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Advancements in 3D Imaging Technologies in Dental and Maxillofacial Radiology: Review

[1]-Rawabi Ibrahim Abdullah Alfulayw,[2]-Salem Abdullah M Almarshid,[3]- Mohammad Salem Alhjaily,[4]-Mohammad Salem Alhjaily,[5] - Mohammed Abdu Sabi,[6]- Yousef Dhikl Almutairi,[7]-Bushra Khalid Alahmadi,[8]-Samar Abdulrhman Alghamdi,[9]-Majed Hazmi H Alotaibi,[10]-Nasser Mohsen Alsahli,[11]- Tariq Mohammed Alrashidi,[12]-Abdulaziz Khalid Alzaaqi,[13]-Mohammed Abdulqader Ahmed Alhazmi,[14]- Saleh Abdullah Saleh Alawad

1. Ksa, Ministry of Health, King Fahd specialist hospital, Buraydah
2. Ksa, Ministry of Health, Hawtat sudayr hospitl
3. Ksa, Ministry of Health, King Salman bin Abdulaziz Medical City
4. Ksa, Ministry of Health, King Salman bin Abdulaziz Medical City
5. Ksa, Ministry of Health
6. Ksa, Ministry of Health, King Salman bin Abdulaziz Medical City
7. Ksa, Ministry of Health, King Salman bin Abdulaziz Medical City
8. Ksa, Ministry of Health, King Salman bin Abdulaziz Medical City
9. Ksa, Ministry of Health, AlDWDMI GENERAL HOSPITAL
10. Ksa, Ministry of Health, Tumair General Hospital
11. Ksa, Ministry of Health, Tumir General Hospital
12. Ksa, Ministry of Health
13. Ksa, Ministry Of Health, Hakemat Abu Areesh Primary Health Care Center
14. Ksa, Ministry Of Health, Utaiqah Center For Family Medicine Advisory Clinics

Abstract

Background: The rapid evolution of 3D imaging technologies has significantly impacted dental and maxillofacial radiology, enhancing diagnostic accuracy and treatment planning. This review explores the integration of technologies such as artificial intelligence (AI), virtual reality (VR), and augmented reality (AR) in dental practices.

Methods: A comprehensive literature review was conducted, focusing on recent advancements in 3D imaging applications within dental and maxillofacial radiology. Peer-reviewed articles and clinical studies were analyzed to assess the effectiveness and clinical relevance of these technologies.

Results: The findings indicate that 3D imaging technologies, particularly those enhanced by AI, have improved diagnostic precision in detecting dental anomalies, fractures, and pathologies. For instance, AI algorithms have demonstrated high accuracy in analyzing dental radiographs and cone-beam computed tomography (CBCT) scans. Additionally, VR and AR technologies have been successfully employed for patient education, surgical training, and treatment simulation, which have proven effective in reducing patient anxiety and improving clinical outcomes.

Conclusion: The integration of advanced 3D imaging technologies into dental and maxillofacial radiology signifies a transformative shift in clinical practice. These innovations enhance healthcare delivery by improving diagnostic capabilities, facilitating effective treatment planning, and enhancing the educational experience for both practitioners and patients. Future research should focus on addressing the challenges of data integration, algorithm transparency, and cost-effectiveness to maximize the benefits of these technologies in dental care.

Keywords: 3D Imaging, Dental Radiology, Artificial Intelligence, Virtual Reality, Augmented Reality

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1. Introduction

The globe has seen significant development in several fields, with technology serving as a crucial catalyst for this change. In healthcare, technology has introduced several advancements, including artificial intelligence (AI), virtual reality (VR), augmented reality (AR), mixed reality (MR), extended reality (XR), and robotic applications, all designed to improve patient care. Despite ongoing apprehensions over technology's intrusion into human responsibilities in healthcare, there is a dominant conviction that these innovations may enable healthcare personnel to provide enhanced patient care. This empowerment manifests as enhanced decision-making powers, superior long-term patient monitoring, accelerated picture processing, and remarkable predictive ability. AI and machine learning (ML) are seen as supplementary instruments that augment human proficiency rather than replace it. Like any invention, these technologies have distinct benefits and disadvantages. This review article examines the many functions of AI, VR, AR, MR, and XR in dentistry. We will concentrate on their applications in oral medicine, oral radiology, oral surgery, and oral pathology, elucidating how these technologies are transforming and enhancing dental practice for both practitioners and patients.

AI involves the theory and development of computer systems that can execute activities usually linked to human intelligence, including visual perception, voice recognition, decision-making, and language translation [1]. In healthcare, AI is used in sophisticated internet search engines, recommendation systems, and innovative technologies [2]. A branch of AI, termed ML, focuses on creating computer algorithms and models that allow computers to learn from data and make predictions or judgments autonomously, without explicit programming for particular tasks. Fundamentally, machine learning enables computers to see patterns, interpret data, and enhance their performance or behavior over time via experience. In dentistry, AI is used to autonomously evaluate dental X-rays, providing essential insights such X-ray type, probable tooth impact, accurate degree of bone loss via color overlays, cavity location, and more information [4]. Deep learning (DL), a distinct subset of machine learning (ML) defined by multi-layered computer networks, has revolutionized medical and dental image processing [3,4].

The potential of machine learning and deep learning in dentistry includes improved diagnostic precision and treatment strategizing. A significant advancement at the University of California was the development of an AI system that achieved a 94% accuracy rate in identifying periodontitis [5,6]. This approach demonstrated diagnostic accuracies of 73% in differentiating normal from sick patients and 59% in categorizing the severity stages of bone loss. Enhanced improvement of the periodontal dataset might convert this computer-aided detection method into an effective instrument for identifying and staging periodontal disease [7]. Besides periodontitis, deep learning systems have shown proficiency in precisely detecting dental cavities in X-rays. These technologies, noted for their impartiality and reduced bias, have the potential to transform dentistry by standardizing and enhancing the diagnostic process [6].

Virtual reality (VR) is a computer-generated simulation of an imagined, immersive, three-dimensional (3D) environment that may be interacted with using certain technology [8]. Virtual reality has been effectively used in medicine as a distraction mechanism during surgeries and as an acclimatization method to prepare individuals for experiences or procedures, as shown by systematic reviews and randomized controlled trials [9]. While it has not yet achieved general adoption in dentistry, it may contribute to exposure-based acclimatization to dental procedures. Three experiments using virtual reality in a dentistry setting demonstrated decreased pain and anxiety compared to no intervention. All three trials were conducted during the perioperative period [9]. Virtual reality may be used to eliminate dental fear in children and elderly patients while also improving patient education. Before executing treatments on real patients, dentists, and dental students may rehearse and evaluate techniques on mannequins with virtual reality technology by employing three-dimensional replicas of teeth or a human cranium. Furthermore,

virtual reality may be used to educate novice dentists and ensure that experienced dentists preserve their competencies [10].

Augmented Reality (AR) is a method that overlays digital information onto the actual surroundings. The integration of computer-generated sensory inputs such as music, video, graphics, or GPS data enhances the user's perception of reality [11]. Augmented Reality principally aims to enhance clinical practice by promptly presenting healthcare data on the patient and integrating the physical and digital realms. Through the use of interactive methodologies, AR and VR technologies may assist dentists in elucidating diverse dental procedures to patients, formulating diagnoses, devising treatment plans, and effectively demonstrating anticipated outcomes using 3D representations of patients' teeth, gums, and oral cavities [12].

Virtual Reality (VR) and Augmented Reality (AR) converge in Mixed Reality (MR), facilitating the integration of digital elements inside a tangible environment via their interaction with the actual world [13]. Magnetic resonance equipment may be used in dentistry for surgical planning and training. It may provide an innovative approach for those undergoing dental treatment regarding the provision of permission. The Microsoft HoloLens is a mixed-reality device capable of presenting information and perhaps generating a virtual world using a real-time, three-dimensional platform that utilizes many sensors and holographic processing. The HoloLens technology might serve as a vital instrument for dental education and surgical planning, considering the rapid advancement of technology and the increasing prevalence of virtual learning [14].

XR is a comprehensive term that includes any technologies that augment our sensory experiences, such as VR, AR, and MR [15]. Moreover, these technologies have been used across other sectors, including entertainment, education, and healthcare. This concept encompasses both concrete and imaginary hybrid realms, together with human-machine interactions facilitated by wearable devices and computer technology. Implantology and orthognathic surgeries are the two most prevalent dental applications of XR. The advancement of reality devices enables users to integrate both medical data and graphical information. Virtual planning for dental implants, which integrates 3D virtual schematics into the operating environment, has enhanced the accuracy of implant placement via the use of either static guides or dynamic navigation [16]. Dental static-guided technologies may provide fewer advantages in dental implantology compared to computer-assisted surgery using dynamic navigation. These technologies superimpose computed cone-beam tomography (CBCT) depth, angle, and drill location onto images, aiding dentists in executing minimally invasive operations and preventing harm to critical structures. The use of computer-aided navigation enhances treatment accuracy and reduces operating risks, making it advantageous in oral and maxillofacial surgery. Users may intermittently don a head-mounted display or a glove that activates their visual, audio, and tactile senses, therefore facilitating an immersive virtual experience [17].

Presently, mock-ups, video analysis, and 3D facial designs have been used to assist in the approach of smile reconstruction throughout dental rehabilitation. The advancement of new technology enhances this program and reduces the time and likelihood of errors in the flow of information among patients, clinicians, and labs. Enhanced realism grin systems identify the smile in the shot and substitute it with an alternative smile for optimal alignment [15]. Technology has fundamentally transformed dentistry, enhancing comfort, efficiency, and efficacy for patients. Additional technological advancements that have impacted contemporary dentistry are laser dentistry, CAD/CAM, 3D printing, and regenerative dentistry. Moreover, these advancements in dentistry significantly influence the delivery of dental treatment.

2. History

In this decade, we are progressively approaching the domain of the fourth dimension, where experiences hitherto inaccessible in the physical sphere become reachable. The inception of AI dates to 1956, but the foundations of VR extend to 1960. In 1962, Morton Heiling created the Sensorama system, a multisensory simulator that integrated color and stereo pre-recorded films, enhanced with binaural aromas, sound, wind, and vibrational elements. Nonetheless, Sensorama's interaction was constrained. In

1965, Ivan Sutherland showcased "The Ultimate Display" technology, which was predicated on the idea of creating an artificial environment that included interactive visuals, force feedback, and sensory aspects such as olfactory, gustatory, and aural components [18]. In 1968, Sutherland unveiled the first head-mounted display (HMD) device including a three-dimensional head-tracking technique, suitably titled "The Sword of Damocles" [19]. In 1971, GROPE, the first prototype of a force-feedback system, was developed at the University of North Carolina (UNC). GROPE integrated haptic displays with visual models [16]. In 1975, Myron Krueger founded an artificial reality laboratory called Videoplace, which created a "conceptual environment that did not exist." This technology projected human silhouettes, taken by cameras, onto a big screen, facilitating user interaction [20,21]. In 1982, Thomas Furness developed the Visually Coupled Airborne System Simulator (VCASS), a sophisticated flight simulator shown at the US Air Force's Armstrong Medical Research Laboratories. Fighter pilots used a head-mounted display that combined the external view with visuals displaying accurate flight path data [16].

In 1984, NASA Ames created the Virtual Visual Environment Display (VIVED), which included a stereoscopic monochrome head-mounted display (HMD) [21]. The VPL firm achieved notable advancements in commercial VR technology, launching the renowned Data Glove technology in 1985 and the market-ready Eyephone HMD in 1988. In 1989, Fake Space Labs unveiled the BOOM technology, a tiny apparatus consisting of two CRT displays observable via ocular apertures. The second half of the 1980s saw the development of several VR equipment, such as optical trackers, head-mounted displays, and the Pixel-Plane graphics engine at the University of North Carolina. The architectural tour highlighted a significant use of these technology. In 1992, the CAVE Automatic Virtual Environment was developed, integrating virtual reality with scientific visualization techniques. Users donned LCD shutter glasses while stereoscopic pictures were projected onto the walls of the room, providing high-resolution visuals and an expanded field of vision in comparison to head-mounted displays (HMDs) [21]. In 1994, Milgram and Kishino proposed the VR continuum, which includes five systems: AI, AR, VR, MR, and XR [16]. AR technology, in this context, augments rather than supplants the physical environment. Augmented Reality utilizes transparent Head-Mounted Displays to superimpose virtual three-dimensional items onto the physical surroundings. Augmented Reality has significant promise for improving human perception and aiding in intricate activities, making it a central subject of several research initiatives [22].

3. Virtual Reality and Augmented Reality in Dental Medicine

Traditionally, exams of the oral cavity and clinical diagnostic assessments of oral lesions were conveyed verbally or via visual aids. The oral medicine residents are required to get a comprehensive clinical history from the patient and conduct a meticulous examination of the mouth cavity. A case history is a structured professional dialogue that allows the patient to articulate their symptoms together with their personal, dental, and medical backgrounds. A 3D-augmented clinical history format may be developed to document the primary complaint, medical and dental histories, along prior investigations. Therefore, using this platform will significantly assist in formulating a preliminary diagnosis for the patient and elucidating the findings via the use of photographs.

The predominant categories of oral lesions seen by an oral medicine resident are erythematous and leukoplakic lesions, vesiculobullous lesions, and ulcerative lesions. The standard chairside diagnostic methods are vital staining, exfoliative cytology, and optical imaging. The efficacy of these technologies may be shown using a 3D-augmented platform. Haptic-based virtual reality training simulators may be used by oral medicine residents to practice these conventional approaches. Moreover, VR may aid the dentist in eliminating false-positive and false-negative outcomes of several important staining techniques, such as toluidine blue, methylene blue, and Lugol's iodine.

Certain oral lesions are managed with medicine, but others are advised for biopsy. An oral premalignant condition, such as oral submucous fibrosis, is often treated with hyaluronidase injections. Injection location and dose may be shown using VR training simulators. The treatment of white lesions may include the use of topical treatments or the oral administration of pharmaceuticals, which may be elucidated by stimulators [23]. Incisional and punch biopsy methods are often used for assessing possibly malignant oral conditions

including oral squamous cell carcinoma. Excisional biopsy techniques are conducted for exophytic growth, pyogenic granuloma, and mucocele. The AR stimulators are applicable for elucidating and rehearsing biopsy techniques for oral medicine residents. Furthermore, the tactile feedback systems need further investigation to improve biopsy techniques (Figure 1).

Figure 1. An oral medicine resident using a virtual reality apparatus to comprehend an exfoliative smear technique employing a cytobrush.

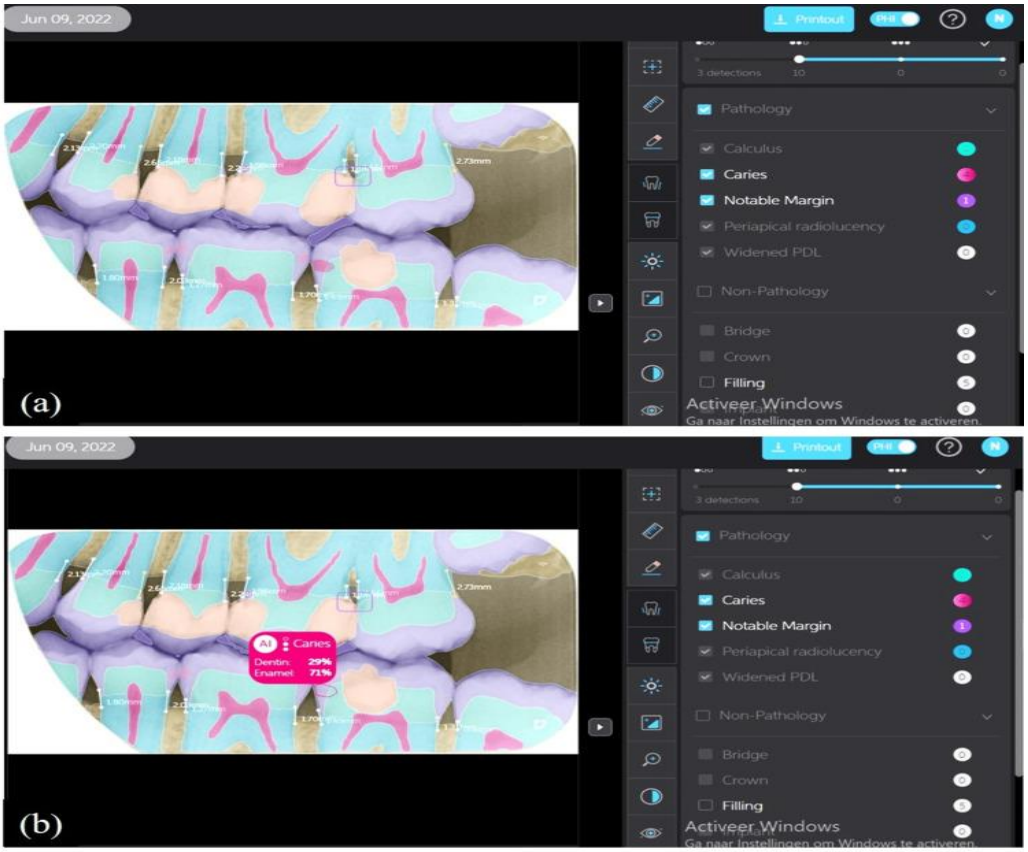
4. Artificial Intelligence in Dentistry

Artificial intelligence is now a prevalent diagnostic tool used for accurate picture analysis using numerous bodily systems. The AI approaches being used include artificial neural networks (ANNs) and genetic algorithms. In the last decade, artificial neural networks (ANNs) have been used to clarify the results of several diagnostic modalities such as ultrasound (USG), dental radiographs, cone beam computed tomography (CBCT), computed tomography (CT) scans, and magnetic resonance imaging (MRI). Furthermore, using artificial neural networks (ANNs) enables the meticulous generalization of parameters by enhancing the congruence between the input data (text or picture processed by the algorithm) and the output data (functional categorization). Moreover, machine learning algorithms may provide precise clinical insights by examining manually annotated hospital medical data [24].

Furthermore, AI may serve as an auxiliary tool for identifying oral lesions and devising effective treatment plans based on clinical observations. AI algorithms may assist in classifying different worrisome lesions that may be undergoing malignant transformations. Consequently, future studies may prudently use AI to screen bigger populations for genetic vulnerability to oral cancer. Furthermore, AI may provide supplementary diagnostic insights in conjunction with primary diagnostic methods such as CT, MRI, and CBCT to identify specific anomalies in anatomical structures that may have been overlooked by human observation [24].

5. Oral radiology

Mouth radiology is a specialist branch of dentistry that utilizes diverse imaging techniques for the diagnosis and treatment of mouth disorders. Its main function is to detect diseases like cysts, tumors, and infections inside the oral cavity. Oral radiology employs many imaging modalities, such as radiography, cone beam computed tomography (CBCT), computed tomography (CT) scans, magnetic resonance imaging (MRI), positron emission tomography (PET) scans, and ultrasonography (USG). Radiographs are often used for identifying dental caries, periodontal illness, cysts, benign and malignant tumors, and various other dental anomalies. CT scans are very beneficial for evaluating bone loss, fractures, and malignancies, but MRI



is proficient at identifying soft tissue irregularities, including cysts and cancers. Ultrasound is mostly used to assess abnormalities of the salivary glands. This dental specialty is essential for the accurate diagnosis and treatment of oral disorders [2, 25].

6. Artificial Intelligence in Dental Radiography

Artificial intelligence applications in oral and maxillofacial radiography have significant potential. Convolutional Neural Networks (CNNs), capable of executing image classification, detection, segmentation, registration, construction, and refinement, have been predominantly used in recent studies on artificial intelligence in oral and maxillofacial radiology. AI algorithms have been developed in this domain for image analysis, forensic dentistry, radiographic diagnoses, and image quality improvement. Dental radiography is progressively using AI, emphasizing diagnostic records in CBCT and digital 3D imagery. To create AI for rapid diagnosis and enhanced treatment planning, extensive data may be collected and analyzed [26]. To get optimal findings, a substantial amount of data is necessary, and oral radiologists must participate in the labor-intensive task of generating precise and consistent data sets. Numerous challenges must be addressed before the widespread use of AI in contemporary clinical practice, including the need for huge, meticulously annotated open datasets, an understanding of AI's evaluative criteria, and the identification of possible AI-related risks to DICOM. Artificial intelligence is expected to progress further and will likely assume a crucial role in developing automated diagnostic systems, formulating treatment plans, and producing therapeutic devices, provided that solutions to these challenges are addressed alongside AI's advancement. Oral radiologists, as experts in the characteristics of radiographic images, will play a vital role in the development of AI applications in this field (Figure 2) [25].

Figure 2. The function of artificial intelligence in the annotation of dental radiographs. (a) Segmentation of various dental structures and (b) specifics on the extent of tooth decay penetration.

7. Virtual Reality and Augmented Reality in Dental Radiology

Virtual and augmented reality technology is an innovative communication tool that may increase radiology education, facilitate interactions with colleagues, refer doctors, and patients, and support

interventional radiology procedures. At now, AR and VR technologies let users just see material; they do not provide interaction with the environment or the reception of haptic feedback. Emerging technologies facilitate human contact with and modification of the environment [27]. Anatomical holograms may be "tagged" to interactive physical objects using affordable, commercially available devices such as the MERGE Cube (Merge VR, San Antonio, Texas). Despite the significant promise of VR and AR in radiography, they now exhibit various limitations, including ergonomic challenges associated with prolonged use, comparatively high adoption and operational costs, and a deficiency of available material. Continuous use of HMDs may lead to neck pain, nausea, and disorientation due to extended exposure [26].

8. Conclusions

Technological developments in AI, VR, AR, MR, and XR have transformed dentistry, initiating a period of accuracy, superior patient care, and greater education. These advances are not intended to replace human employment but rather function as essential instruments in providing more efficient and cost-effective health care. These technologies have already revolutionized several facets of oral health care, encompassing diagnostics, treatment planning, operations, and patient experiences, with the capacity to obviate conventional instruments like drills and injections. In oral medicine, virtual reality (VR) and augmented reality (AR) facilitate three-dimensional enhanced clinical histories, assist in provisional diagnosis, and improve treatment plan elucidations, while haptic-based VR training augments diagnostic competencies.

Artificial intelligence, especially via convolutional neural networks, has enhanced image analysis and diagnostic precision in oral radiology, resulting in accurate treatment planning. Oral surgery utilizes augmented reality, virtual reality, and mixed reality in resident training, surgical operations, and patient education, facilitating enhanced accuracy in surgical planning and assuring patients understand anticipated results. In oral pathology, AI-driven image analysis delivers reliable diagnostic findings, whilst VR and AR simulators facilitate the instruction of laboratory methods and elucidate histological characteristics. Nonetheless, these technologies possess limits, such as the need for further validation, the resolution of ergonomic issues, and elevated prices. The use of AI, VR, AR, MR, and XR into dentistry signifies a pivotal advancement, enabling healthcare practitioners to provide enhanced treatment and achieve cost efficiencies. Current research must concentrate on using these instruments in oral medicine, radiography, surgery, and pathology to fully realize their promise in oral health care, ensuring a more advanced, technology-driven future for dentistry.

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التطورات في تقنيات التصوير ثلاثي الأبعاد في الأشعة السنية والوجهية الفكية

الملخص

الخلفية :أحدث التطور السريع لتقنيات التصوير ثلاثي الأبعاد تأثيرًا كبيرًا في مجال الأشعة السنية والوجهية الفكية، حيث ساهم في تحسين دقة التشخيص والتخطيط العلاجي. تستعرض هذه المراجعة دمج تقنيات مثل الذكاء الاصطناعي (AI) والواقع الافتراضي (VR) والواقع المعزز (AR) في ممارسات طب الأسنان.

الطرق :تم إجراء مراجعة شاملة للأدبيات، مع التركيز على التطورات الحديثة في تطبيقات التصوير ثلاثي الأبعاد في الأشعة السنية والوجهية الفكية. تم تحليل المقالات المُحكمة والدراسات السريرية لتقييم فعالية وأهمية هذه التقنيات من الناحية السريرية.

النتائج :تشير النتائج إلى أن تقنيات التصوير ثلاثي الأبعاد، وخاصة تلك التي تعززها تقنيات الذكاء الاصطناعي، قد حسّنت بشكل كبير دقة التشخيص للكشف عن التشوهات السنية والكسور والأمراض. على سبيل المثال، أظهرت خوارزميات الذكاء الاصطناعي دقة عالية في تحليل الصور الشعاعية

السنية وفحوصات التصوير المقطعي بالحزم المخروطية .(CBCT) بالإضافة إلى ذلك، تم استخدام تقنيات الواقع الافتراضي (VR) والواقع المعزز (AR)بنجاح في تثقيف المرضى، وتدريب الجراحين، ومحاكاة العلاجات، مما أثبت فعاليته في تقليل قلق المرضى وتحسين النتائج السريرية.

الاستنتاج :يمثل دمج تقنيات التصوير ثلاثي الأبعاد المتقدمة في الأشعة السنية والوجهية الفكية تحولاً نوعياً في الممارسات السريرية. تسهم هذه الابتكارات في تحسين تقديم الرعاية الصحية من خلال تعزيز قدرات التشخيص، وتسهيل التخطيط العلاجي الفعال، وتحسين تجربة التعليم للممارسين والمرضى. ينبغي أن تركز الأبحاث المستقبلية على معالجة تحديات تكامل البيانات، وشفافية الخوارزميات، والتكلفة لتحقيق أقصى استفادة من هذه التقنيات في رعاية الأسنان.

الكلمات المفتاحية :التصوير ثلاثي الأبعاد، الأشعة السنية، الذكاء الاصطناعي، الواقع الافتراضي، الواقع المعزز.