

Research Progress of 3D Printing Combined with Virtual Reality Technology in Medical Education Practice: A Bibliometric Analysis Based on Web of Science

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Abstract

Objective: This study aims to systematically review the current research status, hotspots, and emerging trends of the application of 3D Printing (3DP) and Virtual Reality (VR) technology in the field of medical education, providing a reference for the future development of this field. **Methods:** Using the Web of Science Core Collection database as the data source, relevant literature was retrieved, and bibliometric software such as CiteSpace was used to conduct a visual analysis of annual publication volume, countries/regions, research institutions, authors, and keywords. **Results:** 1) Research in this field began in 1991, entered a period of rapid growth starting in 2018, and peaked in 2024, showing strong development momentum. 2) The United States, China, Germany, and the United Kingdom are the core forces in this research field, with close international cooperation. 3) Major research institutions include world-leading universities such as Imperial College London and Harvard University; institutional collaboration shows clear clustering characteristics, and the landscape of influence shows dynamic evolution. 4) Research hotspots focus on anatomy and surgical applications, and delve into core technical challenges such as model accuracy, registration, and simulation of mechanical properties. 5) The current research frontier is highly focused on the deepening of clinical applications, such as development based on mixed reality platforms (HoloLens), applications in fields like cancer radiotherapy, and the evaluation of clinical outcomes. **Conclusion:** 3D printing and virtual reality technologies have become deeply integrated into medical education, and research has progressed from conceptual demonstration to addressing the technical bottlenecks of clinical-level precision. In the future, research in this field will focus more on application implementation on specific hardware platforms, integration with high-risk clinical

workflows, and validation of final treatment outcomes.

Keywords

3D Printing (3DP), Virtual Reality (VR), Medical Education, Bibliometrics, Surgery

1. Introduction

With the in-depth development of the new wave of technological revolution, modern medical education is facing unprecedented transformational opportunities and challenges. The traditional apprenticeship teaching model, centered on the “master-apprentice” relationship, has historically cultivated countless outstanding physicians, but it has shown inherent limitations in terms of standardization, safety, efficiency, and the handling of complex cases (Farmer et al., 2023). Especially in fields highly dependent on practical operation, such as anatomy teaching and surgical skills training, traditional methods face numerous bottlenecks: anatomical specimens are scarce, costly, non-reusable, and lack pathological diversity (Rassie, 2017); clinical practice opportunities are unequal, making it difficult for young doctors to receive sufficient training for rare or high-risk surgeries, and the “trial-and-error” learning directly on patients brings enormous ethical and safety pressures (Sandblom et al., 2024). Furthermore, traditional two-dimensional medical imaging (such as CT, MRI) makes it difficult to intuitively display complex, individualized three-dimensional anatomical structures, increasing the difficulty of spatial imagination for learners (Fidvi et al., 2023).

Against this backdrop, disruptive technologies represented by 3D printing (Three-Dimensional Printing, 3DP) and Virtual Reality (VR) have provided innovative solutions to break through the dilemmas of traditional medical education. 3D printing technology can convert digital medical imaging data into high-fidelity physical models. It can not only accurately replicate standard anatomical structures but also create “tailor-made” pathological models for specific patients, allowing medical students and junior doctors to deeply understand complex spatial relationships and pathological features through touch and observation, thereby greatly enhancing the quality of preoperative planning and surgical simulation (Tejo-Otero et al., 2020). On the other hand, virtual reality technology uses computers to generate a highly immersive, interactive three-dimensional virtual environment, allowing learners to repeatedly conduct standardized surgical procedure training and handle emergency situations under zero-risk conditions, effectively shortening the learning curve and improving operational proficiency and clinical decision-making abilities (Labovitz & Hubbard, 2020).

More revolutionarily, the “physical realism” of 3D Printing and the “dynamic interactivity” of virtual reality are not mutually exclusive; their fusion can create a synergistic teaching effect where “1 + 1 > 2” (Weinstock et al., 2017). Learners

can first establish an intuitive understanding and tactile memory of anatomical structures by holding a 3D printed model, then enter a VR environment for dynamic surgical simulation, thereby constructing a complete learning loop from “physical to virtual” and then to “practice” (Burdall et al., 2016). This model, which combines the virtual and the real, creates an unprecedented high-fidelity, quantifiable, and personalized training paradigm.

Although the application of single technologies in medical education has been extensively studied, a systematic, macroscopic bibliometric review of the research landscape, hotspot evolution, and future trends of the integrated application of 3D Printing and virtual reality technologies is currently lacking. To clearly delineate the knowledge structure and development trajectory of this emerging interdisciplinary field, this study utilizes CiteSpace software to conduct a bibliometric analysis of relevant literature from the Web of Science Core Collection database, aiming to:

- 1) Reveal the developmental history and annual trends of the research field.
- 2) Identify the core global research forces, including countries, institutions, and scholars.
- 3) Investigate the core research hotspots and thematic evolutionary paths of the field.
- 4) Predict future research frontiers and potential development directions based on data-driven insights.

2. Data and Methods

2.1. Data Source and Retrieval Strategy

The data for this study were sourced from the Web of Science (WoS) Core Collection database. To ensure the comprehensiveness and accuracy of the data, the retrieval strategy was set as: Topic (TS) = (“3D print*” OR “three dimensional print*” OR “additive manufactur*” OR “rapid prototyp*”) AND TS=(“virtual reality” OR VR OR “augmented reality” OR AR OR “mixed reality” OR MR OR “extended reality” OR XR OR holograph*) AND TS=(“medical education” OR “nursing education” OR “surgical education” OR “anatomy education” OR “clinical education” OR “dental education” OR “medical training” OR “nursing training” OR “surgical training” OR “clinical training” OR ((medic* OR nurs* OR surg* OR clinic* OR anatom* OR dental) NEAR/3 (educat* OR train* OR simulat* OR learn* OR student* OR resident*)) OR “surgical plan*” OR “preoperative plan*” OR “surgical rehearsal” OR “surgical simulation” OR “clinical simulation” OR “surgical navigation” OR “patient specific model*” OR “anatomical model*” OR “image guided” OR diagnos* OR therap* OR treatment* OR procedur* OR orthoped* OR neurosurg* OR cardiac OR cardiolog* OR maxillofacial OR craniofacial OR hepatic OR liver OR urolog* OR radiolog* OR oncolog* OR gastroenterolog* OR gynecolog* OR obstetric* OR otolaryngolog*); Time span: All years (search up to July 2025); Document type: Article. To ensure the reproducibility of the dataset, we established clear inclusion and exclusion criteria. Inclusion criteria

were: 1) Document type is “Article”; 2) Language is English. Exclusion criteria were: 1) Document types such as conference abstracts, reviews, editorials, letters, etc.; 2) Literature irrelevant to the topic. After the initial retrieval, we first excluded document types that did not meet the criteria and then performed deduplication in CiteSpace software, finally including 714 articles as the final analysis sample.

2.2. Analysis Tools

The bibliometric analysis software CiteSpace (version 6.2.R4) was used for data processing and visualization. The main outputs generated and interpreted were the annual publication trend chart, country/institution/author collaboration network maps, and keyword co-occurrence, cluster, timeline, and burst maps. To ensure methodological replicability, the key parameters in CiteSpace were set as follows: The time slicing was set from 1991 to 2025, with 1 year per slice. For network pruning, we used both Pathfinder and Pruning Sliced Networks algorithms to simplify the network structure and highlight the most important collaborative relationships and knowledge flow paths. Node types (e.g., Country, Institution, Author, Keyword) were selected according to the analysis needs. The thresholds for each map were adjusted based on the number of nodes to ensure readability and aesthetic quality.

3. Results and Analysis

3.1. Annual Publication Trend Analysis

According to **Figure 1**, the earliest research literature in this field can be traced back to 1991. However, before 2017, the annual number of publications was extremely low, indicating a long embryonic and exploratory phase. Starting from

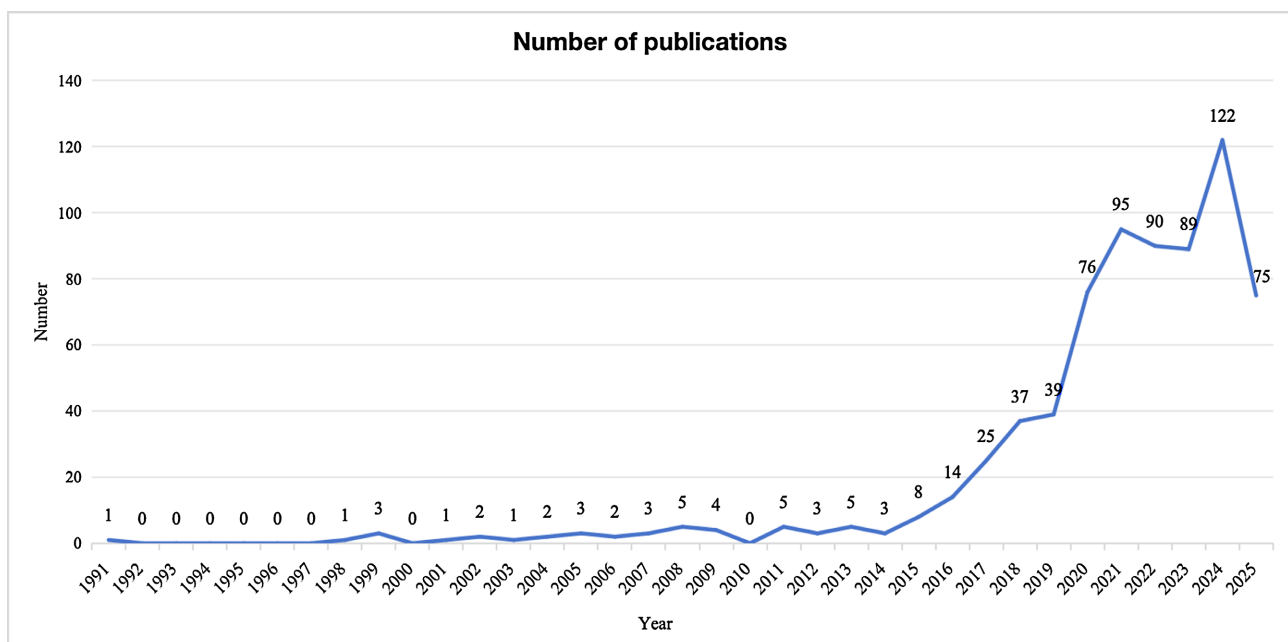


Figure 1. Annual publication trend chart.

2018 (with 25 publications), the field entered a period of rapid growth, with the annual publication volume continuously climbing and peaking in 2024 at 122 articles. This clearly indicates that the application of 3D printing combined with VR in medical education, as an emerging interdisciplinary research area, has received sharply increased attention from the academic community in recent years and has entered a high-speed development stage.

3.2. Analysis of Research Forces

To present the core research forces in this field more intuitively, **Table 1** compactly displays the top five countries, institutions, and authors by publication count and centrality, providing a quantitative basis for the subsequent network map descriptions.

Table 1. Top five countries, institutions, and authors by publication count and centrality.

| Rank | Category | Name | Count | Centrality |
|------|-------------|---------------------------------------|-------|------------|
| 1 | Country | USA | 198 | 0.12 |
| 2 | Country | CHINA | 106 | 0.06 |
| 3 | Country | GERMANY | 87 | 0.18 |
| 4 | Country | ITALY | 64 | 0.14 |
| 5 | Country | ENGLAND | 63 | 0.58 |
| 1 | Institution | University of London | 17 | 0.14 |
| 2 | Institution | Harvard University | 13 | 0.00 |
| 3 | Institution | Helmholtz Association | 13 | 0.02 |
| 4 | Institution | University College London | 13 | 0.17 |
| 5 | Institution | Harvard University Medical Affiliates | 12 | 0.01 |
| 1 | Author | Pascau, Javier | 7 | 0.00 |
| 2 | Author | Moreta-Martinez, Rafael | 5 | 0.00 |
| 3 | Author | Anand, Arun | 4 | 0.00 |
| 4 | Author | Lang, Hauke | 4 | 0.00 |
| 5 | Author | Hansen, Christian | 4 | 0.00 |

3.2.1. Country/Region Cooperation Network Analysis

As shown in **Figure 2**, where node size represents publication volume and lines represent cooperative relationships, the USA's publication volume and network centrality are far ahead, making it the absolute core of the field. The nodes for PEOPLES R CHINA, GERMANY, and ENGLAND are also very prominent, collectively forming the first tier of research. Additionally, ITALY, AUSTRALIA, CANADA, and other countries are important contributors. In terms of network structure, the connections between countries are close, forming an international cooperation network with the US, China, Germany, and the UK as hubs, indicating a high degree of internationalization in this research area.

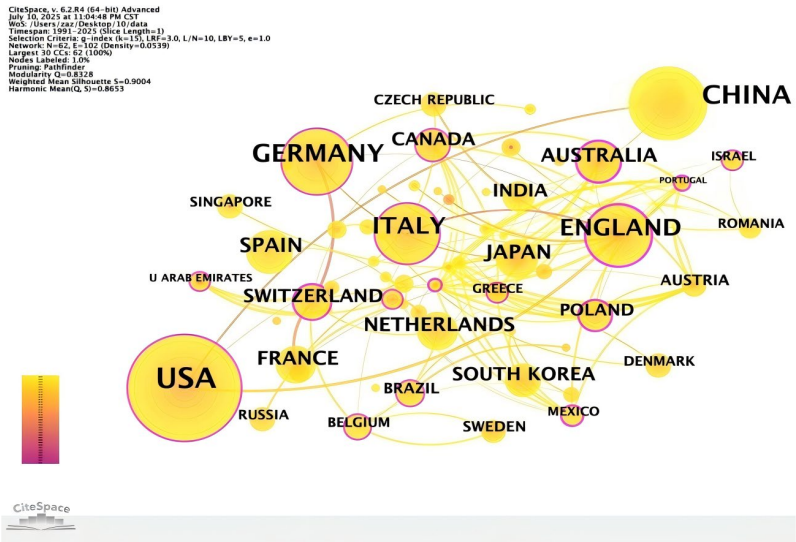


Figure 2. Country cooperation network map.

3.2.2. Research Institution Cooperation Network Analysis

From Figure 3, it is evident that the research forces in this field are highly concentrated in world-leading universities and national-level research institutions. The institutions with the highest publication volumes include Imperial College London, Harvard University, University College London, Shanghai Jiao Tong University, and France's National Institute of Health and Medical Research (Inserm) and National Center for Scientific Research (CNRS).

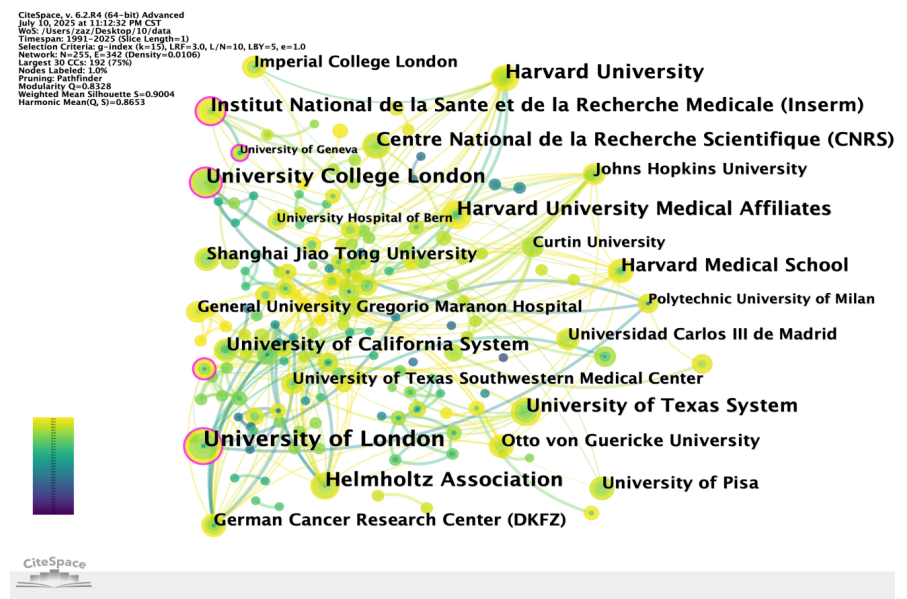


Figure 3. Research institution cooperation network map.

In terms of network structure, the institutional cooperation network exhibits typical characteristics of “large dispersion, small clusters” rather than a sparse web. Several closely connected research clusters have formed, such as the British

cluster centered around the University of London system, the American cluster centered around Harvard University, and the clusters of national research centers in Germany and France. This indicates that stable cooperative relationships and research teams have formed within various academic powerhouses, but there is still room for further strengthening of large-scale cooperation projects across clusters and countries.

3.2.3. Institutional Burst Analysis: Identifying Hubs of Influence

Institutional citation burst analysis can reveal research institutions whose influence grew rapidly during different periods. As shown in **Figure 4**, the academic hubs in this field show a dynamic evolution. Before 2018, Harvard University and its affiliated institutions were the core of early influence. Between 2018 and 2022, the academic influence of institutions like the University of London (strength 3.39) rose sharply. Since 2022, institutions such as the Chinese PLA General Hospital (strength 2.41), France’s Inserm (strength 1.89), and the Polytechnic University of Milan (strength 1.71) have shown strong burst momentum that continues to the present, representing the most dynamic emerging research forces in the field today.

Top 25 Institutions with the Strongest Citation Bursts

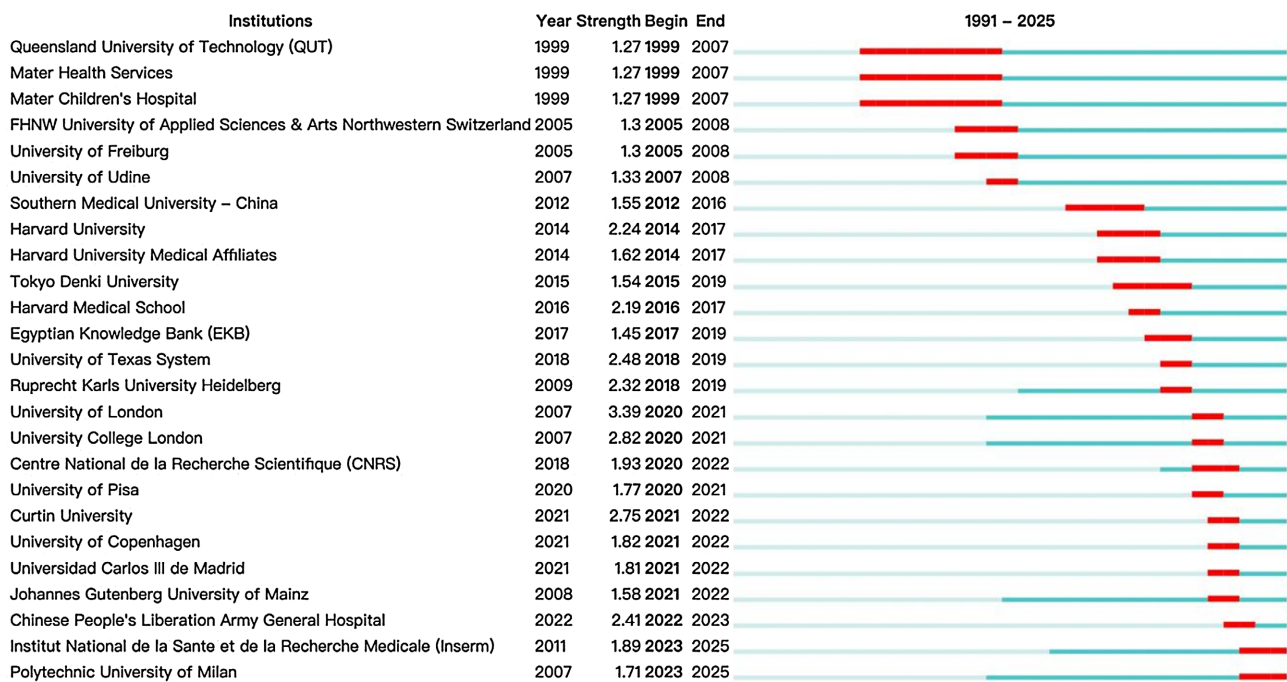


Figure 4. Institutional burst analysis chart.

3.2.4. Author Cooperation Network Analysis

Figure 5 displays the core authors and their cooperative relationships in this field. The network shows a typical “large dispersion, small clusters” cooperation model, forming several closely connected but relatively independent author clusters. Among them, larger research teams include the team centered on Spanish scholars

Top 25 Authors with the Strongest Citation Bursts

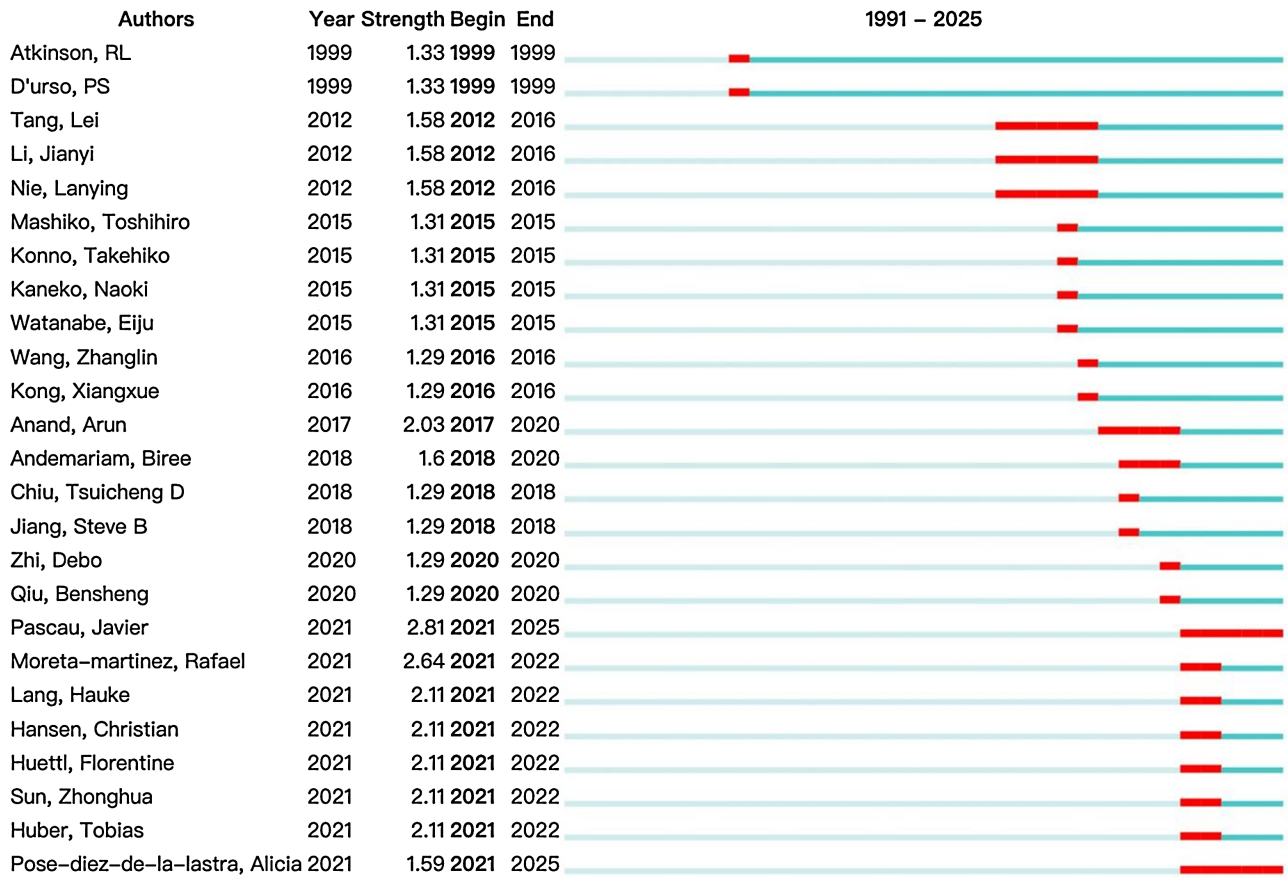


Figure 6. Author burst analysis chart.

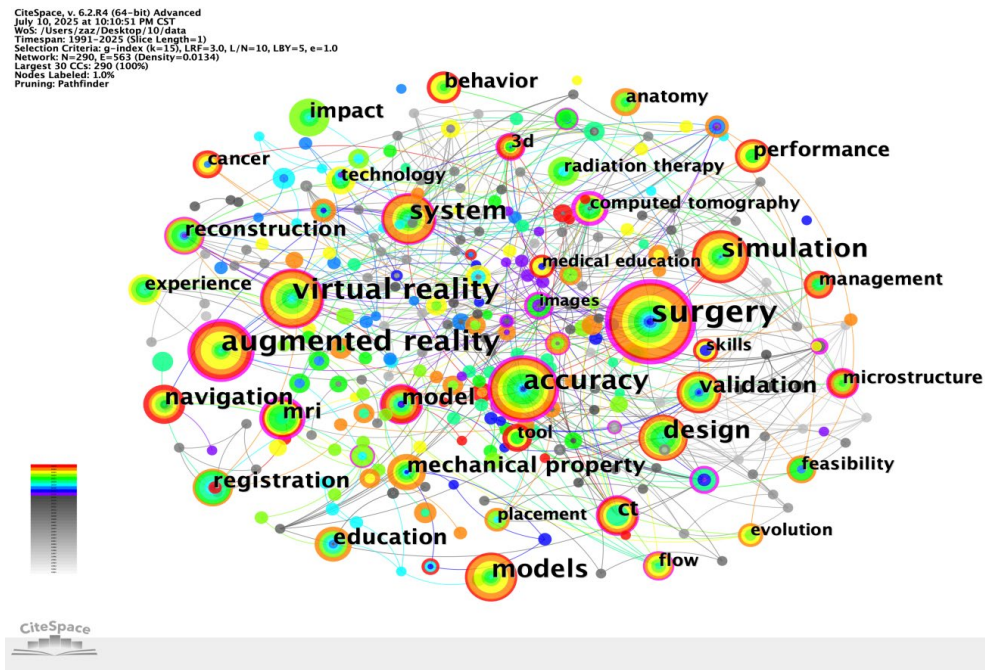


Figure 7. Keyword co-occurrence network map.

research hotspots of the field. The largest and most central nodes in the figure clearly form the four pillars of the research: the core technologies virtual reality and augmented reality, the core application surgery, and the core objective simulation.

A key finding is that accuracy, as a technical keyword, also occupies a central position in the network and is closely connected to nodes such as validation, registration, model, and mechanical property. This indicates that research in this field not only focuses on the application of technology but also places a high degree of focus on improving the precision and reliability of simulation systems in clinical applications. Additionally, words like medical education and anatomy form the broader context of the research.

3.3.2. Keyword Clustering and Thematic Evolution Analysis

To delve deeper into the research themes, we conducted a keyword cluster analysis (Figure 8). As shown, CiteSpace identified 12 major clusters, with a network modularity $Q = 0.8328$ and a mean silhouette $S = 0.9004$, indicating that the clustering structure is significant, the homogeneity is high, and the results are highly credible. These clusters reveal the core technical challenges and application directions of the research, which can be summarized into the following main research themes.

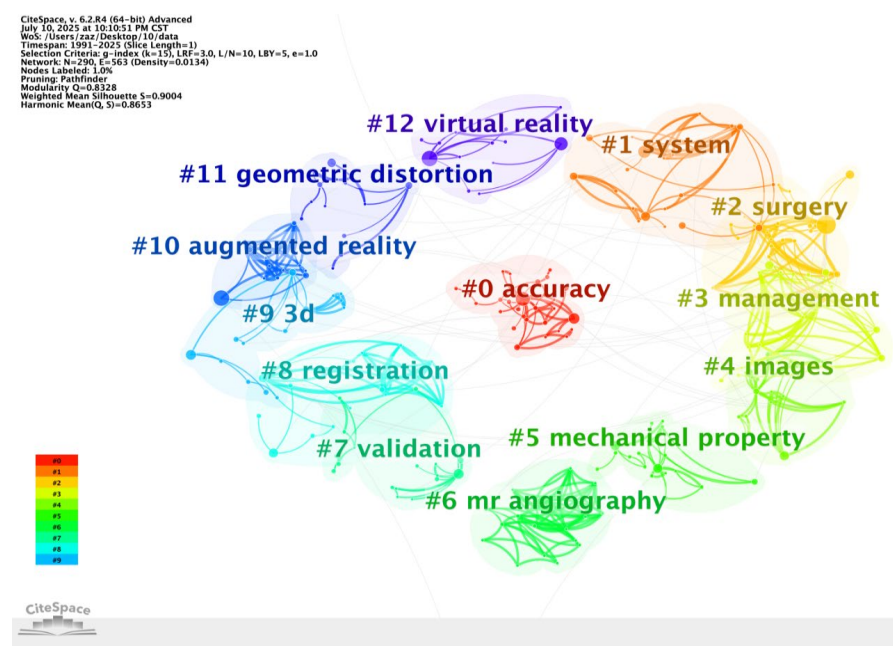


Figure 8. Keyword cluster map.

Theme 1: Core Technologies and Application Scenarios. Comprised of clusters #12 virtual reality, #10 augmented reality, #9 3d, and #2 surgery. This group of clusters clearly defines the fundamental framework of the field, which is centered on VR, AR, and 3D technologies serving the simulation, planning, and training of surgical procedures.

Theme 2: Model Accuracy and Reliability. Comprised of clusters #0 accuracy,

#8 registration, #11 geometric distortion, and #7 validation. This is a key finding of this analysis, indicating that the research has delved into the bottleneck problems of technical implementation. Among these, accuracy and geometric distortion focus on the fidelity from medical images to 3D models; registration is the core technology for achieving precise alignment between virtual information and the real world; and validation is dedicated to verifying the effectiveness of the entire system and model. This signifies that the research has shifted from conceptual demonstration to the pursuit of clinical-grade precision and reliability.

Theme 3: Data Foundation and Physical Simulation. Comprised of clusters #4 images, #6 mr angiography, and #5 mechanical property. This group of clusters reveals the data sources for the research (high-quality medical images, especially MR angiography) and the trend towards higher-level simulation. The emergence of the mechanical property cluster is significant, as it indicates that research is no longer limited to simulating geometric forms but has begun to explore the simulation of the mechanical properties of biological tissues, which is crucial for achieving high-fidelity haptic feedback in surgical simulations.

Theme 4: Systematization and Process Management. Comprised of clusters #1 system and #3 management. This indicates that researchers are also exploring how to integrate various disparate technologies into a complete, usable working system and how to effectively manage the complex process from data acquisition to simulation training.

The timeline view (Figure 9) more intuitively reveals the dynamic evolution of

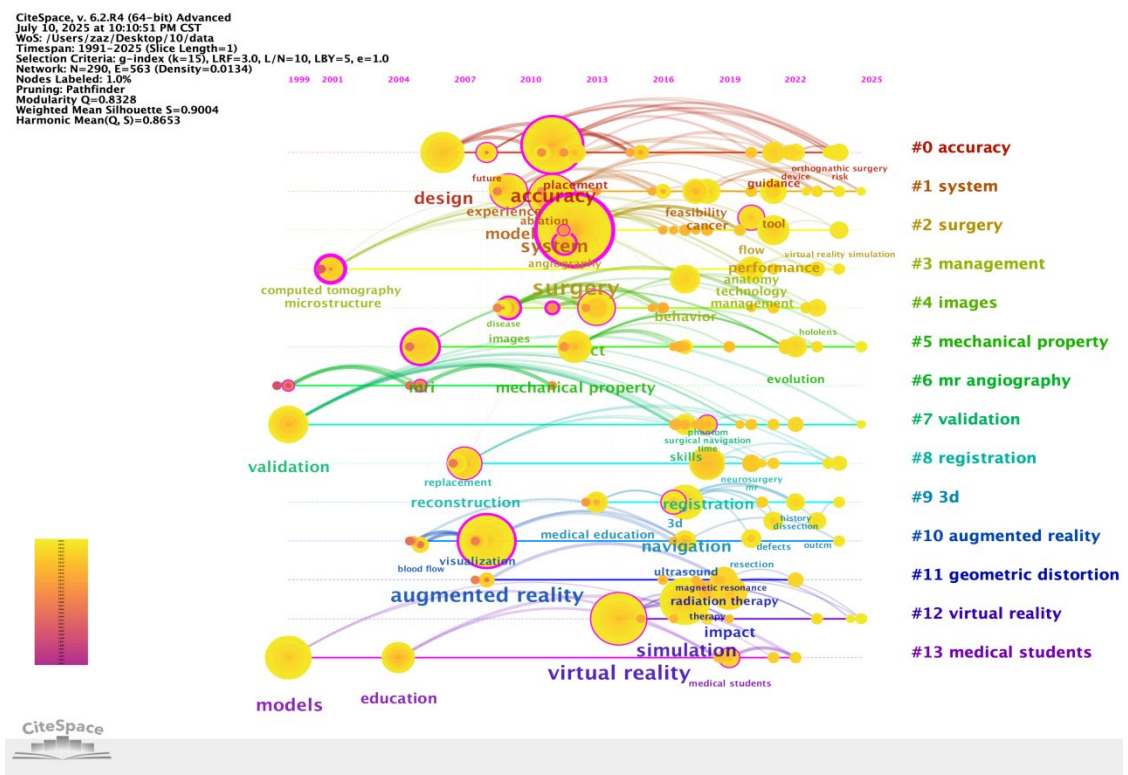


Figure 9. Keyword cluster timeline chart.

these research themes. It can be seen that before 2010, the research was in a foundational stage, mainly revolving around basic concepts such as *surgery* (#2), *images* (#4), and *medical students* (#13). From 2010 to 2018, the field entered a phase of technological emergence, where core technology clusters like *virtual reality* (#12) and *augmented reality* (#10) became active, and attention to technical bottlenecks like *accuracy* (#0) and *registration* (#8) also emerged. After 2018, the field entered a stage of high-speed development and deepening, with the research intensity of all themes increasing sharply. More specific keywords focused on clinical application and evaluation, such as *navigation* and *performance*, emerged, signaling that the research is moving towards more specialized and practical directions.

3.3.3. Keyword Burst Analysis: Research Frontiers

Keyword citation burst analysis (Figure 10) is a powerful tool for identifying the dynamics of research frontiers. As shown, the research frontiers in this field have undergone clear evolutionary stages.

Top 25 Keywords with the Strongest Citation Bursts

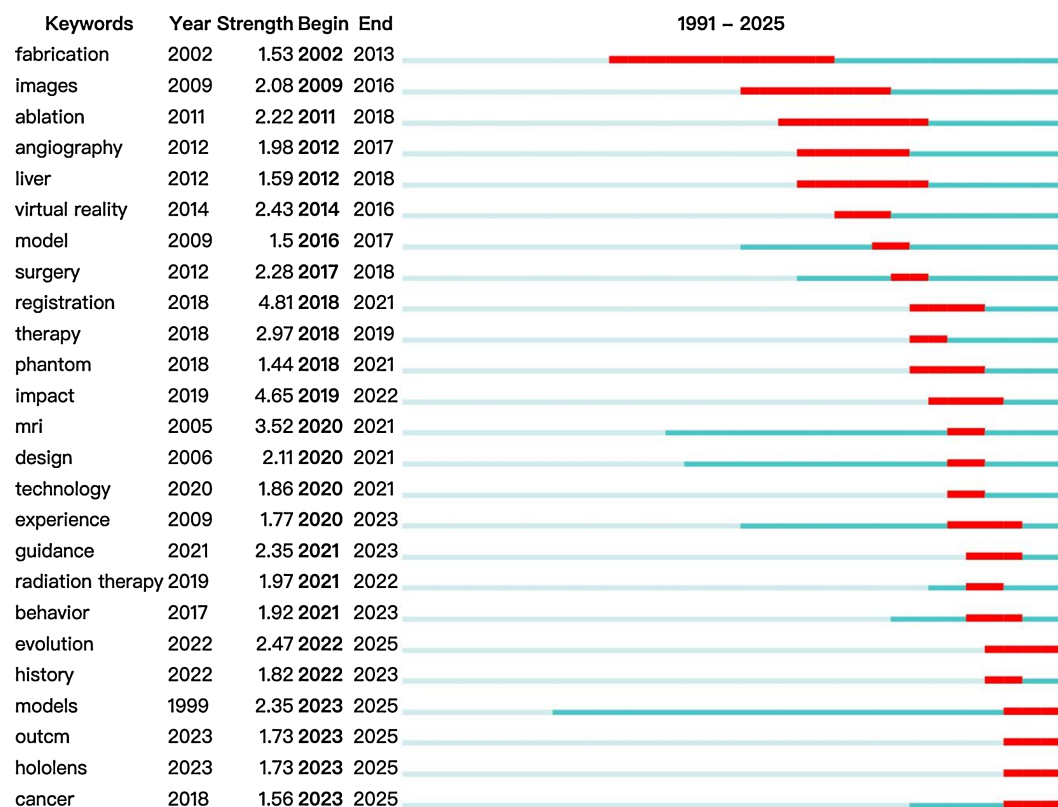


Figure 10. Keyword burst analysis chart.

Foundational Stage (bursts ended around 2018): The early bursts of keywords such as *images*, *virtual reality*, *surgery*, and *models* reflect the initial research interest in exploring the use of medical imaging to construct virtual or physical models for surgical simulation.

Deepening Stage (bursts between 2018 and 2022): The term registration showed an extremely high burst strength (4.81) during this period. Along with the bursts of MRI, design, and impact, this marks a shift in research focus towards overcoming the high-precision registration techniques in virtual-real fusion and beginning to systematically design and evaluate the actual impact of the technology.

Current Frontiers (bursts continuing into 2023-2025): Recently emerged keywords clearly point to the current research frontiers. First, the appearance of HoloLens indicates that research has evolved from exploring generalized AR/VR technologies to developing deep applications based on specific Mixed Reality (MR) hardware platforms. Second, the bursts of guidance, radiation therapy, and cancer reveal that the technology is being deeply integrated into high-risk clinical treatment processes (such as tumor radiotherapy and surgical guidance). Finally, the emergence of outcome (outcome) is highly significant. It marks a shift in the ultimate evaluation criterion of research from technical feasibility to the improvement of actual patient treatment outcomes, which is a key step for research to mature and translate into clinical practice.

4. Discussion

This study has systematically depicted the research landscape of the application of 3D Printing and VR technologies in medical education through bibliometric methods. Based on the analysis, we believe that the development of this field exhibits distinct stage-based characteristics and points towards a highly intelligent, virtual-real integrated future.

4.1. The Field Is Developing Rapidly, but Cooperation Barriers Remain, Urgently Requiring a Collaborative Innovation Paradigm

The publication trend analysis in this study (**Figure 1**) clearly shows that since 2018, research output in this field has grown exponentially, marking its transition from a preliminary exploratory phase to a “fast track” of high-speed development. This is closely related to the surging global demand for precision medicine and medical education reform (Amin et al., 2024). However, the cooperation network maps of countries, institutions, and authors (**Figures 2-5**) also reveal a problem that cannot be ignored: although a few countries led by the US and China have formed a research core, the overall cooperation network density is low, showing a pattern of “large dispersion, small clusters”. This indicates that most research is still confined to the independent exploration of single institutions or small teams, and a large-scale, cross-regional collaborative innovation network has not yet formed.

The existence of these cooperation barriers may stem from several factors: first, the cost of high-quality VR/AR equipment and 3D printing materials and devices remains high, limiting the popularization of the technology and the conduct of multi-center studies (Himavamshi et al., 2024); second, different research teams use varied technology platforms, software algorithms, and evaluation standards,

making it difficult to compare and integrate research results horizontally. The lack of a unified gold standard for evaluating the effectiveness of simulation training is one of the key bottlenecks constraining the development of the field (Strojny & Dużmańska-Misiarczyk, 2023); finally, interdisciplinary knowledge barriers (medicine, engineering, computer science) also pose challenges to deep collaboration (Nunes et al., 2011). Therefore, the key to promoting the future development of this field lies in breaking down these barriers, for example, by developing open-source simulation platforms, establishing shared case model databases, and organizing multi-center, large-scale randomized controlled trials (RCTs) to validate the effectiveness of different teaching models, thereby establishing a collaborative innovation research paradigm.

4.2. Evolution of Research Hotspots: A Deep Transformation from “Conceptual Feasibility” to “Clinical-Grade Reliability”

The keyword cluster analysis (Figure 8) in this study profoundly reveals the shift in the research focus of the field. Research is no longer merely at the stage of proving that 3DP/VR technology is “usable”, but has delved into the core technical level of ensuring it is “easy to use” and “reliable”. The emergence of clusters such as #0 accuracy, #8 registration, and #11 geometric distortion signifies that the research paradigm has shifted from “technology-enabled” to “engineering problem-driven”.

This transformation is of great significance. In high-precision fields such as neurosurgery and vascular surgery, the success or failure of a surgery often depends on millimeter-level accuracy. The emergence of the #6 *mr angiography* cluster in this study also confirms this point. If there is a significant deviation (*geometric distortion*) between a 3D printed aneurysm model or a virtual blood vessel in AR navigation and the actual anatomy, then preoperative planning and simulation training based on it would not only be ineffective but could even mislead doctors, leading to catastrophic consequences (Yuan et al., 2017). Therefore, the ultimate pursuit of *accuracy* and *registration* is driven by these stringent clinical demands. Similarly, the emergence of the #5 *mechanical property* cluster reflects the clinical demand for high-fidelity simulation experiences—a good simulator must not only “look real” but also “feel real” to effectively train a doctor’s tactile sense and operational skills (Owen, 2016).

4.3. Research Frontier Outlook: Marching into a New Era of Deep Clinical Integration and Outcome Validation

The keyword burst analysis (Figure 10) reveals the most dynamic research frontiers in this field. Future development will primarily revolve around the following three directions.

4.3.1. Platform Specialization: From General Technology to Deep Development on Specific Hardware (e.g., HoloLens)

The burst of the keyword HoloLens is a watershed event. It signifies that researchers are no longer satisfied with discussing generalized AR/VR concepts but are

beginning to develop applications with specific clinical functions based on advanced Mixed Reality (MR) platforms like Microsoft's HoloLens. This predicts that future research will focus more on the synergistic optimization of software and hardware, exploring how to best achieve image rendering, spatial positioning, and human-computer interaction on specific platforms to provide stable, reliable, and efficient solutions for clinical practice (Yang & Chai, 2020).

4.3.2. Application Precision: Deep Integration into High-Risk Clinical Workflows (e.g., Cancer Radiotherapy)

The concentrated burst of keywords like guidance, radiation therapy, and cancer clearly indicates that the technology is penetrating from general training simulations into high-risk, high-precision clinical treatment stages. For instance, in radiation therapy, MR technology can be used to superimpose the precise three-dimensional contours of tumors and organs at risk onto the patient's body in real-time, thereby achieving precise guidance for radiotherapy dosage (Ng et al., 2023). In surgery, it can provide doctors with "X-ray vision," guiding the surgical path to avoid critical blood vessels and nerves (Fan et al., 2023). This deep integration with core clinical workflows is a key step in transforming the technology from a "teaching tool" into a "therapeutic weapon". This deep integration with core clinical workflows demonstrates the technology's potential to transform from a "teaching tool" to a "therapeutic weapon". However, it must be emphasized that this assertion requires the support of substantial high-quality clinical evidence. Although the emergence of keywords like "outcome" indicates a trend in the academic community towards validating clinical impact, current research still generally lacks systematic analysis of large-scale clinical trials and concrete examples of improved patient outcomes. Therefore, while the technological potential is evident, confirming this transformation through rigorous clinical research remains a key direction for future studies.

4.3.3. Evaluation Effectiveness: From Technical Metrics to the Ultimate Validation of Clinical Outcomes

The burst of the keyword outcome (outcome) reflects the increasing maturity of research in this field. Early studies focused more on technical indicators (e.g., model accuracy, simulation realism) (Li, 2022), whereas current frontier research is more concerned with a fundamental question: can these advanced technologies bring tangible benefits to patients? For example, does using these technologies for pre-operative planning and simulation shorten surgical time, reduce intraoperative bleeding, lower complication rates, and ultimately improve patients' long-term survival and quality of life? (Dubron et al., 2023) In the future, large-scale, high-quality clinical controlled trials oriented towards clinical outcomes will become the "gold standard" in this field and the core driving force for promoting the clinical acceptance and widespread application of the technology.

4.4. Limitations of This Study

Although this study has systematically revealed the macroscopic picture of the

field, it still has certain limitations. First, the scope of the data source is limited. This study relies solely on the Web of Science Core Collection database, which may exclude relevant publications from other important databases (e.g., Scopus, PubMed, IEEE Xplore) and grey literature (such as conference papers not indexed by WoS). This could lead to a certain selection bias in the analysis results. Second, bibliometric analysis focuses on the external characteristics of literature (such as publication volume, citation counts) and cannot deeply assess the intrinsic quality and actual teaching effectiveness of each study. Future research should combine systematic reviews or meta-analyses to conduct more in-depth mining and integration of high-quality clinical trial evidence in this field.

5. Conclusion

This study systematically analyzed the progress of research on combining 3D Printing and virtual reality in the field of medical education. The research found that the field is in a period of rapid development, with core research forces centered in the US and China already formed. Research hotspots have evolved from early-stage proof-of-concept to addressing core technical bottlenecks in clinical applications, such as accuracy, reliability, and physical simulation. The current research frontier is highly focused on the deepening of clinical applications, with key trends including: deep development on specific mixed reality platforms like HoloLens, integration into high-risk clinical workflows such as cancer radiotherapy and surgical guidance, and ultimately, using the improvement of patient clinical outcomes as the gold standard for evaluating technological effectiveness.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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