UNIVERSITY OF PLYMOUTH
Faculty of Health

Artificial Intelligence and dental service provision: a rapid evidence assessment

Final report

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Glossary

Artificial intelligence terms used in this report

Artificial intelligence (AI)	Technology enabling computers and machines to simulate human learning, comprehension, problem-solving, decision-making, creativity and autonomy.
Artificial neural networks	Computational models inspired by the structure and function of the human brain, designed to learn and make predictions from data.
Deep learning (DL)	A branch of machine learning that uses artificial neural networks with multiple layers to analyse data and make predictions.
Local binary fitting computer intelligent segmentation model	Local binary fitting (LBF) is a method used in image segmentation to incorporate local image intensity information. It uses the intensity values of pixels within an image to support more precise segmentation.
Random Forest machine learning algorithm	Random Forest is an ensemble learning algorithm used in machine learning for both classification and regression tasks. It uses the predictions of multiple decision trees to make a more accurate and robust final prediction.
Robotics	Robotics is an interdisciplinary field that focuses on the design, construction, operation, and application of robots. It involves the creation of machines that can perform tasks, often autonomously.
Supervised machine learning	Supervised machine learning is a type of AI where models are trained on labelled datasets to learn the relationship between input and output. The model learns to map inputs to corresponding outputs by being fed input-output pairs, or examples. This allows the algorithm to make predictions or classifications on new, unseen data.

Dental terms used in this report

Caries	Tooth decay
Calculus	Hardened, calcified deposit that forms on teeth from the buildup of plaque, saliva, and minerals (also known as tartar).
Cone-beam computed tomography (CBCT) scan	A specialised type of CT scan that uses X-rays to create three-dimensional images of the head and neck, particularly the teeth and jawbone.
Dentomaxillofacial	Relating to the craniofacial, dental and adjacent structures of the body.

Gingivitis	A common and mild form of gum disease, also called periodontal disease
Edentulous (patient)	An individual who has lost all their natural teeth.
Endodontics	A branch of dentistry that focuses on the pulp and nerves within a tooth, as well as the tissues surrounding the root.
Intraoral	Within the mouth.
Orthodontics	A branch of dentistry that focuses on the diagnosis, treatment, and prevention of irregularities in the teeth and jaws.
Osteotomy	In dental surgery, an osteotomy involves surgically cutting the jawbone (either the upper or lower jaw) to reposition or realign it for better function and/or aesthetics.
Prosthodontics	A branch of dentistry focused on restoring and replacing missing or damaged teeth and tissues using artificial devices like crowns, bridges, dentures, and implants.
(Gum) recession	The exposure in the roots of the teeth caused by a loss of gum tissue or retraction of the gingival margin from the crown of the teeth, commonly caused by periodontal (gum) disease.

Executive Summary

Introduction

Digital transformation is often seen as key to revolutionising health care provision, with the potential to deliver efficiencies and improve health outcomes. Data driven technologies such as artificial intelligence (AI) and robotics have the potential to transform various aspects of healthcare, including in dentistry. Despite rapid advances in AI research and development, few AI solutions have thus far been deployed in real-world clinical practice. The field is internationally active but the evidence base is largely comprised of proof of concept or validation studies, which go no further than training and testing AI models. Barriers inhibiting the adoption of AI include the quality of the data in training datasets, and issues of cost effectiveness, safety and efficacy. For the General Dental Council, as the UK's dental regulator, it is imperative that the impact of new technologies on the delivery of dental care, and the implications for dental professionals and patients, are understood. Therefore, there is a need for evidence about the extent to which AI has been implemented thus far in dental service provision, and this Rapid Evidence Assessment was completed to meet this need.

Objectives

The aim of this Rapid Evidence Assessment (REA) was to synthesise the evidence base relating to the use of AI in dental service provision including potential future areas of development.

The REA's objectives were:

- To identify and synthesize evidence about applications of AI in dental service provision, including its impact, benefits, best practice, risks and challenges, and implications for equality, diversity and inclusion (EDI) and data protection, as well as its prevalence, profile, and reasons for its use.
- To identify and assess evidence about potential developments of AI in dental service provision.
- To identify and describe methods used to evaluate the role and impacts of AI in dental service provision.
- To identify gaps in the evidence base on AI in dental service provision and recommend priority areas for further research.

Methods

This Rapid Evidence Assessment was conducted according to established rapid evidence synthesis guidelines, following a protocol (see Appendix A) and reported using the PRISMA-2020 guidelines.

Review questions

We conducted a rapid evidence assessment to answer the question:

1) What applications of AI are currently implemented in dental service provision and which areas provide promising opportunities for the future?

Supplementary questions were:

2) Are there any best practice guidelines for specific technologies that use AI in dental service provision?
3) Which of the technologies that use AI in dental service provision have shown effectiveness in experimental studies?
4) What are the risks and challenges associated with technologies using AI in dental service provision? Are there any strategies and interventions suggested to address those challenges?
5) What methods have been used to evaluate AI in dental service provision?

Eligibility criteria

The review included studies from any country which describe the implementation of any form of AI-powered system, service or process in dental services, published from 2020 onwards. All study designs reporting empirical data were included. Proof of concept, validation and demonstration studies were excluded, as were literature reviews. Studies focusing on dental education were also excluded.

Search strategy

On 18th September 2024, searches of key databases were undertaken by an information specialist using search terms designed in consultation with experts in the fields of AI and robotics. A full record of the search terms used is provided in Appendix B. Several pre-print repositories were also searched in October 2024, with a one year date limit, to increase the currency of the searches. These searches used a simplified version of the search terms from the main database searches.

Evidence selection

Search results were collated in Endnote, deduplicated and then uploaded to Rayyan Web for screening. Records were screened first against title and abstract, then later against full text by three reviewers, working independently after an initial calibration exercise. Cases of uncertainty were resolved by discussion between reviewers.

Data extraction

Data were extracted from the included studies using an Excel spreadsheet. Data extraction was undertaken by three reviewers. Data items extracted from the included studies were: source/author, year of publication, study design, population/setting, field of dentistry, AI type and AI application details, impact and benefits, risks, content relating to equality, diversity and inclusion, and content relating to data protection or ethical issues.

Results

The database searches yielded 8972 results, of which 3814 remained after deduplication. After title and abstract screening, 115 items were included and all were obtained for full text screening. The searches of pre-print databases did not yield any additional results. The number of studies included after full text screening was 45.

Study characteristics

Of the included studies, 18 were case reports or case series involving between 1 and 74 patients, but of which 13 involved ten or fewer patients. Thirteen studies reported clinical trials of various types, including small scale single arm prospective clinical trials, pilot clinical trials as well as some randomised controlled trials, plus one study that used data from a prior clinical trial. There were also cross-sectional and cohort studies, involving between 20-194 patients, and studies broadly described as observational or experimental, and surveys.

The countries in which studies were conducted, listed in order of prevalence, were China, the USA, India, Italy, with a single study included from each of Denmark, Indonesia, Japan, Poland, Slovakia, Taiwan, Turkey, and the United Arab Emirates.

The fields of dentistry covered were restorative dentistry, particularly the diagnosis of treatment of caries, and its subfields including prosthodontics, specifically implant dentistry, as well as endodontics and periodontology. Other studies focused on paediatric dentistry, again with a focus on caries treatment, orthodontics, and non-implant related dental surgery.

Included studies covered treatment provision, diagnosis, treatment monitoring and treatment planning. Some studies covered more than one of these areas.

The types of AI discussed in the included studies, broadly categorised, were robotics, deep learning, and supervised machine learning. Other studies involved the use of AI but did not clearly define the nature of the AI application being used.

It should be noted that there are multiple subcategories of robotics for use in dentistry and that not all involve the use of AI. Where it was unclear whether AI was involved in a robotics system described in one of the included papers, we have erred on the side of including the study for review as these robotic systems represent emerging technologies being implemented in dental service provision and raise many of the same issues for dental professionals and the dental regulator.

Best practice guidelines

No best practice guidelines for specific technologies were identified from the included studies.

Effectiveness and impacts of AI applications

Robotics were predominantly reported as being used in prosthodontics, for implant surgery. There were several types of robotic systems identified as having been implemented to some degree in dental service provision, including haptic robotics, Dynamic Navigation, semi-active or semi-autonomous robots, and autonomous robots. Several papers specifically reported on the use of the Yomi robot (Neocis) which gives aural, visual and physical (haptic) guidance to the dentist during surgery.

The benefits of using robotic systems in dental surgery described in the literature were that these systems offer enhanced accuracy, reduce complications and improve post-operative outcomes.

Deep learning AI applications were described as being used in a variety of ways in dental service provision in the included studies. One key use for these applications is in the identification and treatment of caries, with patients asked to use AI smartphone applications to take intraoral photographs to be analysed by the application. Several studies reported the use of a commercially available AI application called Dental Monitoring, for which patients take intraoral photographs and which can also send messages encouraging good oral hygiene practices. Some noted that such applications are more effective at identifying the absence of caries. Deep learning AI models and applications show promise in enhancing dental care through early detection, remote monitoring, diagnostic support and treatment planning.

Supervised machine learning Several studies described the use of supervised machine learning algorithms and models in dental service provision. Several of these related to children's dental care, notably the identification and treatment of childhood caries. Uses included identifying metabolites significantly associated with early childhood caries and identifying predictors of active caries in children. One study evaluated the use of an AI-enabled toothbrush, which collected monitoring data to be sent to clinicians and sent text message feedback to patients.

Risks and challenges

As well as beneficial impacts or potential impacts, the included studies also identified a number of risks and challenges related to the implementation of robotics and AI in dental service provision.

Some of the reported risks related to the specifics of operating technologies, for example in relation to the use of robotics in implant surgery where it was noted that poor bone quality may result in deviation in implant placement from the planned site. Patient movement during surgery was also identified as a risk during robotic-assisted surgery. Aside from purely clinical challenges, challenges identified included the high investment costs associated with robotic systems and the need for additional training for dental professionals.

While some papers reported positive patient responses to robotics-assisted surgery, it was also noted that the presence of the machinery may increase patient anxiety. Studies investigating AI-based remote monitoring systems reported that patient adherence to the monitoring requirements typically reduced over time, and that patients may find taking intraoral photographs correctly challenging.

There was little evidence in the included studies about issues relating to **equality, diversity and inclusion** or about **data protection and ethical considerations.**

Conclusion

This rapid evidence assessment reviewed the literature on the implementation of AI and robotics in dental service provision since 2020. Most of the evidence concentrates on the use of robotic systems in implant dentistry, and the development of deep learning based remote monitoring systems for caries detections as well as monitoring other forms of treatment, with some studies reporting the use of supervised machine learning in relation to the identification and treatment of childhood caries. It seems likely that the development and implementation of these systems will continue and that they will become more accessible and more prevalent over time.

There is a need for research to consider the training needs of dental professionals, the implications of the growth of AI for dental education more broadly, and the regulatory implications of these new technologies. It would be beneficial to see **future research focusing specifically on the use of AI in dentistry in the UK**, encompassing equality, diversity and inclusion considerations and in the context of the UK regulatory environment.

Introduction

The digital transformation of healthcare is seen as the key to a revolution in health services, delivering efficiencies and improving health outcomes.[12] Data driven technologies such as artificial intelligence have the potential to transform administration, diagnostics, monitoring and clinical decision making across all areas of healthcare including dentistry. Despite rapid advances in artificial intelligence research and development, few AI solutions are actually deployed in real-world clinical practice, due to the challenges of translating AI research into safe, clinically validated and regulated systems.[13, 14] In dentistry, there has been a similar escalation of research into potential applications of AI, especially since 2015.[15]

Numerous reviews have summarised the research literature and categorised the areas of active research and development within dentistry. Dental radiology has seen the most AI research activity.[15] Advances in digital imaging have led to an ability to deconstruct images into their component features which can be identified, measured and classified. This analysis can be performed through algorithms which are trained on datasets. The datasets can be either labelled, which is called supervised machine learning, or unlabelled which is unsupervised learning.[16] With greater precision and accuracy than the human eye, machine learning can analyse images, detect anomalies, diagnose disease and predict outcomes.

AI in orthodontics has innovated cephalometric analysis which measures facial tissues and structures to provide orthodontic diagnostics. These can inform skeletal diagnoses, surgical decision-making and maturation predictions.[17] With the increased computational power of deep learning (DL), artificial neural networks can learn complex patterns directly from data. Applied to orthodontics, DL can plan the optimal steps needed for orthodontic movements.[17] During orthodontic treatment, AI can continually and precisely monitor the patient, allowing orthodontists to make treatment modifications.[17]

Oral and Maxillofacial Surgery has also seen many promising applications of AI for detecting oral lesions and predicting disease outcomes. The accuracy, speed and efficiency of AI applications can improve diagnostic and prognostic processes. AI can also be used to plan surgical interventions, predict adverse events and monitor patient recovery.[18]

This field is internationally active but the evidence base is largely comprised of proof of concept or validation studies followed by literature reviews.[19] Most of the AI systems which have been developed have not achieved technological readiness for deployment into clinical dentistry,[20] when measuring the maturity of a technological system on a scale ranging from early developmental principles through proof of concept and validation work to successful deployment in services.[21]

Despite the promising potential of AI, there are many barriers inhibiting the implementation of AI applications into healthcare. The quality of the data in the training datasets is an ongoing concern. Models need to be trained on big data sets which represent diverse demographic characteristics to avoid amplifying ethnic and socioeconomic biases. Access to such big datasets of electronic health records is limited by the fragmentation of patient record systems. There are issues with privacy and regulations vary, making the combining of datasets challenging.[22] AI solutions must be validated, not just from a technical perspective, but also clinically and economically. Without a sound promise of safety, efficacy and cost effectiveness, stakeholders will be reluctant to adopt. Clinical trials in a real world setting are required, and these will require collaboration between dental professional and AI developers.[23] Successful implementation will require alterations to workflows, staff training, and support infrastructure.[22] There is a need for evidence about the extent to which AI has been implemented thus far in dental service provision, and there are currently no published systematic reviews with this focus.

As the UK regulator of dental professionals, with over 120,000 registrants, it is imperative that the GDC keeps abreast of developments that may have an impact on dental service provision, and therefore on dental professionals' practice and patients' experiences of dental care. Given the potential for AI to impact extensively in many areas of life, it is therefore important that the GDC is aware of the current evidence base regarding its use in dental service provision, and any benefits, risks or other implications from those uses. By providing a comprehensive and evidence-based assessment, this rapid evidence assessment (REA) has been undertaken to support the GDC in encouraging technological advancements while maintaining the highest standards in dentistry.

Objectives

The aim of this Rapid Evidence Assessment (REA) was to synthesise the evidence base relating to the use of AI in dental service provision including potential future areas of development.

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- To identify and assess evidence about potential developments of AI in dental service provision.
- To identify and describe methods used to evaluate the role and impacts of AI in dental service provision.
- To identify gaps in the evidence base on AI in dental service provision and recommend priority areas for further research.

Methods

The review was conducted according to established rapid evidence synthesis guidelines (Varker *et al*, 2015), followed a protocol which was prepared *a-priori*, and was reported using the PRISMA-2020 guidelines (Page et al, 2021). A rapid evidence synthesis method was chosen in order to establish the current extent of implementation in a rapidly developing field. The rapid methodology adheres to the principles of systematic reviewing through explicit, transparent methods addressing a clear and focused question. Key decisions about the question, inclusion criteria and review processes were agreed between the reviewers and commissioners of the project.

Review questions

We conducted a rapid evidence assessment to answer the question:

1) What applications of AI are currently implemented in dental service provision and which areas provide promising opportunities for the future?

Supplementary questions were:

2) Are there any best practice guidelines for specific technologies that use AI in dental service provision?
3) Which of the technologies that use AI in dental service provision have shown effectiveness in experimental studies?
4) What are the risks and challenges associated with technologies using AI in dental service provision? Are there any strategies and interventions suggested to address those challenges?
5) What methods have been used to evaluate AI in dental service provision?

Eligibility criteria

The review included studies from any country which describe the implementation of any form of AI-powered system, service or process in dental services. We defined AI drawing on a definition from IBM, as 'technology that enables computers and machines to simulate human learning, comprehension, problem-solving, decision-making, creativity and autonomy.'[24]

We defined dental service provision as any service in which patients received oral health care from dentists or dental care professionals in both the public and private sectors, including both primary dental practice, hospital-based dental services, and community or home-based care.[25] We defined implementation as meaning that an AI model, application or tool had been used in delivering patient care or in the prospective collection or analysis of patient data.

Studies which were set in the context of dental education were excluded. Proof of concept, validation and demonstration studies which were focused on developing and testing an AI-driven system using artificial datasets or retrospective analysis of existing patient-derived datasets were excluded. Reviews, editorials, commentaries, conference abstracts, non-English language and papers prior to 2020 were excluded.

Table 1: Inclusion and exclusion criteria

Category	Inclusion	Exclusion
Population	Dental professionals; dental patients;	Dental education and training
Intervention	AI; machine learning; deep learning; natural language processing; large language models; generative pre-trained transformer; transformer; supervised machine learning; unsupervised machine learning;	
Comparison	*Not applicable*	
Outcomes	Prevalence; impact; benefits; risks; equality, diversity and inclusion; data protection.	
Context	International; dental services settings; dental care	Dental students
Study design	All study designs reporting empirical data (quantitative or qualitative) on implementation of AI in dental services	Literature reviews; grey literature; editorials; commentaries; letters; conference abstracts.
Language	English	
Date range	2020 to present	

Information sources

The following bibliographic databases were searched on 18/09/24: Embase and MEDLINE via Ovid; CINAHL and DOSS (via EBSCOhost); Scopus (Elsevier); Web of Science (Clarivate); IEEEXplore. To increase the currency of the evidence searches, the following preprints repositories were searched from 01/10/24-31/10/24 with a one year date limit: MedRxiv; Research Square; JMIR Preprints; Lancet Preprints; OSF Preprints; Preprints.org; SciELO Preprints; bioRxiv; arXiv.

Search strategy

The database searches were executed by an information specialist (LB) and terms were designed in consultation with experts in the field of AI and robotics (AH, SZ, MN) and with reference to published search strategies from recently published systematic reviews. The searches comprised two blocks of terms to represent the concepts of AI or robotics and dentistry. Subject headings and free-text terms were used. Searches were translated across interfaces using appropriate syntax. A simplified form of searching was used in the pre-print repositories due to the reduced functionality of these interfaces. A full record of the search strategies is provided in Appendix B.

Selection process

Search results were collated in EndNote and de-duplicated. Thereafter the records were uploaded into Rayyan Web for screening. Records were screened first against title and abstract, and second against full text. Screening was undertaken by three reviewers (MB, AH, LB) following a calibration exercise of 10% of the records. Thereafter screening was undertaken singly except in the case of doubt, where two reviewers would discuss in order to reach consensus.

Data collection process

Data were extracted from the included studies using an Excel sheet which had been piloted against a sample of sentinel papers during the protocol design phase. Data extraction was undertaken by three reviewers (LB, MB, HA).

Data items

The items that were extracted from the studies were: source/author, year of publication, study design, population/setting, field of dentistry, AI type and AI application details, outcome measures, impact and benefits, risks, content relating to equality, diversity and inclusion (EDI) issues, content relating to data protection or data management issues, and any ethical issues reported by the study. We also recorded whether studies had received ethical approval.

Study risk of bias assessment

The included studies were not critically appraised. Appraisal is commonly not performed in reviews where the purpose is to explore the nature of the evidence base. The aim of this review was primarily to establish the extent and nature of the implementation of AI in dental service provision, and we therefore did not undertake critical appraisal, in line with REA methodology.

Results

Study selection

The database searches yielded 8972 results, which after deduplication left 3814 to screen. After title and abstract screening, 115 items were included, and all 115 were obtained for full text screening. The searches of pre-print databases did not result in any further documents being added to the review. The number of included studies was 45. The PRISMA-2020 flow diagram (Figure 1) depicts the flow of records from searching through to included studies.[26]

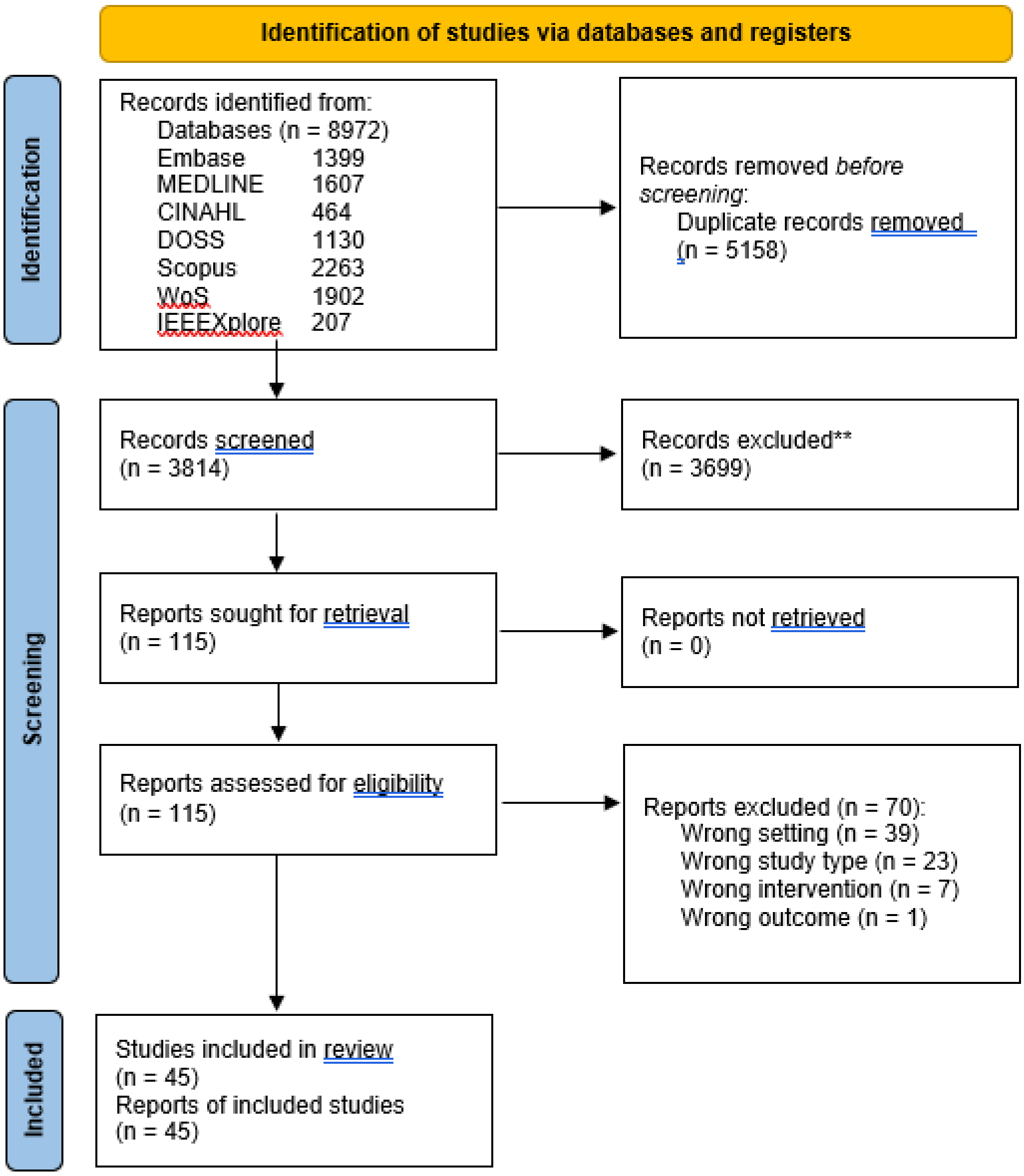

Figure 1: PRISMA 2020 diagram

Study characteristics

Of the 45 included studies, 18 were case reports or case series[3, 27-43] involving between 1 and 74 patients, but of which 13 involved ten or fewer patients; 13 were clinical trials of various types,[44-56] involving from 7 to 180 patients, including small scale single arm prospective clinical trials, pilot clinical trials as well as randomised control trials, plus one study that used data from a prior clinical trial;[57] 6 studies were cohort studies, involving between 20-194 patients;[58-63] 4 were cross-sectional studies[64-67], three of which included between 124-289 patients, and one of which included 50 dentists. The remaining three included studies were a survey with 182 patient participants,[68] an experimental study involving 50 patients,[69] and an observational study involving 55 patients.[70]

In terms of geographic scope, 18 studies reported findings from China,[30-35, 37-41, 45, 46, 50, 55, 56, 63, 64, 69],13 from the USA,[3, 27, 36, 43, 44, 47, 53, 54, 58, 60, 61, 66, 68] four from India,[29, 48, 59, 67] and two from Italy.[28, 42] There was a single study included from each of the following countries: Denmark,[57] Indonesia,[64] Japan,[51] Poland,[70] Slovakia,[62] Taiwan,[49] Turkey,[65] and the United Arab Emirates.[52]

The fields of dentistry covered by the papers were: restorative dentistry, particularly the diagnosis and treatment of caries;[36, 57, 63, 64] and subfields of restorative dentistry, including prosthodontics, specifically implant dentistry,[3, 27, 29-33, 35, 37, 39-42, 44, 47, 48, 50, 51, 54-56, 59, 64] as well as endodontics[34, 38, 43, 65, 67, 70] and periodontology.[46, 49] Other studies focused on paediatric dentistry,[45, 58, 66, 68] again typically relating to the diagnosis and treatment of caries. Finally, the remaining included studies focused on orthodontics[28, 52, 53, 60-62] and non-implant related oral surgery.[69]

The most common activities or service areas covered were treatment provision,[3, 27, 29-35, 37-44, 47, 48, 50, 54-56] diagnosis,[36, 51, 63, 64, 66-68, 70] treatment monitoring[28, 46, 49, 53, 58, 60-62, 65] and treatment planning.[52, 57, 59, 69] It should be noted that some studies covered more than one of these areas. Further details on the ways AI has been applied in these areas is provided below.

Categorised broadly, the types of AI discussed in the included studies were robotics,[3, 27, 29-35, 37, 39-41, 43, 44, 47, 48, 50, 54-56] deep learning,[28, 49, 57, 59-64, 69, 70] supervised machine learning,[45, 46, 58, 66-68], and computer-aided diagnosis.[51] One included study involved the use of unsupervised machine learning in dental services but in data analysis only, and did not ultimately yield findings relevant to our research questions.[65] Other included studies involved use of AI but did not clearly define the nature of the AI application being used.[36, 38, 42, 52] Further details of the AI applications used in the included studies, where available, are presented below.

Many of the studies included in this review focused on the use of robotics in dental service provision, especially its use in implant surgery. However, it should be noted that there are multiple subcategories of robotics that have been developed, and continue to develop, for use in dentistry and that not all necessarily involve the use of AI. In some studies, due to the way in which they have been reported, it was difficult to determine the extent of AI use in the robotics being described. We have erred on the side of including these studies, as they represent emerging technologies being implemented in dental service provision and raise many of the same issues for dental professionals and the dental regulator.

Results of individual studies

Best practice guidelines

No best practice guidelines for specific technologies using AI in dental service provision were identified from the included studies.

Effectiveness and impacts of AI applications

In this section, we summarise the evidence on the impacts, benefits and effectiveness of the AI interventions reported in the included studies.

Robotics

ROBOTICS

The employment of robots or robotic devices to support clinical processes is known as robotics in dentistry. These robots can be programmed to carry out extremely precise activities, such as helping with orthodontic treatments or inserting dental implants. Robots lower the possibility of error and frequently result in shorter processes with superior results [1-3]. These robots improve the skills of dentists by combining sophisticated sensors, artificial intelligence algorithms, and mechanical accuracy. These technologies are being employed more and more in dentistry to help with procedures like implant insertion, where robots may deliver unmatched accuracy by guiding surgical instruments with pre-programmed 3D image data. This lessens the chance of problems, speeds up recovery, and minimizes tissue damage. Robots are transforming the design and manufacturing of braces and aligners in orthodontics by precisely bending wires, something that is challenging to accomplish by hand [3-5].

Robotics were predominantly reported as being used in prosthodontics, for implant surgery. There were several types of robotic interventions used, including haptic robotics, Dynamic Navigation, semi-active or semi-autonomous robotic systems, and autonomous robotic systems.

Several included papers reported on the use of the Yomi robot, produced by Neocis.[71] This system gives aural, visual, and physical (haptic) guidance to the dentist during surgery and uses cone-beam computed tomography (CBCT) scanning for precision in planning the placement of implants.[43] While using the robotic system, the dental surgeon retains the ability to intervene in the surgery to pause or modify the placement of the implant if necessary.[43]

In a case report detailing the use of the Yomi robot for implant surgery with a single patient in the USA, Ali described using the system to place 11 implants and stated that the robot was engaged with the patient for 118 minutes in all, describing this as 'very reasonable in comparison to published data on dental implant surgical times.'[27] Ali stated that in their experience, the use of robotics helps to 'increase confidence and acceptance' of patients in a case of complicated, multi-implant surgery and also 'increases the confidence and comfort level' during the operation for the dental surgeon.[27] Bolding et al described a single-arm prospective clinical trial involving implant surgery for five completely edentulous patients in the USA also using the Yomi robot, with a total of 38 implants placed.[54] They assessed accuracy by measuring deviations from the planned placement of the implant, and found that 'robotic guidance of implant placement was at least as accurate as both static and dynamic navigation.'[54] Likewise, Klass et al reported a small clinical trial of the Yomi robot, involving seven patients in the USA, and found that the system 'minimizes inaccuracies' by allowing surgical adjustments in real time.[44] In a case report describing the use of the Yomi robot for implant surgery on a single patient in the USA, Talib et al state that benefits of the system include the ability to ensure correct positioning and to maintain an adequate distance from key anatomical structures.[3]

Isufi et al[43] used the Yomi robot system in endodontic surgery, describing in a case report its use in root-end resection surgery on one patient in the USA. They state that the system is 'safe and easy to use', and allowed 'good localization of the root' and facilitated the performance of the osteotomy and root resection in one step.[43] Further, they report that such robotic technology may offer shorter healing times and reduce the incidence of complications.[43]

Neugarten reported a randomised controlled trial including 108 patients in the USA who underwent haptic robotic-guided implant surgery.[47] Their findings were that the method is safe, accurate and efficient, while retaining intraoperative flexibility, and that it supports same-day procedures, and improves efficiency and patient outcomes.[47]

Yang et al reported a randomised controlled clinical trial involving 140 patients in China, in which they compared the accuracy of dental implant placement using semi-active robot-assisted implant surgery (RAIS) versus free-hand placement.[50] This study found that the RAIS method showed better accuracy than free-hand placement in single dental implant surgery. The authors noted that the semi-active or semi-autonomous robotic system enhances surgical safety by allowing the robot arm to respond to sudden movements by the patient, as the dental surgeon is required to assist in guiding the robotic arm.[50]

Other studies reported the use of autonomous robotic systems for dental surgery, again typically for the placement of implants. Li et al reported the use of a robotic computer-assisted implant surgery (r-CAIS) system that autonomously performed implant osteotomy and placement for ten fully edentulous patients in China, under the supervision of dental surgeons.[31] They state that the system provided high accuracy and reliability, with no adverse events or complications.[31] Several others studies also reported the use of autonomous robotic systems for implant surgery in China.[35, 37, 39-41, 56] These studies, a mix of case reports and clinical trials, found that the systems showed high accuracy for implant placement,[39-41, 56] comparable to that reported for static and dynamic computer-assisted implant surgery.[35] Wu et al report that, compared to a computer-aided dynamic navigation system, the autonomous robot system offers superior manoeuvrability and mitigates issues such as operator fatigue, visual obstructions and ergonomic challenges.[56] Xie et al also found that autonomous robotic-assisted implant surgery showed excellent accuracy, and furthermore that it alleviated the impact of issues such as hand tremors or limited surgical experience.[37]

Wang et al described the use of an autonomous robot system in endodontic surgery with a single patient in China in a case report.[34] They suggest that the system can provide minimally invasive and accurate endodontic treatment as well as minimising treatment duration.[34]

In summary, the benefits of using robotic systems in dental surgery described in the literature were that such systems enhance accuracy, reduce complications and improve post-operative outcomes. The systems were also reported to offer better patient experiences and deliver high patient satisfaction.

Deep learning

DEEP LEARNING
Deep learning is a branch of artificial intelligence that uses layers of artificial neurons to evaluate massive information in a manner similar to that of the human brain. It is frequently utilized in image analysis in dentistry, such as the detection of cavities or oral malignancies using CT or X-ray images. In many situations, deep learning models are able to identify patterns more quickly and precisely than people. Deep learning systems in dentistry are incredibly accurate at automatically detecting cavities, fractures, or indications of oral cancer[6]. These systems are an effective diagnostic tool because they get better at identifying patterns the more data they are trained on. In the field of dental and maxillofacial radiology, deep learning has demonstrated impressive results in the analysis of radiographic images, including CT scans and X-rays, to help diagnose diseases like tumors, bone loss, and tooth caries [8]. For instance, by seeing minute anomalies in radiographic data, deep learning systems can automatically identify early-stage oral malignancies, enabling quicker and more precise diagnoses to support prompt treatment initiatives. Deep learning algorithms are used in orthodontics to evaluate 3D scans and provide customized, ideal treatment regimens for braces or aligners[8, 11].

Deep learning based AI applications were described as being used in a variety of ways in dental service provision in the included studies. Abdat et al reported the use of a teledentistry application called DentMA [72] to detect caries and determine treatment needs in a cross sectional study involving 124 children aged 4-6 years in Indonesia.[64] DentMA is described as an Android-based application using segmentation algorithms, deep learning models, and convolutional neural networks. Patients' parents were asked to take intra-oral photographs using the DentMA application on their smartphones. The application detected enamel-dentin caries in 74.1% of the participants, indicating that teledentistry can be used to detect caries and can determine the need for treatment.[64] The authors argue that use of the application can encourage the use of preventive measures before caries develop further.[64]

Zhang et al also focused on the use of an AI model for caries detection using intraoral images.[63] Using a commercially available device – Aiyakankan (Aicreate, Zhuhai, China) – that combined MobileNet-v3 and U-net architectures, in a cohort study with 191 patients in China, the authors found that while the system was excellent at ruling out non-caries, it fared less well at identifying all cases of caries. However, they suggest that intraoral photographs could be incorporated in daily oral hygiene regimes as an approach to caries prevention.[63]

Several studies reported the use of a commercially available AI application called Dental Monitoring[73] for orthodontic and periodontal treatment monitoring.[28, 49, 53, 60-62] This application allows patients to take intraoral photographs using their smartphones, which can then be analysed by the application to track various conditions. The application can also send messages to patients reminding them to practice good oral hygiene, and to their dentists about any arising treatment needs. Snider et al reported that Dental Monitoring has low sensitivity, high specificity and moderate accuracy when detecting plaque and calculus, gingivitis and recession, indicating a tendency to underreport these conditions, though demonstrating very high accuracy in identifying their absence.[61] Also focusing on periodontal treatment, Shen et al reported a randomised controlled trial including 33 patients in Taiwan using Dental Monitoring.[49] They found that patients who had AI monitoring and those who had AI monitoring and also received AI-assisted oral health advice both showed better improvement in their periodontitis than patients in a control group, and that those who received both AI monitoring and health advice did better than those who only received monitoring.[49]

In relation to orthodontic treatment, Thurzo et al report that Dental Monitoring can reduce, but not eliminate, the need for face to face consultations but also noted that, in some cases it may prompt more frequent face to face consultations as it alerts when any issue with a dental aligner (or brace) occurs, rather than these not being identified until a pre-scheduled check-up appointment.[62]

Other examples of deep learning AI applications being used in experimental studies include it being used as a decision support tool. For example, as a means of initiating the seeking of second opinions in diagnosis and treatment decisions, so that a disagreement between a clinician and an AI tool's judgements would trigger a referral for a second opinion from another clinician,[57] or by diagnosing dentomaxillofacial deformities and creating treatment plans for consideration by clinicians and patients.[69] In another study, treatment plans generated by a deep learning AI algorithm were compared to those developed by clinicians for the same patients in need of implant surgery, and were found to closely align thereby potentially offering additional efficiency and consistency.[59] One study reported on the diagnostic accuracy of the Diagnocat AI platform, trained on 35,000 dental radiographs, for endodontic treatment and suggested that it demonstrated excellent accuracy and could be a reliable tool for radiographic assessment.[70]

In summary, deep learning AI models and applications show promise in enhancing dental care through early detection, remote monitoring, diagnostic support, and treatment planning.

Supervised machine learning

SUPERVISED MACHINE LEARNING

Training an AI model with labeled data such as a collection of X-rays classified as either healthy or diseased is known as supervised machine learning. Using patterns found in the data, the AI learns to forecast results. In dentistry, this kind of AI is frequently used to support diagnostic procedures like cavity detection, early detection of gum disease or decay, periodontal disease, or even condition progression prediction [6, 7].

Supervised machine learning is a very useful tool in periodontology for forecasting the course of periodontal disease. In order to enable dentists to carry out early, individualized preventative interventions, models trained on patient data, such as clinical measurements (e.g., pocket depth, bone loss) and lifestyle factors (e.g., smoking, oral hygiene), can identify patients at higher risk of severe periodontitis [9]. Furthermore, machine learning models evaluate patient data to track gum disease development and evaluate the long-term efficacy of treatment [10].

Several included studies described the use of supervised machine learning algorithms and models in dental service provision. Of the six included studies that used supervised machine learning, four focused on aspects of children's dental care, and three of those related to the identification and treatment of childhood caries. Heimisdottir et al used the Tree-based Pipeline Optimization Tool (TPOT) AutoML to identify metabolites significantly associated with early childhood caries, using data from a cross-sectional study with 289 patients in the USA.[66] They argue that their findings pave the way for the development of diagnostic tools that could support dental professionals to improve the identification and management of early childhood caries.[66] Ramos-Gomez et al used Random Forest machine learning algorithm to identify from a survey in the USA of 182 patients' parents the items most likely to predict the presence of active caries in children.[68] They argue that the development of algorithm 'toolkits' to aid dental professionals to evaluate patient's oral health could be useful in preventing caries among children.[68] Ruff et al used artificial neural networks and lasso regression analysis to predict treatment outcomes for children with caries, focusing specifically on treatment non-response.[58]

Not related to caries specifically, but still focused on children's dental care, Li et al undertook a randomised controlled trial with 82 patients in China, using the CV-LBF (local binary fitting) computer intelligent segmentation model to improve CBCT imaging accuracy for children's dental diagnoses, achieving higher precision compared to traditional algorithms.[45] The authors suggest that using AI to improve CBCT image segmentation could support more precise treatment planning and improve outcomes in children's dental care.[45]

Li et al undertook a randomised controlled trial involving 100 patients in China to evaluate an AI-enabled multi-model toothbrush and an accompanying smartphone application offering real-time feedback and guidance on effective brushing.[46] The system sent anonymised data to clinicians for monitoring purposes and sent text message feedback to patients. The authors report that the intervention improved adherence to good oral hygiene practices, and provides a way to integrate AI and remote monitoring into patient care.[46]

Following a literature review to identify key advances in dental technology, Kumar et al undertook a survey of 50 dentists in India to establish their awareness and use of new technologies, including digitization, AI and robotics in endodontics.[18] They found that clinicians' awareness of these technologies varied, and that none had used these technologies in practice.[67]

The uses of supervised machine learning AI technologies demonstrated in the included papers are varied, and include some uses focused primarily on data analysis rather than more direct patient care. However, these analyses indicate potential value for supporting improved identification of caries, for example. Other uses, such as an AI-enabled toothbrush, bring patients directly into using AI themselves.

Risks and challenges

Alongside the findings relating to effectiveness, accuracy, and the benefits of robotics and AI applications in dental service provision described above, the included studies also identified a range of risks and challenges arising from the use of these technologies.

Clinical risks and challenges for clinicians

Many of these risks related to the specifics of using or operating the technology for clinicians. For example in relation to the use of robotics in implant surgery, Bolding et al noted that poor bone quality may affect the final implant location compared with the planned site, and that clinicians must recognise deviations from the planned placement and ensure that implants are not placed in the sinus, nerves or adjacent tooth roots.[54] Other studies noted that limited mouth opening or dense bone can reduce the effectiveness and usability of robotic systems for implant surgery.[37, 41] It was also reported that patient movements during implant surgery using robotic systems could necessitate additional interventions,[50, 56] and it is important that the clinical team ensures that the patient's head is stabilized during the drilling process.[56] Other studies noted that preoperative steps such as imaging, calibration and registration required by robotic systems can make these more time-consuming and complex.[32, 55] Aside from purely clinical challenges, it was also noted in some papers that the high investment costs associated with robotic systems and the need for dental professionals to undertake additional training to use the technology could hinder widespread adoption of these tools.[32, 56]

The Dynamic Navigation system, used to guide implant surgery, was also reported to require additional training for dental surgeons, and it was noted that the hand piece is heavy, and that utilising the system requires very skilled hand-eye co-ordination which can be difficult to achieve without experience in using the technology.[29] The learning curve for dental surgeons using robotic systems was noted in several papers,[3, 31, 43, 44] and semi-autonomous robotic systems were reported to require ‘a longer learning curve’ for surgeons than fully autonomous systems.[30]

Other potential challenges identified included the issue of trust among clinicians, whose willingness to adopt new technologies may vary.[57] Another study suggested that, while a deep learning model may support the technical aspects of implant planning, AI should be viewed as a complementary tool rather than as a replacement for clinical expertise, noting the nuanced decision-making that experienced dentists provide.[59]

False-negative results

One study, analysing the use of the Diagnocat diagnostic platform, noted that there was a risk of false-negative results for subtle findings like voids and short fillings that might delay intervention and further treatment.[70] False-negative results were also noted by Zhang et al in relation to caries detection, and they noted that this is a consequence of reliance on visual information alone, and that AI may be more suitable as a screening tool than as a standalone diagnostic method.[63]

Patient response and compliance

While some papers reported on positive patient responses to robotics-assisted surgery, as described previously, it was also noted that the presence of the machinery in the clinic or operating room may increase patient anxiety.[48]

Studies investigating the use of AI-based monitoring systems also noted some limitations and risks, notably that automatically-generated advice messages to patients were not personalised and could be repetitive, potentially causing patients to disengage.[46, 49] Thurzo et al also noted that patient compliance with the Dental Monitoring system was best within the first 60 days then worsened over time.[62] Similarly, Arqub et al noted the number of patients performing Dental Monitoring scans regularly as instructed declined over time.[53] In another study on the Dental Monitoring system, in which patients were required to take intraoral photographs for monitoring during orthodontic treatment, patient burnout with the weekly scan schedule was reported with some patients having completion rates lower than 50% despite regular automated reminders.[60] In a further study, the same authors reported that there was a risk of patient error when taking the intraoral photographs or scans, as patients tended to sometimes not adequately capture all surfaces of the posterior teeth.[61] Similar issues were reported by Caruso et al, also describing the use of Dental Monitoring.[28]

Equality, diversity and inclusion considerations

There was very little evidence within the included studies on issues relating to equality, diversity and inclusion. Some studies noted that the use of AI-driven monitoring applications, to be used by patients using their smartphones, could be useful for populations with limited access to in-person care.[36]

Ramos-Gomez et al reported the relevance of demographic and socio-economic characteristics, including ethnicity but also parent's age, the number of people in a household and length of time at current address, for the dental problem for which AI use was being investigated, in this case childhood caries.[68] Likewise, Ruff et al focused their study on predicting treatment non-response for childhood caries specifically in Hispanic/Latino children, but this was not related to their use of AI in the analysis.[58]

One study reported participants' demographic and socio-economic characteristics and used these in analysis, though found no statistically significant differences.[36] In some other studies, ethnicity was noted as a potentially relevant factor, for example in dento-maxillofacial deformities,[69] or participants' ethnic backgrounds were reported but not analysed specifically.[66]

Ethics, data protection and management considerations

There was also very little evidence in the included studies about issues relating to ethics, data protection or data management with regards to the use of AI in dental services provision. One study noted that patient data were anonymised and that participants, using an AI-enabled toothbrush, had been shown how to disable data sharing if desired.[46] One further study identified ethical considerations, data security, and regulatory compliance as needing to be addressed when integrating AI into dental practice but without further exposition.[59] One study noted that the use of the Dental Monitoring system generated considerable additional data about the users, both patients and dentists, that were not the main focus of the research, including for example time taken to clean teeth, to eat, drink, and clean the appliance.[62] While not identified as such in the paper, the generation of such 'collateral' data by such systems may present ethical and data protection challenges.

Evaluation methods

As detailed above in describing the characteristics of the studies included in this review, the methods used to evaluate the use of AI interventions in dental service provision have largely been small scale case reports or case series,[3, 27-43] and clinical trials of various types including some randomised controlled trials.[44-56] While RCTs are considered the gold standard of clinical experimental studies, even these can sometimes involve quite small numbers of patients, with one trial included in our review involving just 33 patients.[49] There were also papers describing cross sectional studies looking at a group at a point in time[58-63] and cohort studies looking at a group over time,[64-67] though the differentiation between these observational study types, particularly when this nomenclature is adopted for smaller studies, is not always applied consistently.

Our focus on implementation is likely to have resulted in the predominance of these types of studies within the review, and while they may produce scientifically robust results, there may also be some limitations, particularly in respect to some of our review questions. As has been noted above, there was little focus within the studies on issues relating to EDI considerations or to ethics and data management issues. Some of the studies included information about the benefits and risks or challenges arising from the implementation of AI for dental professionals and patients, but this was not consistent or extensive across the included literature.

Discussion

Through this REA, we have provided a synthesis of the evidence available on the implementation of AI and robotics in dental service provision. Despite a significant amount of research and development focusing on developing AI applications and tools for dentistry,[15] only a limited amount of tools and applications have reached the implementation stage and are in use, or have been tested for use, in actual patient care and service delivery.

We found that, in the recent literature included from 2020 onwards, the most commonly implemented new technologies in dental service provisions were various forms of robotic systems, most typically being used for implant surgery. The extent to which these robotic systems operate autonomously varies, from semi-autonomous guidance systems to fully autonomous systems. These systems were reported to provide precision and consistency, but are also costly, and bring requirements for additional training for the dentists operating them. We also identified differing evidence on their acceptability to patients. However, it seems likely that the development and implementation of these robotic systems will continue, and that they may in time become more accessible and therefore also more prevalent.

The other main area where AI has been implemented is through the use of AI-based smartphone applications enabling treatment to be monitored by patients taking their own intraoral scans and, in some cases, receiving AI-generated oral health advice messages. These systems may be a useful tool for populations with limited access to dental care, including potentially so-called ‘dental deserts’ in the UK.[74]While many of the included studies focused on the identification of caries, for example, clinical judgement is still required as to what treatment, if any, is warranted. Moreover, there is also the risk that dental services provision may not be sufficient in some areas to provide subsequent treatment once issues have been identified. In addition, the findings of this review also show that patient adherence to the requirements of such systems tends to wane over time, and that the health advice messages may not be effective. These caveats serve to highlight that while novel technologies may offer great potential benefits, they can also generate additional demand on services, and they should not be seen as a silver bullet.

We identified limited information from the literature about areas such as ethical dimensions of the implementation of AI in dental service provisions and data protection issues, and this is in common with other research in this field. For example, an earlier review from 2021 specifically focusing on artificial intelligence and ethics in dentistry found that only 12.4% of the studies it identified, albeit mostly from the testing and validation development phase literature, reported on ethical issues.[75]

Similarly, we found little evidence that EDI considerations are being considered in the development and implementation of AI tools for use in dental service provision. It is probable that the researchers and dental professionals undertaking these studies are early adopters of the new technologies being investigated and as such they are perhaps likely to be enthusiasts or advocates for those technologies, and may be less likely to focus on limitations and challenges. The limited attention paid to EDI considerations in developing AI applications for use in healthcare has been noted elsewhere, and the recently published EDAI framework seeks to remedy this.[76]

The nature of the evidence base on the implementation of AI in dentistry is mixed, with a lot of small-scale studies and case reports contributing to the literature. In future, it is to be hoped that larger scale, robust trials are undertaken to test the efficacy and acceptability of new technologies. There is also a clear need for prospective research to encompass the training needs for dental professionals engendered by AI and robotics, and the implications of the growth of AI for dental education more broadly, and also to consider the regulatory implications of these new technologies.

It is also notable that none of the included literature reported on the implementation of AI and/or robotics in dental service provision in the UK. While it is clear that the development of AI applications and robotics systems is an international field, with some systems such as Dental Monitoring and the Yomi Robot already evidenced as being used across a number of countries, it would be beneficial to see future research to gather evidence specifically on the use of AI in dentistry in the UK. Such research could then ensure that aspects such as equality, diversity and inclusion, and data protection, were properly considered in regard to the UK's cultural and social context and in line with UK regulatory expectations.

The included studies largely focused on patients as participants, and in receipt of treatment from dentists. However, the issues raised are likely to be relevant to all groups of dental professionals as the use of AI within dental service provision continues to develop and expand. The increasing use of AI within dental service provision also carries several potential implications for the GDC as the UK regulator of dental professionals. For example, the introduction of novel technologies will require dental professionals to undergo appropriate training in their use, and dental education providers – regulated by the GDC - will have to address this need in future. The GDC may need to consider how and where the use of AI is covered by its *Standards for the Dental Team.*[77] For instance, if a complaint arises where an AI tool has informed clinical decision-making, to what extent would a dental professional be expected to understand how and why an algorithm suggested a particular treatment pathway? Research in the wider health services sector in the UK found that clinicians look to their professional regulators for guidance on such matters.[78] More broadly, the continued development of AI has vast potential to impact on all fields of work, including in healthcare and the full implications of this are not yet known. It may be that some tasks come to be performed by AI entirely, or we may see the creation of new AI-focused roles in the workforce, requiring technological skills and training as well as, or even instead of, clinical qualifications. How professional regulation responds to such developments, and how much of the development of AI in health services provision falls under the remit of professional regulators remains to be seen. It is clear that AI will increasingly be part of dental service provision in future, and that both the dental professions and their regulator will need to adapt to maximise benefits to patients while mitigating risks.

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