction motion", 65, S = 0.97, 2005) [26]. Clusters related to treatment outcome evaluation include cluster #12 ("rectum complication", 51, S = 0.932, 1994) [27] and cluster #14 ("hormonal manipulation", 30, S = 1, 1994) [28].

The third major research trend was related to specific metastatic patterns of PC. The relevant clusters include cluster #6 ("skeletal metastases", 73, S = 1, 1993) [29], cluster #15 ("bone metastases", 27, S = 0.994, 1993) [30], and cluster #3 ("oligometastatic prostate cancer", 92, S = 0.966, 2018) [31].

The evolution trends predominantly focused on recent research developments in SBRT for PC, combination therapies, and the assessment of treatment outcomes [32–34]. SBRT has unique radiobiology and tumor immunology advantages, showing remarkable effectiveness in treating localized and metastatic PC [32]. Therefore, it is evident that SBRT technology is a crucial and essential component of treating PC.

4. Discussion

Globally, prostate cancer is among the most prevalent cancers diagnosed in men. Radical prostatectomy is one of the main treatment options; however, patients who undergo this surgical intervention frequently experience adverse effects, including sexual dysfunction and urinary incontinence [35]. For patients with low-risk PC, active surveillance is recommended according to clinical guidelines. For those with intermediate to high-risk prostate cancer, radiotherapy is a primary treatment option. There is no significant difference between radiotherapy and surgery in terms of tumor control rates, survival rates, and the incidence of adverse events [36]. However, patients who undergo radiotherapy tend to have experienced better urinary control and sexual function, despite enduring more significant bowel-related side effects [37].

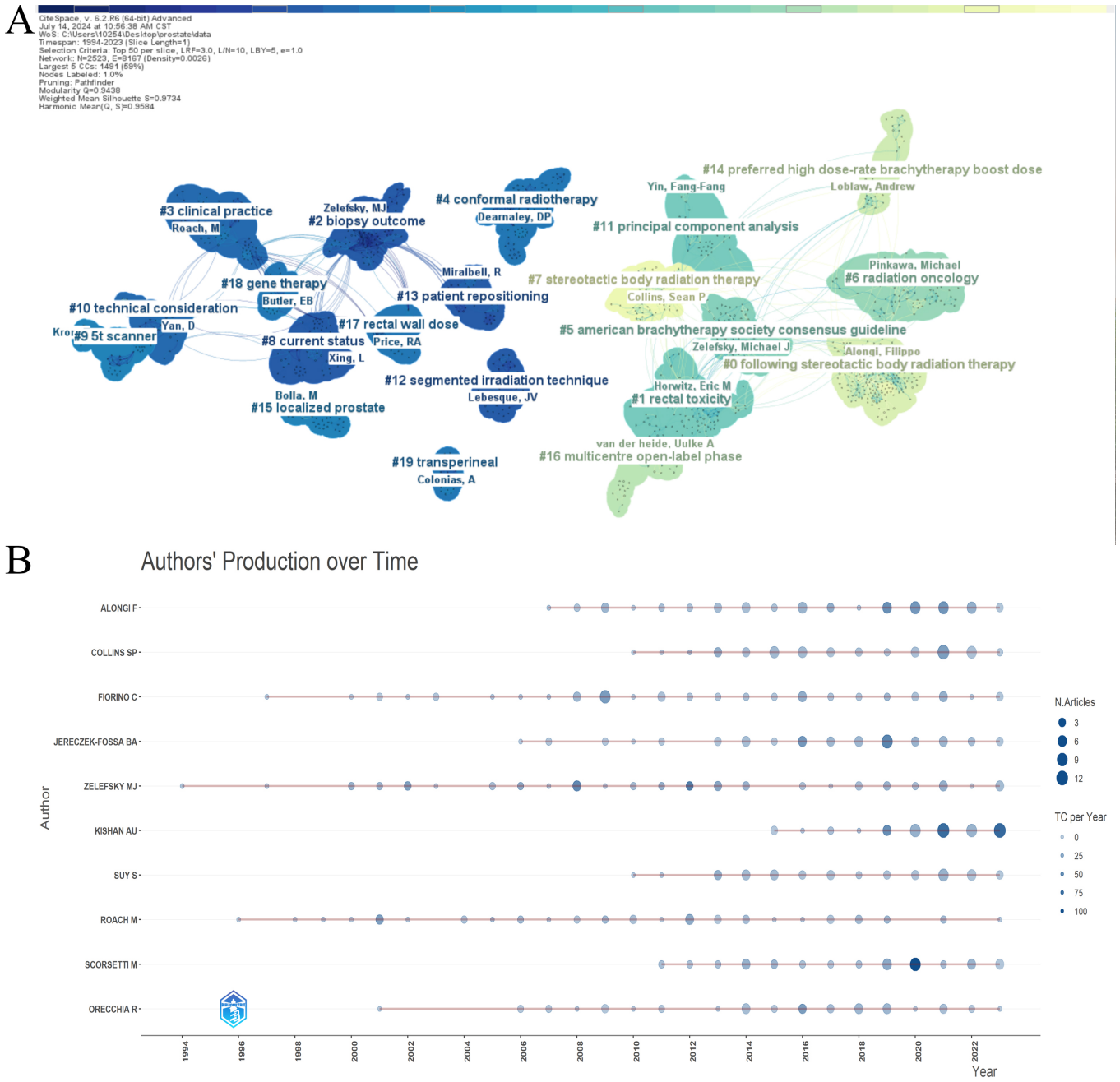
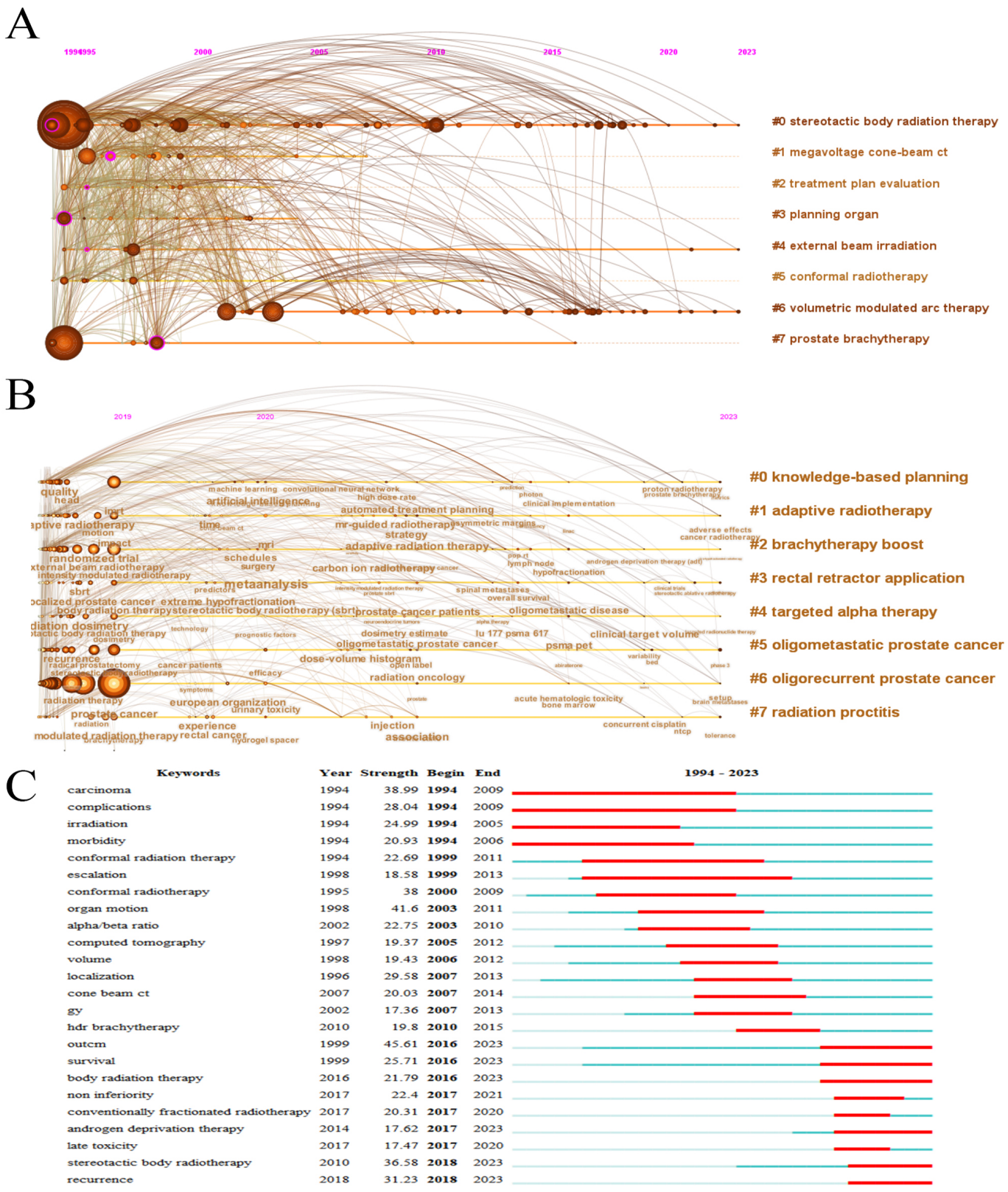


FIGURE 3. Visual analysis of authors in the field of radiotherapy for prostate cancer. (A) Cluster analysis of cooperation among authors. A cluster analysis of authors was conducted via the software tool CiteSpace (Q = 0.9438, S = 0.9734). The color of the clusters represents the proximity in time, with lighter colors indicating more recent time periods. The cluster labels are automatically generated by the software, and the names next to the labels represent the representative authors within each cluster. The nodes in the clusters represent individual authors. (B) Timeline distribution of the top 10 most productive authors. This graph was generated using The Bibliometrix Package in the R language. It showcases the top 10 authors with the highest output over 30 years. The size of the nodes represents the annual output of each author, with larger nodes indicating greater output in that year. The depth of the node's color reflects the number of citations received. Among them, Alongi F leads in total publications, Zelefsky MJ in highest research duration, Kishan AU in highest annual output (12 publications in 2021 and 2023), and Scorsetti M had the highest count in 2020. TC: total count.

The main radiotherapy techniques for PC include three-dimensional conformal radiotherapy (3D-CRT), intensity-modulated radiotherapy (IMRT), volumetric modulated arc therapy (VMAT), SBRT and brachytherapy [38]. 3D-CRT reduces the volume of normal tissue exposed to high radiation doses and modifies individual beams to conform to the tumor volume of PC. Further optimizing irradiation for irregularly shaped volumes in IMRT can obtain a more precise dose distribution to the PC target area [39]. VMAT combines the intensity modulation capability of IMRT with increased dynamic radiation delivery. It achieves more complex dose distribution in a shorter time by rotating the treatment beam



Keywords	Year	Strength	Begin	End
carcinoma	1994	38.99	1994	2009
complications	1994	28.04	1994	2009
irradiation	1994	24.99	1994	2005
morbidity	1994	20.93	1994	2006
conformal radiation therapy	1994	22.69	1999	2011
escalation	1998	18.58	1999	2013
conformal radiotherapy	1995	38	2000	2009
organ motion	1998	41.6	2003	2011
alpha/beta ratio	2002	22.75	2003	2010
computed tomography	1997	19.37	2005	2012
volume	1998	19.43	2006	2012
localization	1996	29.58	2007	2013
cone beam ct	2007	20.03	2007	2014
gy	2002	17.36	2007	2013
hdr brachytherapy	2010	19.8	2010	2015
outcm	1999	45.61	2016	2023
survival	1999	25.71	2016	2023
body radiation therapy	2016	21.79	2016	2023
non inferiority	2017	22.4	2017	2021
conventionally fractionated radiotherapy	2017	20.31	2017	2020
androgen deprivation therapy	2014	17.62	2017	2023
late toxicity	2017	17.47	2017	2020
stereotactic body radiotherapy	2010	36.58	2018	2023
recurrence	2018	31.23	2018	2023

FIGURE 4. Visual analysis of keywords related to prostate cancer radiotherapy. (A) A visual timeline of author keyword contribution network from 1994 to 2023. (B) A visual timeline of author keyword contribution network from 2019 to 2023. (C) CiteSpace's strongest citation bursts for the top 25 keywords. Note: The timeline visualization of keywords and the burst strength of keywords were constructed using CiteSpace. Nodes represent keywords, with the dot size reflecting the frequency of keyword co-occurrence bursts. The co-occurrence network was weighted by the total link strength of different keyword nodes and scored based on the average year of publication. The cluster labels were displayed in yellow on the right-hand side, along the progress of the timeline. (C) shows the time-ordered burst of keywords, revealing significant changes in the citation frequency of keywords within the field of PC radiotherapy during a specific period.

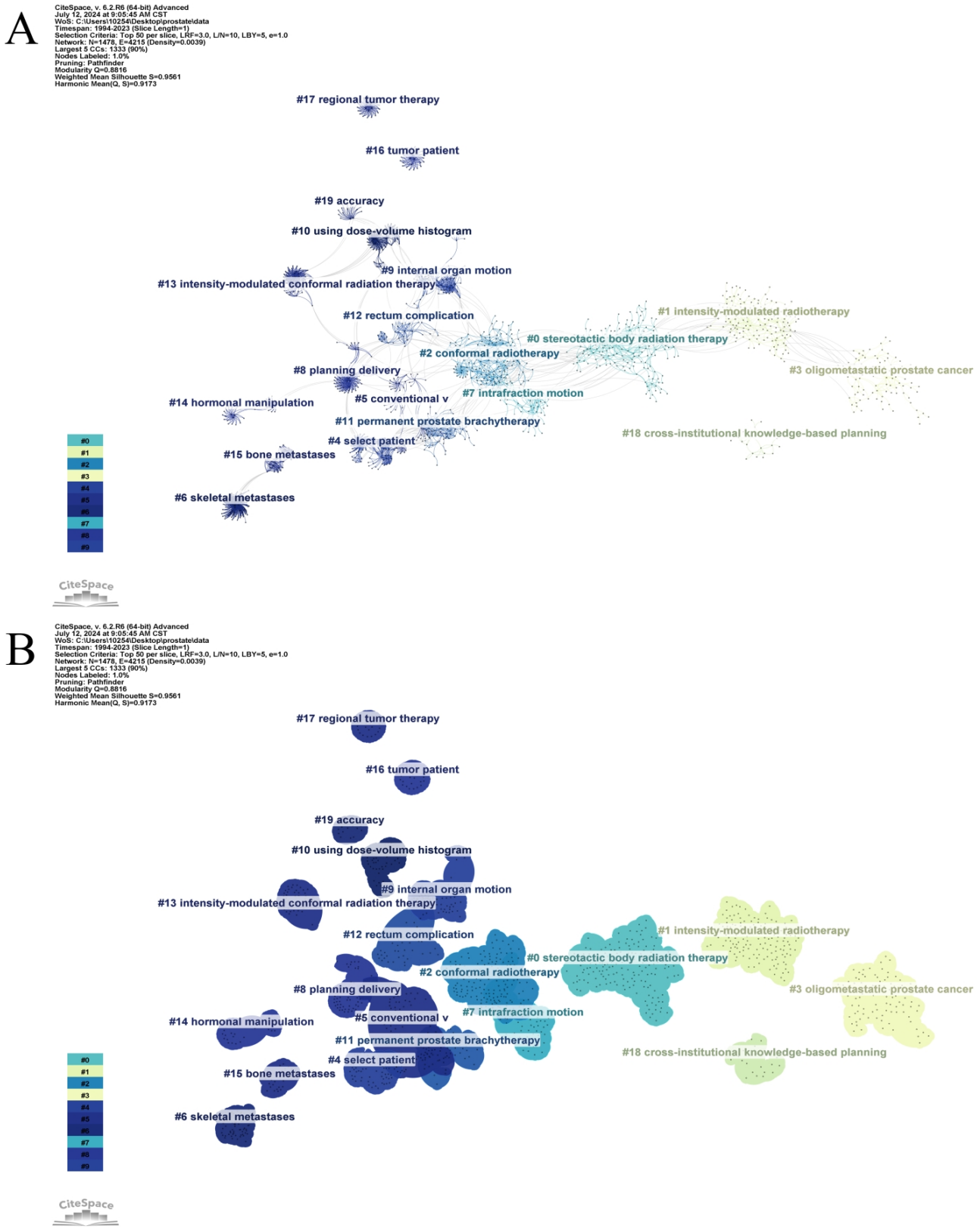


FIGURE 5. Visual network of co-citation reference analysis related to radiotherapy for prostate cancer. (A) Co-citation reference network featuring cluster visualization and hotspot burstiness. The size of a node (representing an article) scales with the frequency of its co-citations. (B) Visualization map of the corresponding clusters. The co-citation analysis and clustering map were generated by CiteSpace. The software automatically generates the clustering labels, and the nodes in the clusters represent co-cited documents. The colors in the two figures represent the proximity of time, with lighter colors indicating more recent periods. (A) displays the co-citation relationships among documents within clusters, while (B) shows the labels of each cluster along with their corresponding sizes and levels of importance (Q = 0.8816, S = 0.9561).

around the target area. Compared to IMRT, VMAT requires more complex planning and optimization, but it provides better tumor dose coverage and significantly improves dose delivery efficiency [40]. SBRT is an emerging treatment for prostate cancer. Due to its precision in radiation therapy, higher radiation doses, fewer side effects, and shorter treatment duration, it is gradually becoming an important option for the treatment of prostate cancer. In recent years, proton therapy has gained increasing attention as an emerging treatment method due to its unique "Bragg peak effect" in human tissues, which contrasts with traditional photon therapy. Several clinical studies have now validated the efficacy and safety of proton therapy in the treatment of prostate cancer [41–43].

This study has uncovered several remarkable trends and characteristics in this field. The significant number of publications indicates a clear trend of rising research output in the field. Among the top ten journals with the highest publication volume, the average impact factor approaches 3.0, with the highest recorded at 6.4. Collectively, these journals represent approximately 49% of the total publications, underscoring a growing global focus on radiotherapy for PC. Research on PC radiotherapy is currently being conducted globally, with the US leading in both the number of published papers and citation frequency in this field. Among them, the University of California System stands out as the institution with the highest number of citations and centrality. Some conventional radiotherapy methods for PC are being increasingly refined due to technological advancements, resulting in a more sophisticated radiotherapy framework. This study has identified SBRT as a research hotspot in this field through clustering analysis of keywords and co-cited references. Scholars have analyzed, compared and improved various aspects of this technology, including dose distribution, dose delivery, precision, and efficacy assessment, making SBRT a preferred option in PC radiotherapy.

Prostate cancer shows significant sensitivity to hypofractionated radiation, and substantial global research has been conducted on this treatment modality for PC. Moderate fractionation radiotherapy (using doses of 2.5–3 Gy per session) serves as an alternative to traditional radiotherapy and is typically delivered through IMRT or IMRT combined with image-guided radiotherapy (IGRT). This approach significantly reduces the total number of treatments while maintaining the therapeutic effects of traditional radiotherapy, which has led to extensive academic research. Dearnaley D *et al.* [44] demonstrated in a comparison between conventional radiotherapy and hypofractionated radiotherapy that delivering 60 Gy in 20 fractions was not inferior to delivering 74 Gy in 37 fractions of conventional fractionation. Some studies consistently demonstrate that administering higher doses per session while decreasing the number of sessions and the total dosage in hypofractionated radiation considerably reduces the treatment frequency, proving more effective than conventional fractionation [45, 46]. Kishan *et al.* [47] conducted a meta-analysis on 2142 men who received SBRT, with doses ranging from 33.5 to 40.0 Gy delivered in 4 to 5 fractions. Treatment was administered consecutively, every other day, or weekly depending on the specific protocol of each regimen. They found that SBRT is an effective technique for treating intermediate- to low-risk PC patients [47]. Another prospective study demonstrated that SBRT also yields favorable outcomes in treating high-risk localized cases [48]. Recent keyword studies reveal that adaptive radiation for prostate cancer has attracted considerable attention. This method can detect and measure specific changes in patient treatment during therapy, allowing plan modifications and enhancements. Adaptive radiotherapy for PC has the potential to further reduce target margins, enabling significant increases in target dose, and clinical trials have shown that it has significantly improved tumor control with low toxicity [49, 50]. Alongi *et al.* [51] first reported the feasibility of adaptive SBRT for PC in 2020. The study involved treating 25 patients with localized PC with SBRT, which was administered using an adaptive strategy requiring daily re-planning of critical structures and target contours. The results indicated no adverse events of ≥Grade 3. Only three patients experienced acute genitourinary toxicity of ≥Grade 2, and one patient reported mild rectal pain [51]. These data highlight the excellence of adaptive radiotherapy for prostate cancer.

The treatment principles and techniques for primary and metastatic PC are different. In the treatment of primary PC, the goal is to cure. Radiation therapy (such as IMRT, VMAT and brachytherapy) is used to achieve thorough tumor control and prevent disease recurrence. For intermediate- to high-risk PC patients, radiation therapy is often combined with androgen deprivation therapy (ADT) to improve local control rates and long-term survival. Combination treatment strategies have been shown to have better efficacy in many clinical studies. Bolla M *et al.* [52] assessed that adding androgen suppression adjuvant therapy during primary radiotherapy improved disease-free survival (DFS) in intermediate- to high-risk PC patients. A meta-analysis of data by Kishan AU *et al.* [53] demonstrated that combining radiation therapy with ADT significantly improved metastasis-free survival in patients with localized prostate cancer. For metastatic PC, a combined treatment strategy is typically required. For example, the combination of ADT and local radiation therapy can achieve better local control and survival outcomes. The combination of ADT and second-generation anti-androgens has proven to be more effective than using ADT alone [54].

The research findings also summarized several representative authors in this field. Alongi, the most prolific author in this field over the past thirty years, found in early comparative studies that IMRT poses a lower risk of acute toxicity than 3D-CRT during whole-pelvis irradiation after prostatectomy, allowing for better bowel preservation [55]. Dr. Zelefsky, a pioneering researcher in PC radiotherapy, highlighted in his 2011 study that IMRT lowers both acute and late rectal toxicity compared to conventional 3D conformal radiotherapy [56]. SBRT, which is distinguished by its precise targeting, high-dose delivery, and shorter treatment course, provides effects such as lowered radiation exposure to adjacent organs and high-dose conformity. It is currently a typical example of high-precision photon radiotherapy. Higher radiation doses have been shown to be more effective than lower doses. In terms of physician-reported toxicity outcomes, SBRT outperforms both IMRT and low-dose-rate (LDR) brachytherapy [57].

The current research has also identified significant uncertainties in PC radiotherapy. Scholars are exploring various imaging modalities to address these uncertainties and improve treatment outcomes. Cone-beam computed tomography (CBCT) is the most commonly used image-guided radiotherapy (IGRT) technique in radiotherapy. However, CBCT has some drawbacks, including excessive scatter, poor image quality, and ionizing radiation [58, 59]. Magnetic resonance image-guided radiotherapy (MRIgRT) can alleviate these concerns due to its high soft tissue contrast. Combining a linear accelerator with MRI's remarkable soft tissue contrast can improve treatment outcomes and increase precision, particularly when treating tumors in intricate anatomical regions [60]. Ma TM *et al.* [61] discovered that MR-guided radiotherapy for PC markedly diminishes initial genitourinary toxicity and enhances urine and bowel function compared to CT-guided radiotherapy. Another prospective study showed that in patients with intermediate- to high-risk localized PC treated with MR-guided stereotactic body radiotherapy (SBRT), the incidence of Grade 2 or higher acute genitourinary toxicity was 23.8%, which is much lower than the toxicity rates associated with conventional radiotherapy [62]. The high soft tissue contrast makes MRI an ideal imaging modality for online adaptive radiotherapy (ART), as MRI images provide greater accuracy in target and organ-at-risk delineation. This allows the clinical target volume (CTV) margin to the planning target volume (PTV) to be safely reduced to <3 mm [63]. Reducing the PTV margin decreases toxicity or allows for safe dose escalation to eradicate the tumor [64]. Furthermore, motion detection during treatment, enhanced by real-time anatomical imaging, allows for more accurate target dose administration, enhancing therapeutic efficacy [65, 66]. In contrast to functional imaging, MRIgRT can detect changes during treatment in real-time. Cine MRI enables the observation of target drift and organ-at-risk motion throughout treatment fractions. It establishes MRI, with its higher soft tissue contrast, as the ideal imaging technology for PC radiotherapy [67]. Multimodal imaging techniques that combine the anatomical information from CT with the soft tissue contrast of MRI can more accurately define the tumor and surrounding normal tissues, thereby improving treatment precision and efficacy. A study by Tzikas *et al.* [68] showed that the CTV volume delineated on fused CT-MRI images was 46.1 ± 17.8 cm^3, much smaller than the volume observed using CT images alone, and CT-MRI fusion images resulted in better dose distribution and a reduced probability of bladder and rectal complications.

This study has several limitations. Firstly, the data sources were restricted to the WoSCC database, which may have excluded relevant information from other significant databases, thus introducing bias into the study. Therefore, incorporating publications from additional databases like Scopus would be advantageous. Secondly, the bibliometric analysis predominantly depended on published literature, neglecting unpublished studies or negative results, which may exclude specific research hotspots or trends.

5. Conclusions

In conclusion, prostate cancer radiotherapy is rapidly advancing, with key areas of focus on SBRT, multimodal imaging, adaptive radiotherapy, and proton and heavy-ion therapy. The United States is at the forefront of these developments, demonstrating a strong commitment to improving precision and treatment efficacy. These trends underscore the ongoing efforts to enhance therapeutic outcomes for prostate cancer.

AVAILABILITY OF DATA AND MATERIALS

The data in this study is accessible in the public domain and not of a confidential nature. The corresponding author: bzg19564133451@163.com could be contacted for all data for scientific purposes.

AUTHOR CONTRIBUTIONS

QFS and ZGB—designed the research study. ZGB and LLZ—performed the research. ZGB and YCW—analyzed the data. ZGB and YPX—wrote the manuscript. SWJ, YXD and JQC—provided the critical advice for this study. All authors contributed to editorial changes in the manuscript. All authors read and approved the final manuscript.

ETHICS APPROVAL AND CONSENT TO PARTICIPATE

No ethical approval and patient consent were required for all analysis.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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