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Artificial intelligence in dentistry: A bibliometric analysis from 2000 to 2023

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KEYWORDS
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Abstract *Background/purpose:* Artificial intelligence (AI) is reshaping clinical practice in dentistry. This study aims to provide a comprehensive overview of global trends and research hotspots on the application of AI to dentistry.
Materials and methods: Studies on AI in dentistry published between 2000 and 2023 were retrieved from the Web of Science Core Collection. Bibliometric parameters were extracted and bibliometric analysis was conducted using VOSviewer, Pajek, and CiteSpace software.
Results: A total of 651 publications were identified, 88.7 % of which were published after 2019. Publications originating from the United States and China accounted for 34.5 % of the total. The Charité Medical University of Berlin was the institution with the highest number of publications, and Schwendicke and Krois were the most active authors in the field. The Journal of Dentistry had the highest citation count. The focus of AI in dentistry primarily centered on the analysis of imaging data and the dental diseases most frequently associated with AI were periodontitis, bone fractures, and dental caries. The dental AI applications most frequently discussed since 2019 included neural networks, medical devices, clinical decision support systems, head and neck cancer, support vector machine, geometric deep learning, and precision medicine.
Conclusion: Research on AI in dentistry is experiencing explosive growth. The prevailing research emphasis and anticipated future development involve the establishment of medical devices and clinical decision support systems based on innovative AI algorithms to advance precision dentistry. This study provides dentists with valuable insights into this field.

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Introduction

The concept of artificial intelligence (AI) was introduced by Professor John McCarthy in 1956 at the Dartmouth Conference. It was defined as the development of intelligent machines capable of perceiving, understanding, reasoning, learning, and making decisions in the same way as humans.[1] Since then, AI has evolved into an independent discipline covering a wide range of areas, such as machine learning, deep learning, natural language processing, computer vision, knowledge representation, and reasoning. Machine learning is the foundational method for realizing AI, and its core concept is enabling computers to learn from data rather than executing specific functions through explicit programming.[2] Deep learning is a machine learning technique that utilizes neural networks, particularly deep neural networks, to learn about the complex structure of data.[3] Natural language processing and computer vision are critical research areas in the field of AI, that aim to assist humans in recognizing and analyzing language and images. From providing initial diagnostic aids based on simple rules to the application of the da Vinci surgical robot, and further to the development of deep learning algorithms that exhibit diagnostic capabilities comparable to specialized doctors, AI is gradually transforming the methods and efficiency of medical practice.[4–6]

With the intensifying trend of global aging, oral health issues are receiving increasing attention. Traditional oral diagnosis and treatment mostly rely on the professional knowledge, extensive experience, and observational skills of dentists. Such reliance can result in subjective biases, increased risk of misdiagnosis, and reduced efficiency. Therefore, the use of AI to enhance dental research and its applications has emerged as a significant research direction. The growing volume of publications suggests that the application of AI in dentistry has progressed in theory and practice. AI has been utilized in various aspects of dentistry, including the diagnosis of precancerous oral lesions, periodontal disease, caries, and temporomandibular joint disease; formulation of personalized orthodontic treatment plans; positioning and navigation of oral and maxillofacial surgery; and use of dental implant robots.[7–12] Although many reviews have described the current research landscape of the field from various perspectives, bibliometric analyses that offer a comprehensive overview are lacking.

Bibliometric analyses are widely used for qualitative and quantitative analyses of publications.[13] In addition to analyzing the contributions of various countries, institutions, journals, and scholars in a specific field, bibliometric analyses use software and conduct visual evaluations to systematically review the knowledge structure and developmental trends of a particular discipline.[14] This study employed bibliometric tools to conduct a comprehensive review of research on AI use in dentistry and reveal trends and future directions in this field.

Materials and methods

Search strategy

We searched the Web of Science Core Collection (WoSCC) using the following items: TS = ("artificial intelligence" OR AI OR "machine learning" OR "deep learning" OR robot OR "neural network" OR "expert system") AND TS = ("oral medicine" OR dentistry OR "maxillofacial surgery" OR prosthodontics OR endodontics OR periodontology OR orthodontics OR "oral implantology") from 2000-01-01 to 2023-07-19. The language was restricted to English and document types restricted to original or research article and review article (Fig. 1). The WoSCC was accessed with the support of the Data Services Platform of Southwest Medical University Library (https://lib.swmu.edu.cn). To avoid changes in citation information due to rapid updates of publications, the retrieval process was independently completed by two researchers within a single day (July 19, 2023). Disagreements were resolved by discussing with a senior dentist until a consensus was reached.

Data extraction and analysis

The title, author, institution, country, publication year, keywords, and citations were listed as extracted information for bibliometric analysis and imported into Microsoft Excel 2010 (Redmond, Washington, USA). Citexs AI (Wuhan, China) was used to identify associated diseases. Countries, institutions, authors, journal, diseases, and keywords were further visualized via VOSviewer 1.6.18 (Centre for Science and Technology Studies, Leiden University, The Netherlands) and Pajek 64 5.16 (University of Ljubljana, Slovenia). Node size and thickness of lines between nodes in the VOSviewer maps represent the number of publications produced and the strength of links. CiteSpace 6.1.6 (Chaomei Chen, China) was used for keyword and reference analysis. For the co-cited literature analysis, CiteSpace was configured with the following parameter settings: timespan (2000–2023), slice length (1), and g-index (k = 10).

Results

Growth in publications

We retrieved 651 articles related to AI in dentistry, including 505 original or research articles and 146 review articles (Supplementary Table S1). The annual growth rate of publications was modest from 2000 to 2018; however, explosive growth was observed from 2019 to 2023. Between January 1, 2023, and July 19, 2023, 120 articles were published (Fig. 2).

Countries/regions and institutions

From 2000 to 2023, 32 countries/regions published a minimum of five papers on AI in dentistry (Fig. 3A). The United States had the highest number of publications (n = 117, 18.0%), followed by China (n = 108, 16.6%) and India (n = 62, 9.5%). The US showed the highest tendency to collaborate, with a total link strength (TLS) of 105. The collaboration between the US and China was the strongest. Furthermore, 1106 research institutions contributed to the publication of the 651 articles. The top 10 most prolific institutions are listed in Table 1. Charité Medical University of Berlin had the highest number of publications (n = 26),

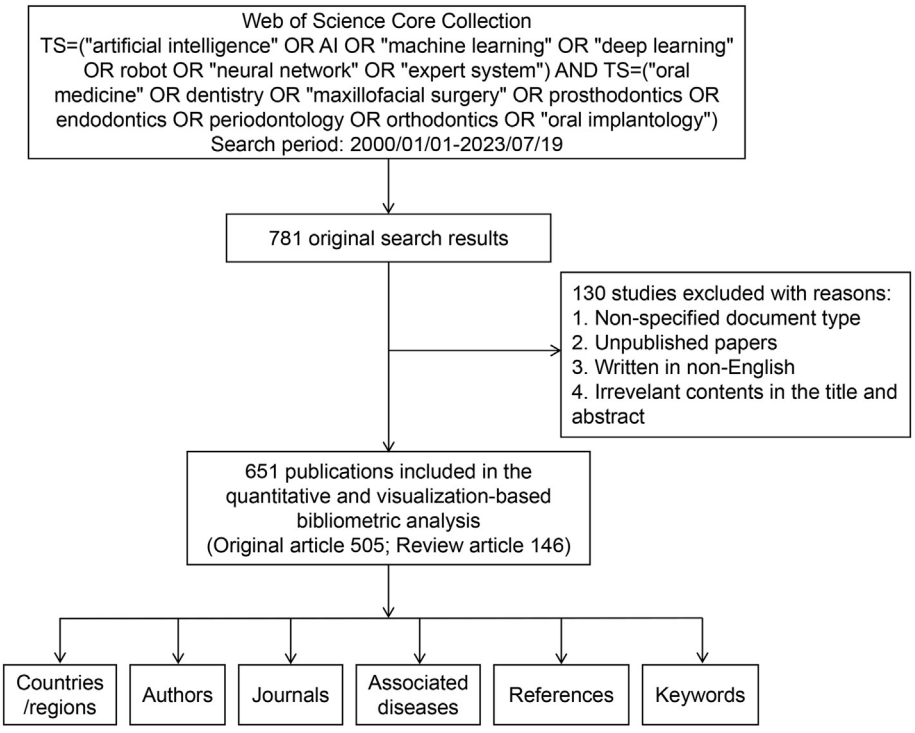


Figure 1 Flowchart of data screening and bibliometric analysis.

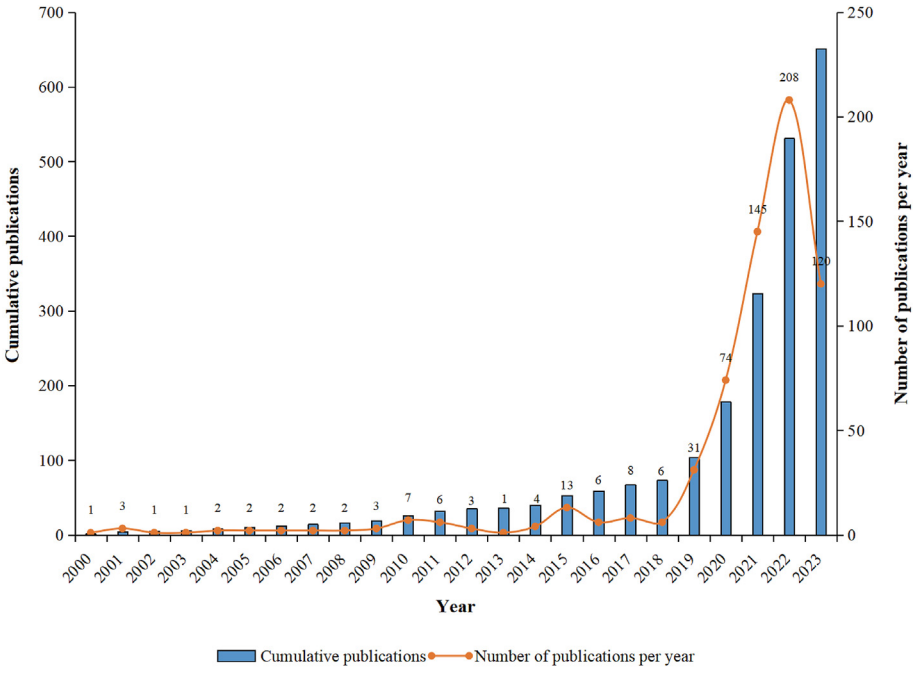


Figure 2 The number of articles on AI in dentistry annually from 2000 to 2023.

followed by Yonsei (n = 18), Peking (n = 18), and Ankara (n = 18) Universities. Institutions that published at least four papers were used for visualization (Fig. 3B). The results showed that the Charité Medical University of Berlin had the highest tendency to collaborate (TLS = 55). Ankara and Eskisehir Osmangazi Universities exhibited the closest collaborative ties.

Authors

Author information from the publications was analyzed to identify influential scholars in the field of AI in dentistry. The top 10 most productive authors are listed in Table 2. Schwendicke, F. (Germany, n = 25) was the most prolific author, followed by Krois, J. (Germany, n = 17) and Orhan,

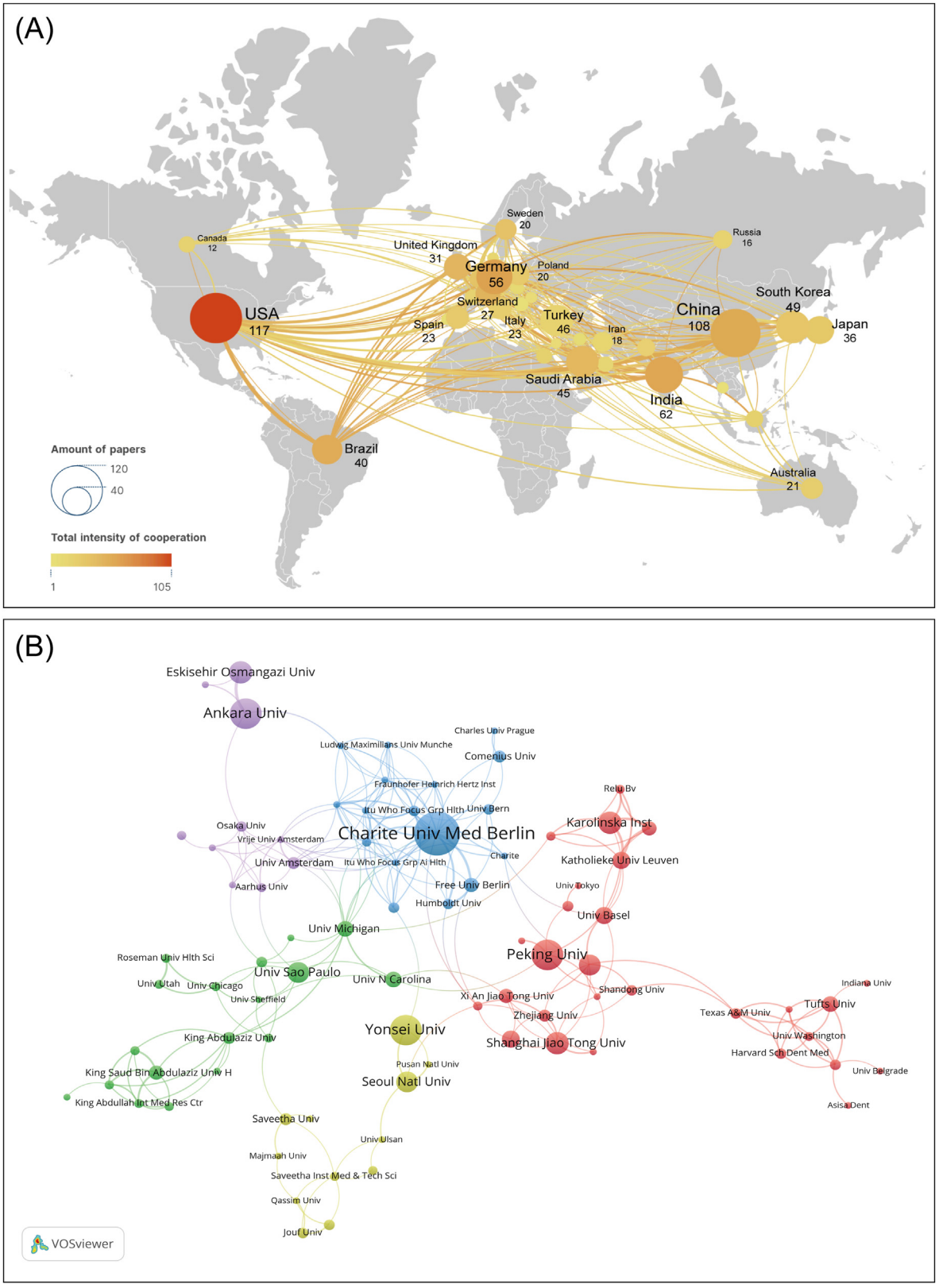


Figure 3 Visualization of research on AI in dentistry in countries (A) and institutions (B).

Table 1 The top 10 productive institutions on research of AI in dentistry.

Rank[a]	Institutions	Publication	Country	TC	CPP
1	Charité Medical University of Berlin	26	Germany	696	26.77
2	Yonsei University	18	Korea	515	28.61
3	Peking University	18	China	249	13.83
4	Ankara University	18	Turkey	210	11.67
5	Karolinska Institutet	13	Sweden	201	15.46
6	Eskisehir Osmangazi University	13	Turkey	133	10.23
7	Shanghai Jiao Tong University	13	China	113	8.69
8	Seoul National University	12	Korea	192	16.00
9	University of Hong Kong	12	China	190	15.83
10	University of São Paulo	12	Brazil	82	6.83

[a] In cases where the number of publications is identical, ranking is determined by the total citations. TC: total citations, CPP: citations per publication.

K. (Turkey, n = 19). Notably, JH Lee from Germany has the highest average citation count per paper (n = 57.86). Authors who published at least three papers were further visualized (Fig. 4). The results indicate that collaborating authors were mostly from the same country or region. Among them, the collaboration between Schwendicke, F., and Krois, J. was the strongest.

Journals

From 2000 to 2023, 275 journals published 651 articles related to AI in dentistry. Journals that published at least two articles were subjected to visualization (Fig. 5). The top 10 journals in terms of the number of published articles are listed in Table 3. *Applied Sciences-Basel* ($IF_{2022} = 2.7$, n = 25), *Journal of Dental Research* ($IF_{2022} = 7.6$, n = 23), and *Diagnostics* ($IF_{2022} = 3.6$, n = 23) were the top three journals in terms of the total number of published articles, constituting 11.3 % of all published articles. *The Journal of Dentistry* ($IF_{2022} = 4.4$, n = 18) had the highest number of total citations (n = 597), followed by the *Journal of Dental Research* (n = 576).

Associated diseases

To explore the current interests of clinical researchers, 564 diseases from 651 articles were extracted from the Citexs platform for big data. Diseases appearing at least twice were visualized with VOSviewer (Fig. 6). The results demonstrated that the most prevalent disease was periodontitis (n = 54), followed by bone fractures (n = 45) and dental caries (n = 41). Other frequently associated diseases included jaw diseases (n = 40), infections (n = 37), alveolar bone loss (n = 29), and tooth loss (n = 25).

Cited and co-cited references

To investigate the knowledge foundation of dental AI, CiteSpace was used to conduct a cluster analysis of co-cited references, divided into seven categories: complexity, three-dimensional (3D) displays, panoramic radiography, orthodontics, estimation, radiography, and artificial neural networks research (Fig. 7A). Of the top 10 most co-cited references, four were reviews, and six were original research articles (Table 4). The article with the highest co-citations (n = 85) was.[15] This study provided data on the applicability of convolutional neural networks (CNNs) in diagnosing dental caries.

Increased citations reflect articles that researchers focus on in a specific period. The top 20 most cited references are shown in Fig. 7B. Most articles began to be explosively cited in 2020. The paper with the highest burst strength was.[16] This study used machine learning with neural networks to build a system for expert decision-making in treatment plans for orthodontic extractions.

Table 2 The top 10 prolific authors on research of AI in dentistry.

Rank[a]	Author	Publication	Country	Institutions	TC	CPP
1	Schwendicke, Falk	25	Germany	Charité Medical University of Berlin	638	25.52
2	Krois, Joachim	17	Germany	Charité Medical University of Berlin	417	24.53
3	Orhan, Kaan	15	Turkey	Ankara University	158	10.53
4	Bayrakdar, Ibrahim Sevki	11	Turkey	Eskisehir Osmangazi University	120	10.91
5	Celik, Ozer	11	Turkey	Eskisehir Osmangazi University	88	8.00
6	Bilgir, Elif	10	Turkey	Eskisehir Osmangazi University	130	13.00
7	Jacobs, Reinhilde	9	Belgium	Katholieke Universiteit Leuven	145	16.11
8	Lee, Jae-Hong	7	Germany	ITU WHO Focus Grp Hlth	405	57.86
9	Aslan, Ahmet Faruk	7	Turkey	Eskisehir Osmangazi University	95	13.57
10	Odabas, Alper	6	Turkey	Eskisehir Osmangazi University	95	15.83

[a] In cases where the number of publications is identical, ranking is determined by the total citations. TC: total citations, CPP: citations per publication.

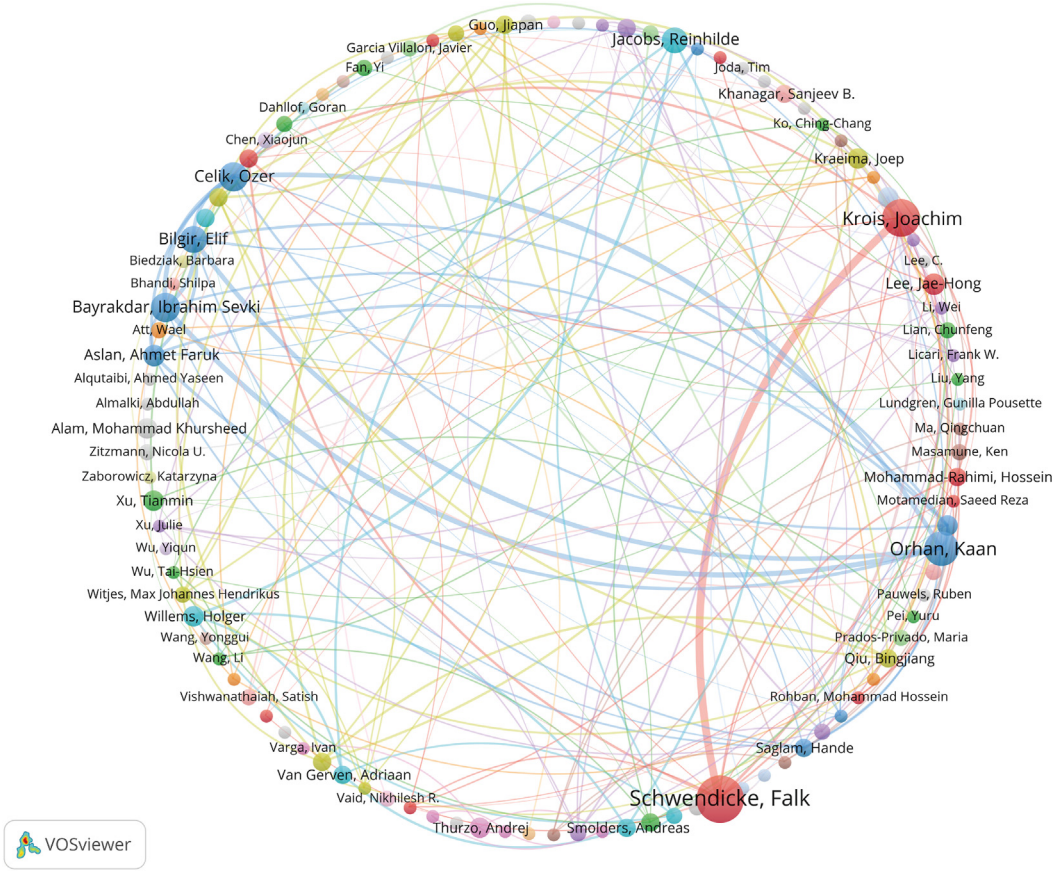


Figure 4 Collaborative networks among authors. Different colors represent different countries.

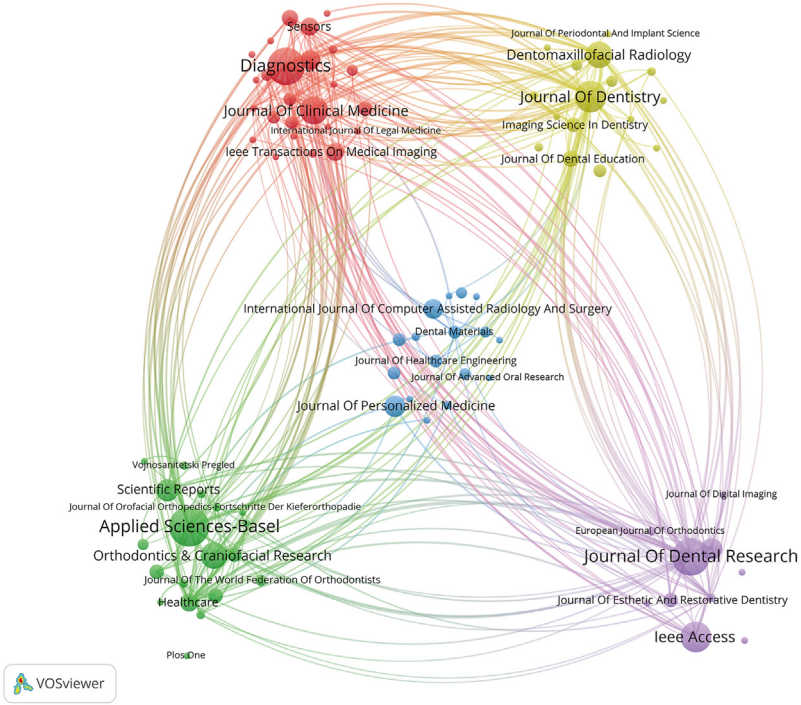


Figure 5 Co-occurrence network of journals publishing AI in dentistry research.

Table 3 The top 10 productive journals for research of AI in dentistry.

Rank[a]	Journal	Publications	IF (2022)	TC
1	Applied Sciences-Basel	25	2.7	125
2	Journal of Dental Research	23	7.6	576
3	Diagnostics	23	3.6	109
4	Journal of Dentistry	18	4.4	597
5	Ieee Access	17	3.9	112
6	Journal of Clinical Medicine	15	3.9	129
7	Dentomaxillofacial Radiology	14	3.3	203
8	Orthodontics & Craniofacial Research	14	3.1	95
9	Scientific Reports	11	4.6	106
10	Clinical Oral Investigations	10	3.4	61

[a] In cases where the number of publications is identical, ranking is determined by the total citations. IF: impact factor, TC: total citations.

Keywords

After merging duplicate keywords and setting a minimum occurrence of three times for each keyword, 114 keywords were subjected to visualization. These keywords were automatically categorized into four clusters in VOSviewer, with emphasis on machine learning, deep learning, CNN, and periodontal disease research (Fig. 8A). Furthermore, CiteSpace was used to visualize the top 40 keywords (Fig. 8B). The results indicated that the keyword "medical robotics" had the strongest emergence, particularly between 2001 and 2019. The keywords "neural network," "medical device," "clinic decision support systems," "diagnostic imaging," "panoramic images," "support vector machine," "geometric deep learning," "computer-assisted diagnosis," "head and neck cancer," and "precision medicine" were prominent between 2019 and 2023.

Discussion

Our findings revealed that 73 countries, 1106 institutions, and 3008 authors published 651 articles on AI in dentistry

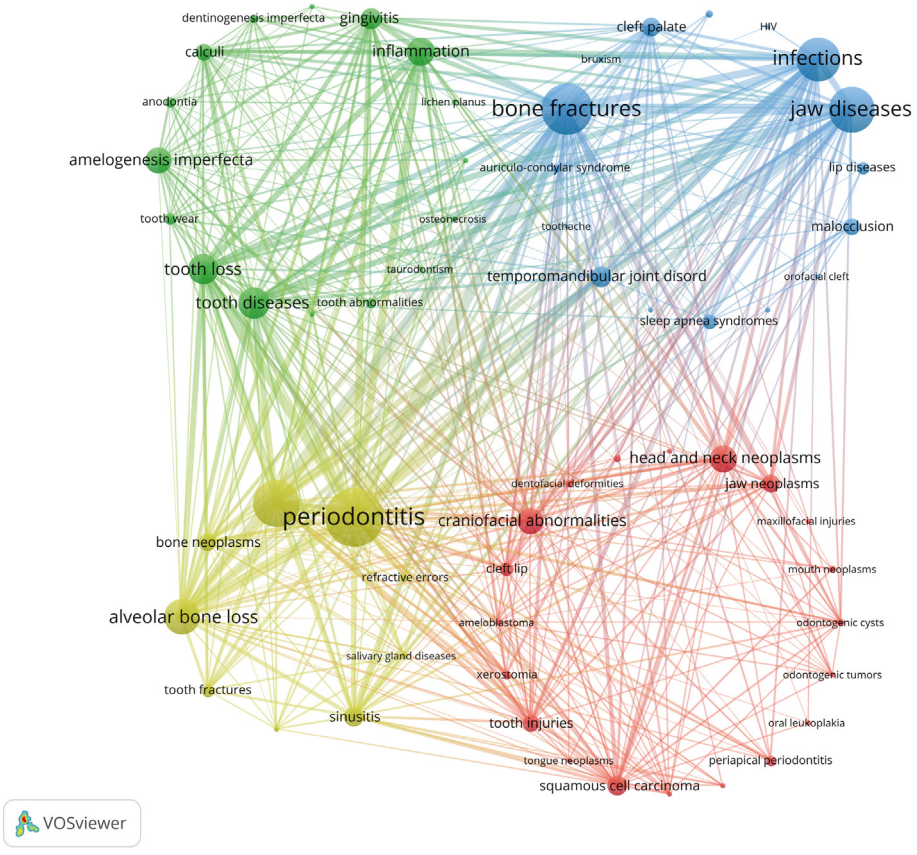
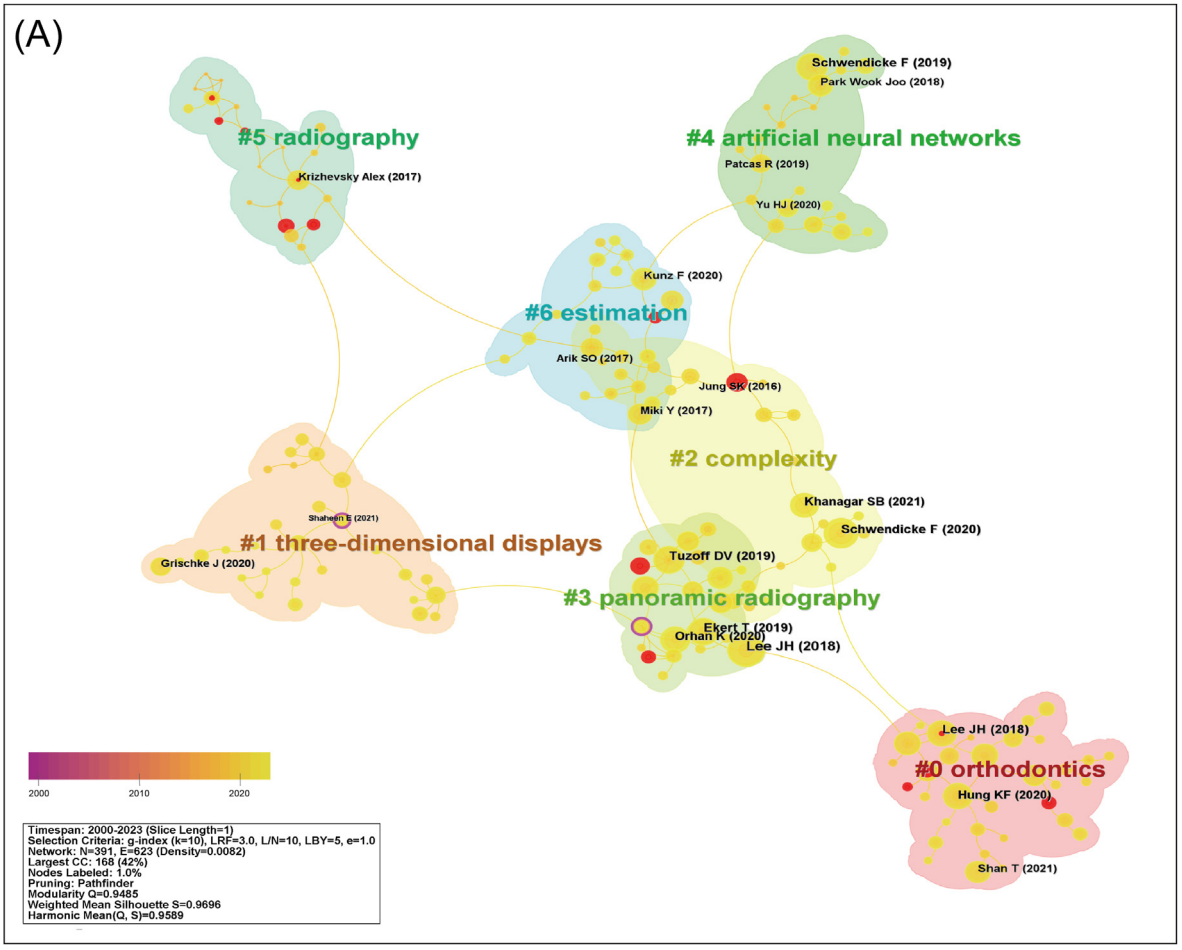


Figure 6 Dental diseases associated with AI.



(B)

Top 20 References with the Strongest Citation Bursts

References	Year	Strength	Begin	End	2000 - 2023
Esteva A, 2017, NATURE, V542, P115, DOI 10.1038/nature21056, DOI	2017	4.48	2018	2020	
Gulshan V, 2016, JAMA-J AM MED ASSOC, V316, P2402, DOI 10.1001/jama.2016.17216, DOI	2016	3.49	2018	2020	
He KM, 2016, PROC CVPR IEEE, V0, PP770, DOI 10.1109/CVPR.2016.90, DOI	2016	2.7	2018	2021	
Jung SK, 2016, AM J ORTHOD DENTOFAC, V149, P127, DOI 10.1016/j.ajodo.2015.07.030, DOI	2016	8.99	2019	2021	
Rusk N, 2016, NAT METHODS, V13, P35, DOI 10.1038/nmeth.3707, DOI	2016	5.51	2019	2021	
Lee JH, 2018, J PERIODONTAL IMPLAN, V48, P114, DOI 10.5051/jpis.2018.48.2.114, DOI	2018	3.91	2019	2020	
LeCun Y, 2015, NATURE, V521, P436, DOI 10.1038/nature14539, DOI	2015	2.94	2019	2020	
Poedjiastoeti W, 2018, HEALTHC INFORM RES, V24, P236, DOI 10.4258/hir.2018.24.3.236, DOI	2018	4.15	2020	2021	
Hosny A, 2018, NAT REV CANCER, V18, P500, DOI 10.1038/s41568-018-0016-5, DOI	2018	3.94	2020	2021	
Wang CW, 2016, MED IMAGE ANAL, V31, P63, DOI 10.1016/j.media.2016.02.004, DOI	2016	3.94	2020	2021	
Thanathornwong B, 2018, HEALTHC INFORM RES, V24, P22	2018	3.31	2020	2021	
Ariji Y, 2019, OR SURG OR MED OR PA, V128, P424, DOI 10.1016/j.oooo.2019.05.014, DOI	2019	3.22	2020	2021	
De Tobel J, 2017, J FORENSIC ODONTOSTOMATOL, V35, P42	2017	2.5	2020	2021	
Miki Y, 2017, COMPUT BIOL MED, V80, P24, DOI 10.1016/j.compbiomed.2016.11.003, DOI	2017	2.49	2020	2021	
Chen QX, 2016, SCI REP-UK, V6, P0, DOI 10.1038/srep27855, DOI	2016	2.14	2020	2021	
Murata M, 2019, ORAL RADIOL, V35, P301, DOI 10.1007/s11282-018-0363-7, DOI	2019	2	2020	2021	
Gupta A, 2016, INT J COMPUT ASS RAD, V11, P1297, DOI 10.1007/s11548-015-1334-7, DOI	2016	1.79	2020	2021	
De Tobel J., 2017, J FORENSIC ODONTOSTO, V35, P42	2017	1.79	2020	2021	
Joda T, 2019, PUBLIC HEALTH GENOM, V22, P1, DOI 10.1159/000501643, DOI	2019	1.79	2020	2021	
Nino-Sandoval TC, 2017, FORENSIC SCI INT, V281, P0, DOI 10.1016/j.forsciint.2017.10.004, DOI	2017	1.54	2020	2021	

Figure 7 Analysis of cited and co-cited references in dental AI research. (A) Cluster analysis of co-cited references by CiteSpace. The size of the circles is proportional to the number of co-citations, and the color of the circles represents the time of the citation. The color of the modules represents different clusters. (B) Visualization of the top 20 cited references with the strongest citation bursts. The red line shows the burst time.

Table 4 The top 10 co-cited references on research of AI in dentistry.

Rank	Title	First author	Journal	Year	Citations
1	Detection and diagnosis of dental caries using a deep learning-based convolutional neural network algorithm	Lee JH	Journal of Dentistry	2018	85
2	Artificial Intelligence in Dentistry: Chances and Challenges	Schwendicke F	Journal of Dental Research	2020	66
3	Tooth detection and numbering in panoramic radiographs using convolutional neural networks	Tuzoff DV	DentoMaxilloFacial Radiology	2019	61
4	Deep Learning for the Radiographic Detection of Apical Lesions	Ekert T	Journal of Endodontics	2019	59
5	Convolutional neural networks for dental image diagnostics: A scoping review	Schwendicke F	Journal of Dentistry	2019	59
6	Diagnosis and prediction of periodontally compromised teeth using a deep learning-based convolutional neural network algorithm	Lee JH	Journal of Periodontal and Implant Science	2018	55
7	Developments, application, and performance of artificial intelligence in dentistry - A systematic review	Khanagar SB	Journal of Dental Sciences	2021	50
8	The use and performance of artificial intelligence applications in dental and maxillofacial radiology: A systematic review	Hung KF	Dentomaxillofacial Radiology	2020	49
9	Evaluation of artificial intelligence for detecting periapical pathosis on cone-beam computed tomography scans	Orhan K	International Endodontic Journal	2020	48
10	Deep Learning for the Radiographic Detection of Periodontal Bone Loss	Krois J	Scientific Reports-United Kingdom	2019	46

between 2000 and 2023. The recent explosive growth in global publications underscored the rapid development of AI in dentistry. The US and China were the global leaders in this field. As US scientists initially introduced the concept of AI, the field had an extended developmental history in the country.[1] Due to supportive national policies, China's progression in AI in dentistry recently exhibited a positive trend[17] Among numerous global research institutions, Charité Medical University of Berlin in Germany was prominent, primarily due to contributions by Schwendicke and Krois. Their close collaboration on utilizing deep learning in dental imaging for diagnosis provided a wealth of invaluable data for reference[18] Focusing on these countries, institutions, and authors would facilitate the understanding of research directions in this field.

The 10 most co-cited articles focused primarily on the value of deep learning based on CNNs to diagnose dental caries, periapical disease, and periodontal disease.[15,19–22] Dental diagnosis and treatment often involve analyzing various types of imaging data, including periapical and panoramic radiograph, lateral cephalogram, and cone beam computed tomography (CBCT). CNNs can automatically learn and recognize features in images and provide automated solutions. For instance, Lee et al. trained and tested a CNN algorithm on 3000 periapical radiographic images and found that its diagnostic accuracy for dental caries was above 80 %, indicating the tremendous potential of CNN algorithms in dental diagnoses.[15] Periodontal disease was the most associated with AI. CNNs are practical for diagnosing periodontal disease. For instance, a CNN trained on a restricted amount of radiographic image segments demonstrated at least a similar discrimination ability as dentists for assessing periodontal bone loss on panoramic radiographs.[20]

Analysis of keywords can be employed to construct knowledge networks and depict the current status of hot topics. We observed that between 2000 and 2010, research on AI in dentistry was primarily focused on dental surgery. Emerging keywords from 2010 to 2018 included "surgical navigation," "dental education," "pediatric dentistry," "periodontal disease," "artificial neural network," and "supervised machine learning." This indicated that research on AI in dentistry began to diversify into multiple subfields with the emergence of various AI technologies. Surgical navigation, also known as computer-assisted surgery, is a technology that provides real-time, dynamic visual information to guide surgeons during operations. The utilization of dynamic navigation systems in dental implant surgery enhances the precision of implant placement compared to traditional manual implantation, effectively enhancing aesthetic outcomes and helping prevent nerve damage.[23] Dental education was another research focus in the field of AI in dentistry. The advent of virtual reality (VR) and augmented reality (AR) technologies has made difficult-to-imagine anatomical structures visually accessible, enhancing the interest and performance of students.[24] Moreover, virtual simulation technology provides essential operational training for dentists before clinical practice. Lu et al. evaluated the effects of virtual simulation technology in the teaching of pulpotomy and identified

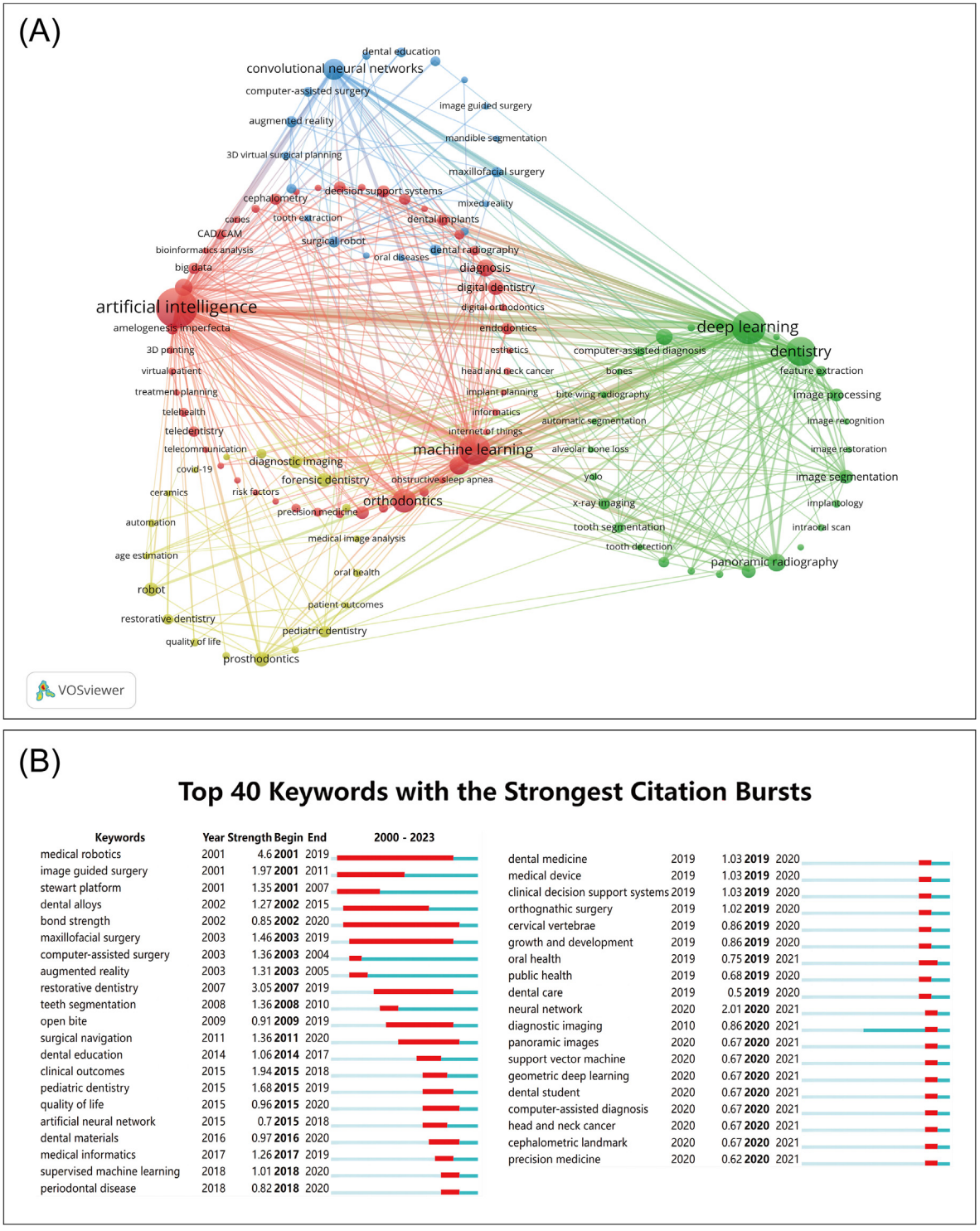


Figure 8 Analysis of dental AI research keywords. (A) The map of keywords co-occurrence network. Different colors represent different clusters. (B) Visualization of the top 40 keywords with the strongest citation bursts.

a significant improvement in dental students' learning outcomes.[25]

The main emerging keywords from 2019 to 2023 were "neural network," "support vector machine," "geometric deep learning," "medical device," "clinical decision support system," "computer-assisted diagnosis," "head and neck cancer," and "precision medicine." This indicated that systems and devices based on new AI algorithms are being developed for dental clinical practice. Geometric deep learning is an emerging machine-learning technique used mainly to process data with complex structures or topological properties.[26] The application of geometric deep

learning in dentistry is in its infancy, and is mainly focused on the analysis and processing of 3D dental models. Lang et al. proposed a graph-based geometric deep learning approach (TeethGNN) for analyzing 3D digital dental models, which improved the accuracy of dental landmark localization.[27] Moreover, there has been a significant increase in the application of the support vector machine (SVM), which is a supervised learning model used for data classification and regression analysis, in dentistry. These applications were primarily focused on the diagnosis of dental caries and periodontal disease. For instance, Bui et al. used SVM to automatically segment the tooth region of interest from panoramic radiographs for dental caries diagnosis, revealing that the method had an accuracy of 93.58%, sensitivity of 93.91%, and specificity of 93.33%, indicating promising potential for a wider application.[28] The advancements in these emerging technologies are promising.

The evolution of keywords revealed future trends in AI research in dentistry. First, the development of increasingly intelligent medical devices is anticipated. Studies have shown the availability of oral wearable devices for various applications, including caries detection, force measurement on orthodontic teeth, detection of implant abnormalities, and assessment of salivary biochemical indicators.[29–32] While the majority of these studies are still in the laboratory phase, these devices are likely to be used in future to collect data to enhance people's lifestyle choices and oral health practices. These collected data could be sent to dental professionals for effective patient management. Second, clinical decision support systems are likely to be applied more widely, particularly in the emergent area associated with the keyword "head and neck cancer." Oral cancer often develops from oral potentially malignant disorders (OPMD) such as leukoplakia, erythroplakia, and oral lichen planus.[33] These disorders present with a variety of clinical manifestations and pose significant diagnostic challenges. The application of AI as a diagnostic tool has been shown to enhance the diagnostic efficacy of OPMD.[7] Finally, precision medicine is predicted to become mainstream. The use of AI to analyze massive omics data and clinical examination results to identify risk factors associated with head and neck cancer, orofacial clefts, periodontitis, and caries has shown preliminary success.[34] These advancements facilitate the formulation of individualized prevention and treatment plans, as well as risk assessment and prognosis prediction for patients.

This study had several limitations. All the publications were drawn from a single database (WoSCC), which could potentially have introduced selection bias. Further, this study focused only on English-language publications. However, only 11 non-English publications were excluded, and we believe these articles have little impact on our main findings. The findings presented in this study still offer valuable insights into the developmental trends of AI in dentistry.

In conclusion, this study summarized the progressive global trends of AI research in dentistry. The analysis of imaging diagnostic data was a critical intersection of AI and dentistry. Extant research focus and future trends centered on the development of medical devices and clinical decision support systems based on new AI algorithms, aiming to promote the development of precision dentistry. In light of this emerging trend, dental professionals should continuously enhance their knowledge and skills in dental AI to effectively leverage its advantages for improved diagnosis and treatment services, thereby fostering advancements in dentistry.

Declaration of competing interest

The authors have no conflicts of interest relevant to this article.

Acknowledgment

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jds.2023.10.025.

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