

AR and MR in Dentistry: Developments, Applications, and Prospects

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Abstract—Augmented Reality (AR) and Mixed Reality (MR) are cutting-edge technologies that are substantially impacting digital dentistry. These innovations not only propel dentistry into the digital age, but also introduce novel, non-invasive, and immersive treatment methodologies. This review collates and summarizes the latest developments and applications of AR and MR in digital dentistry. In contemporary practice, digital information, such as CT scans, is predominantly used for presurgical verification. However, integrating patients digital 3D information into real-world environments through AR and MR allows dental professionals to visualize diagnostic and therapeutic data using a Head-Mounted Display (HMD). This integration enhances not only efficiency and safety, but also elevates surgical training. Despite these benefits, further enhancements are required for these technologies to achieve broader acceptance in clinical dentistry. In this review, we have dedicated a separate section discussing the prospective applications and future directions of AR and MR, including optimizing HMD technology, developing intraoperative feedback navigation technology, advancing human-machine interaction (HMI) technology, and improving soft-tissue visualization technology. The literature suggests that AR and MR applications are particularly advantageous in dentistry, despite some limitations. With ongoing developments in areas such as haptics and robotics, it is expected that AR and MR will become increasingly integral to dental practices in the near future.

Index Terms—Augmented reality, mixed reality, digital dentistry.

LIST OF ABBREVIATIONS

Virtual Reality	VR
Augmented Reality	AR
Mixed Reality	MR
Extended Reality	XR
Head-Mounted Display	HMD
Human Machine Interaction	HMI
Computed Tomography	CT
Cone-beam Computed Tomography	CBCT
Magnetic Resonance Imaging	MRI
Artificial Intelligence	AI
Video-see Through	VST
Optical-see Through	OST
Minimal Invasive Surgery	MIS
Infrared	IR
Degree of Freedom	DOF
Simultaneous Localization and Mapping	SLAM
Time of Flight	TOF
Computer-assisted Implant Surgery	CAIS
Iterative Closest Point	ICP
Video Graphic Array	VGA
Electromagnetic	EM
Skin-attached Dynamic Reference Tool	SRT

I. INTRODUCTION

MODERN dentistry uses digital technologies to incorporate computer-generated components to perform dental procedures more efficiently [1], [2]. In recent years, visualizations of three-dimensional (3D) technologies have become increasingly popular, including virtual reality (VR), augmented reality (AR), and mixed reality (MR). With the increasing power of computational resources, it is now possible to fuse 3D models in real time and run simulations of complex dental structures. Extended reality (XR) has entered into a different domain, from entertainment to education, due to its accessibility and affordability. In addition to providing an immersive experience, XR technologies enable 3D visualization of content that would otherwise be limited to two-dimensional (2D) displays.

The terms AR and MR, according to the popular definition of the “virtuality continuum” by Milgram and Kishino [3], through which they established a “reality-virtuality continuum” between the real and virtual worlds. VR is an artificial computer-generated simulation of a real environment. It immerses the user in a digital environment, typically by wearing an HMD or by using a handheld controller to interact

Received 13 August 2024; revised 8 October 2024; accepted 29 October 2024. Date of publication 21 November 2024; date of current version 27 February 2025. This article was recommended for publication by Associate Editor T. Haidegger and Editor P. Dario upon evaluation of the reviewers' comments. This work was supported in part by the National Natural Science Foundation of China under Grant U2013205 and Grant 62073309; in part by the Chinese Academy of Sciences Youth Innovation Promotion Association Excellent Member Program under Grant Y201968; in part by the Guangdong Basic and Applied Basic Research Foundation under Grant 2022B1515020042 and Grant 2020A1515010651; and in part by the Shenzhen Science and Technology Program under Grant JCYJ20210324115606018. (Corresponding authors: Zeyang Xia; Jing Xiong.)

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Digital Object Identifier 10.1109/TMRB.2024.3503999

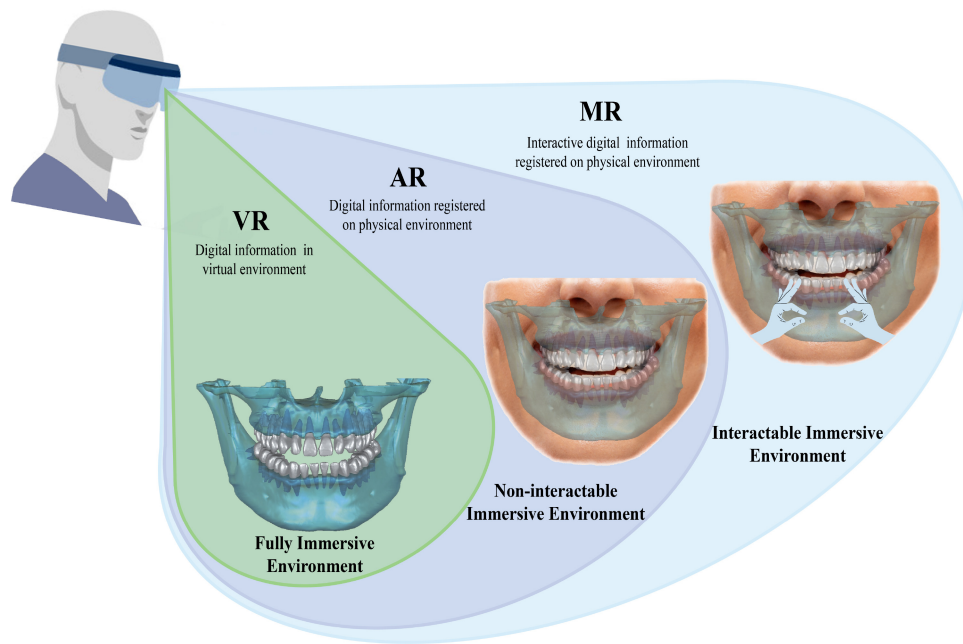


Fig. 1. Illustration of distinctive features and applications of three immersive technologies: Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR) in clinical settings. VR exclusively displays 3D objects within a fully virtual environment, completely immersing the dentist in a digital world for training and simulation purposes. AR blends 3D models onto real-world objects, enhancing the dentist's perception of the actual clinical environment by overlaying digital information onto the patient's anatomy. MR facilitates interaction between virtual and real-world objects, creating a hybrid environment where dentists can engage with both digital and physical elements simultaneously.

with the virtual environment. VR can create impossible or challenging experiences in the real world, such as exploring remote locations or interacting with virtual objects. AR technology superimposes digital content on a user's real-world view. It enhances the real environment by adding virtual objects, information, or graphics to the user's field of vision, typically through a camera-enabled device, such as a smartphone or tablet. MR is a type of immersive technology that blends the elements of both VR and AR. It combines virtual and physical environments, thereby allowing users to interact simultaneously with digital and real-world objects. MR is achieved through a combination of sensors, cameras, and displays, which enables the user to see and manipulate digital objects in real scenarios [4]. Unlike AR, which overlays digital content onto the real world, MR creates a more seamless integration between the digital and physical world, as shown in Fig. 1.

Since 2010, the development and proliferation of VR, AR, and MR devices have significantly enhanced their capability of displaying immersive and interactive digital scenes within 3D environments. This technological evolution has led to their broad acceptance in various fields, including education, commerce, and biomedicine. VR technology, with origins dating back to the 19th century, gained notable popularity in the 1990s [5] due to advancements in computer graphics and interface technologies. The rapid progress in headset design and computer hardware, especially digital effects, has led to substantial investments in the entertainment industry. Despite these advancements, the widespread adoption of VR was hindered in the 2000s due to technical limitations, such as bulky headsets, slow processing speeds, inadequate sensory input quality, and low-resolution graphics. Conversely, AR technology has shown exceptional promise in the medical

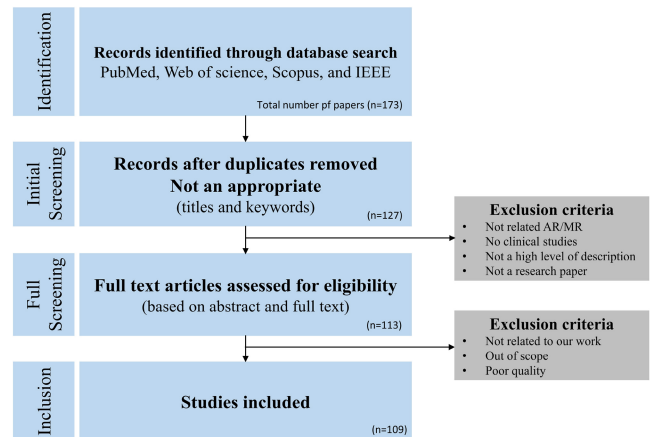


Fig. 2. PRISMA flow chart showing inclusion and exclusion criteria used for the search [10].

field, with the introduction of the first AR system in 1986 [6], followed by considerable advancements that have enhanced its application and effectiveness in medical practice [7], [8], [9].

AR and MR technologies have distinct applications that integrate computer-generated content with real objects. AR overlays digital images, audio, and video onto real-world settings, thereby enabling the superimposition of virtual content onto real objects. This integration allows for the enhanced interaction and visualization of real environment with augmented elements. MR, a more advanced technology, merges AR and VR capabilities, enabling users to interact simultaneously with both virtual and real objects in real-time. These virtual and real elements can interact with and modify each other, providing a dynamic and immersive experience. This environment awareness facilitates seamless integration, enhancing the user's interaction with both the

TABLE I
COMPARISON OF AR AND MR DEVICES UTILIZED IN DIGITAL DENTISTRY: TECHNICAL SPECIFICATIONS AND CLINICAL USE

Device	Type	Display Type	Resolution (Per-eye)	Field of View (Diagonal)	Applications in Dentistry
Microsoft HoloLens 2	MR HMD	Holographic	2048 x 1536	52°	Surgical planning, student training, patient education
Magic Leap 2	MR HMD	Holographic	1440 x 1760	70°	3D visualization of dental scans, treatment planning
Vuzix M400	AR smart glass	Monochrome DLP	854 x 480	16°	Remote assistance, hands-free documentation
Google Glass Enterprise Edition 2	AR smart glass	Optical prism	640 x 360	83°	Real-time guidance, remote consultation
Epson Moverio BT-40S	AR smart glass	Waveguides	1920 x 1080	34°	Overlay of digital information during procedures
X-Nav X-Guide	AR navigation system	Stereoscopic	—	—	Precise implant placement, real-time surgical guidance

virtual and real components. In contrast, VR immerses users in a completely artificial environment, isolating them from the external real world. AR has attracted significant interest in various fields including industry, maintenance, entertainment, education, medicine, and architecture. In particular, surgeons aim to improve patient outcomes and have tested AR in different types of surgeries, such as neurosurgery, spine surgery, orthopedic surgery, and dental surgery. Additionally, AR has been used to help with cognitive impairment, psychological disorders, motor rehabilitation, and surgical procedures, and anatomical studies through telementoring. These applications demonstrate the wide-ranging impact and potential of AR technology for improving medical practices and other fields.

Dentistry has unique characteristics and shares several features with other medical subspecialties. It is imperative to recognize that traditional dentistry often encounters limitations in its direct visualization techniques [11], particularly when addressing complex anatomical structures. These structures may include intricate root canal systems, difficulty in finding precise tooth positions, or intricate bone formation, which pose significant challenges to conventional dental examinations and treatment procedures. Consequently, AR technology is a promising solution for enhancing dentist's ability to navigate and manipulate these intricate dental structures with greater accuracy and efficiency. Although most surgeons have precise knowledge, a better understanding of these internal structures greatly facilitates the surgical procedure. Many attempts have been made to overcome these issues using AR technology, resulting in the development of various instruments and technologies that enable direct manipulation and visualization during surgery, such as conventional navigation systems that use a 2D display [12]. Therefore, AR and magnetic resonance imaging have the potential to revolutionize the field of digital dentistry by enabling clinicians to visualize and interact with complex dental structures in a more intuitive and immersive way.

AR and MR are versatile technologies with infinite possibilities; however, it is also important to recognize their limitations in dentistry. In this paper, we provide a perspective review of the current and potential applications of AR and MR based immersive surgical procedures in different fields of

dentistry. We will also discuss the different procedures and treatments used in dental surgery. Furthermore, the study discusses current AR-based dental treatments and possible future recommendations that can be made to enhance the use of AR and MR in dentistry. Our research strategy was to identify articles whose abstracts or titles included the terms "Virtual Reality", "Augmented Reality", "Mixed Reality", "Digital Dentistry", "Artificial Intelligence", and "Dental Robotics". For our literature review, we searched PubMed, Scopus, and Web of Science for publications published between 2010 and 2024. We followed the protocols established by the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) [10]. To identify the trends of AR and MR in dentistry, we defined the following criteria that must be met for an article to be considered as part of the database used in this review: 1) the paper discusses the clinical impact of AR/MR in digital dentistry and 2) the use of head-mounted display in a clinical setting. Fig. 2 presents the flow diagram of the articles included in the analysis, which follows the PRISMA guidelines. In the process of identification, we gathered 173 articles. Afterward, we removed duplicates that were present across each database. In the screening process, we filtered the 127 articles to follow inclusion criteria and were left with a total of 113 articles. In the eligibility process, the articles were read carefully, and the authors confirmed whether they satisfied the inclusion criteria of AR/MR in dentistry. Finally, 109 articles were selected. What is excluded are works that describe purely VR-based applications.

II. IMMERSIVE TECHNOLOGY

HMDs provide an interface for displaying AR and MR content, which is highly suitable for medical visualization, training, and various other applications. The first immersive visualization system utilized an HMD invented in 1968 [13]. Since then, continuous advancements have been made in the quality, ergonomic design, resolution, and cost-effectiveness of AR and MR devices. Early displays, such as Sony Glasstron (1996), required a connection to a computer for AR display. However, recent developments have led to the creation of complete systems incorporating multiple sensors, allowing for standalone operation or wireless data transmission,

thereby eliminating the need for cable attachment. A notable example of such a system is Microsoft HoloLens, first introduced in 2016 and updated in 2020 with HoloLens 2. Furthermore, HoloLens integrates a standalone computer with a display to provide a comprehensive MR solution that delivers holographic images that are accurately registered in a real environment. It allows spatial mapping to precisely align holographic images with physical surroundings, and supports gesture and speech recognition, 3D sound, and other advanced capabilities. Currently, several AR and MR displays are commercially available, such as HoloLens, Magic Leap, and Vuzix, Google Glass, Epson Moverio, and X-Nav X-Guide. These displays have enhanced functionalities including a wide viewing range, object tracking, and automatic calibration. Table I presents comprehensive overview of leading AR and MR devices employed in dental practices. It compares key technical specifications such as display type, resolution, and field of view, alongside specific applications in dentistry case.

These modern HMDs integrate advanced features, such as high-resolution displays, wide field-of-view optics, and precise head-tracking capabilities, which are essential for creating a seamless and immersive user experience. Spatial mapping and environmental recognition technologies further enhance their utility in dentistry, enabling real-time interactions with 3D anatomical models and patient data. In dental education, HMDs equipped with AR and MR technologies allow interactive simulations of complex procedures, providing a risk-free environment in which users can hone their skills. In clinical settings, HMDs offer dentists augmented views of patient anatomy during operations, improving precision and outcomes by overlaying critical information directly onto the surgical field. Additionally, the integration of artificial intelligence (AI) with HMDs enhances functionality by providing predictive analytics, automating routine tasks, and personalizing user experience based on real-time data and interactions. This convergence of technologies has significantly advanced the capabilities of HMDs, making them indispensable tools in modern dentistry.

Roberts et al. [6] introduced the first medical AR system in the 1980s, which consisted of an operating microscope augmented with segmented CT images. In the early days of medical AR, HMDs were a popular choice [7], [14] for video see-through (VST)-based applications. HMDs were an obvious choice for medical use because they align the wearer's head gaze with the content viewpoint and keep the hands free. However, early HMD designs cannot easily fulfill the high demands of medical AR systems in terms of performance, latency, and accuracy, which require powerful computational resources. As a result, these systems were often bulky with wired connections between HMDs and computers, making them challenging to implement in real-time clinical scenarios. Although optical-see-through (OST) displays remained relevant, there was a shift towards world-localized displays such as stationary monitors or projector systems [15] between 2011 and 2017. With the release of HoloLens 1, the first self-contained AR-HMD with a slim form factor, research attention has again turned to OST displays [16].

A. Display Hardware

In principle, the hardware technology used for immersive AR and MR experiences is a combination of various components that work together to deliver real-time interaction and visual immersion. These devices typically consist of displays, sensors, and input methods that allow users to experience digital content in a fully immersive environment. There are three main types of visual displays can be identified based on their underlying concepts:

1) *Video-See Through (VST) Display*: VST displays use a camera to capture the surrounding environment and digitally merge it with virtual information to create a composite image. VST displays offer a seamless integration of virtual and real images, enabling the depiction of fully opaque virtual objects with accurate colors. Additionally, VST displays can minimize the lag between reality and virtuality by slightly delaying real-time viewing [17]. However, the resolution and image quality of VST displays are limited by the capturing optics.

2) *Optical-See Through (OST) Display*: OST displays capture the real world without a camera. Instead, they use an optical combiner to superimpose virtual imagery directly onto the user's view of reality [18]. OST displays offer several advantages over VST displays, such as providing unobstructed vision to the user, eliminating distortions caused by camera optics, and allowing high-resolution visualization of real information [19], [20]. To ensure that the virtual content aligns accurately with reality, it is necessary to determine the user's eye position in relation to the display, which requires camera calibration [21]. A limitation of OST displays is that the virtual image appears as an overlay on the real image, making it challenging to identify structures within real objects, unlike VST displays, which enable the manipulation of reality.

3) *Spatial Display*: Spatial displays use projectors to cast images directly onto real objects captured by a camera. Modern projectors offer high resolution, refresh rates, and stereo projection support, but their image quality may not match that of the VST and OST displays. This can be problematic when projecting onto uneven surfaces or in environments with bright natural light [22], [23].

Schmalstieg and Hollerer [24] classified AR displays based on the distance between the eyes and display. HMDs are considered headspace devices because the display is located directly in front of the user's eyes, thereby facilitating the natural integration of real and virtual objects from the user's perspective and actions [25]. Various types of HMDs, including VST, OST, and projector-based HMDs, have been developed for different AR applications. In contrast, handheld displays, such as smartphones and tablets, fall into the body-space category, in which the display is positioned further from the eyes. As the distance increases, estimating the relationship between the eye and display becomes more challenging, making VST or spatial systems more prevalent in this category. VST handheld displays utilize cameras to capture the environment and merge it with virtual information, offering seamless integration, but are limited by the camera's resolution and image quality. Spatial systems use projectors to cast images

onto real objects, which can be problematic on uneven surfaces and in bright environments, but they support high-resolution and stereo projection. The classification into headspace and body-space categories underscores the varying challenges and advantages of each type, with HMDs providing immersive integration, and handheld displays offering flexibility and ease of use, albeit with more complex calibration requirements. Understanding these distinctions is essential to developing effective AR applications tailored to specific user needs and environments.

B. Registration and Tracking

In digital dentistry, proper selection of registration and tracking methods is crucial, particularly for image-guided interventions that demand high precision and cannot tolerate delays or tracking errors. Accurate image-to-patient registration is essential for effective in situ visualization because it maximizes the potential benefits of the AR technology. The tracking method must also be straightforward to avoid introducing unnecessary technical challenges to the complex workflows. Registration is necessary for combining real and virtual content, aligning real and virtual coordinate systems, and linking computer-generated content to a real scene. The development of medical image processing technology underscores the importance of these factors in the field of image-guided surgery (IGS) [26], and AR technology has been progressively employed as a novel navigation method for minimally invasive surgeries (MIS) [2]. AR navigation assists clinicians in precisely capturing the image data of the surgical site without introducing obstructions. Registration typically involves aligning preoperative patient data (e.g., CBCT, MRI) with real-time treatment in a clinical setting. To maintain the registration and synchronization of the viewpoint from the perspective of the user, it is necessary to continuously track the position and orientation of the AR or MR viewing camera relative to the surgical environment. This continuous tracking ensures that the virtual overlays remain accurately aligned with the patient's anatomy, thereby enhancing the precision and effectiveness of surgical intervention.

There are two main approaches for registration and tracking in AR systems: outside-in and inside-out. Outside-in tracking utilizes external sensors, such as cameras, positioned around the user to monitor the movement of the device. Although this method can be highly precise, it requires additional components and operates only within a limited space. Conversely, inside-out tracking places sensors within the AR headset, enabling the device to self-locate in any environment. Various sensors can be employed for tracking, but vision-based techniques that utilize visible light, infrared cameras, or depth sensors are particularly popular [27]. Vision-based tracking relies on visible features for the cameras to detect, which can be categorized into artificial features for marker-based tracking and natural features for markerless tracking. Marker-based tracking uses predefined markers in the environment to facilitate accurate positioning, whereas markerless tracking identifies and tracks natural features in the environment, offering greater flexibility and ease of use. The choice between these tracking methods depends on the specific requirements of

the application, including the need for precision, complexity of the environment, and availability of features to track. Effective tracking is critical for maintaining the alignment of virtual and real-world coordinates and ensuring accurate and seamless integration of AR content in digital dentistry.

1) *Marker-Based Tracking*: Optical marker-based registration is employed in various dental applications including tooth movement analysis, orthodontic treatment planning, and dental implantology. This method involves attaching optical markers to a patient's teeth or jaw and capturing images of these markers and adjacent structures using imaging technologies, such as CBCT. The use of standard RGB visible-light cameras to monitor known image patterns (fiducials) is a quick and cost-effective approach. However, this method is susceptible to inconsistent and uncontrolled lighting conditions. A more stable alternative involves using infrared (IR) cameras to track retroreflective spheres [28]. Using the markers as reference points, images can be accurately registered, allowing dentists to align the images and plan treatments with precision. This technology provides a more precise and reliable method for analyzing dental anatomy than conventional techniques. Commercial tracking and motion capture solutions, such as OptiTrack (Natural Point, Inc., Corvallis, Oregon, USA) and Vicon (Vicon Motion Systems Ltd, UK), utilize this technology in an outside-in manner. Marker-based methods offer the advantage of providing single tracking and registration solutions. To achieve precise marker-based registration, markers and real objects are rigidly calibrated together, enabling accurate 6-DOF (Degrees of Freedom) pose estimation of the real object attached to the markers. Additionally, stationary markers can be used to facilitate inside-out tracking.

Despite these advantages, marker-based systems have notable drawbacks. They require a highly optimized environment, in which markers and their real-world counterparts must be meticulously calibrated. Line-of-sight constraints must be observed and lighting conditions must be customized to ensure the accuracy of the tracking system. These requirements can limit the flexibility and applicability of marker-based systems in more dynamic or less-controlled settings.

2) *Markerless Tracking*: Markerless registration is a method in which a tracking device detects naturally visible features in an environment. For instance, Simultaneous Localization and Mapping (SLAM) [29] algorithms simultaneously construct a map of the surroundings and determine the device position within the map by using data from various sensors on the device. Additionally, markerless tracking techniques employ models or templates in which a 3D model of portions of the environment is compared to camera images to estimate the 6-DOF pose via 3D to 2D matching [24], [27]. Some AR systems directly incorporate 3D surface information of the scene by capturing it using stereo cameras, structured light, or time-of-flight (TOF) depth sensors. These captured surfaces can be directly registered with a 3D model of the target, although this requires dynamic calibration of additional sensors with the rest of the system components, leading to more complex setups.

Registration can be performed either manually or semi-manually. For instance, the position of a real object to be labeled with augmented content can be digitized by registering

known surface points with a tracked instrument, allowing point-based registration methods to align the virtual object with the real model. Alternatively, the position of a virtual object can be manually adjusted using controls provided by an AR application, such as touch buttons and gestures. However, the lack of dynamic registration is a disadvantage of manual registration: if the real object moves, consistency is lost, necessitating a repeat of the procedure. Consequently, manual registration techniques are frequently used in conjunction with marker-based systems, where user input is required only for initial calibration and fiducial markers are then used to achieve real-time tracking. Despite these complexities, markerless registration and tracking methods offer significant advantages in terms of flexibility and ease of use, as they do not rely on predefined markers. This makes them suitable for dynamic and less controlled environments. Understanding these techniques and their applications is essential for developing effective AR systems in digital dentistry, where precise tracking and registration are crucial for accurate image-guided interventions.

In dentistry, markerless registration refers to the alignment of 3D data, such as CBCT or intraoral scans [30], without depending on physical or artificial fiducial markers. This technique is used in dental procedures to align multiple scans taken at separate instances to track changes in a patient's oral structures or to align digital models with the actual patient during treatment planning and simulation. Markerless registration enhances dental diagnosis and treatment accuracy and efficiency while eliminating the requirement for physical markers that may cause discomfort to patients. The expansion of markerless registration research and development in dentistry aims to make digital dentistry more accessible and user friendly.

C. Visual Coherence

Visual coherence plays a crucial role in immersive visualization technologies in AR and MR, particularly in dentistry, where precision and seamless integration of digital content are vital [31]. Visual coherence ensures that virtual objects, such as dental models or surgical guides, blend naturally into the real-world environment. This smooth blending is essential for maintaining clarity and ensuring that virtual objects are contextually relevant and valuable during dental procedures. Moreover, maintaining visual coherence is crucial for reducing clinicians' cognitive load. By ensuring that virtual objects blend naturally into the real-world environment, clinicians can focus on the treatment without distraction, improving dental treatment outcomes. As AR and MR technologies continue to evolve, innovations in visual coherence will likely further refine, making these tools indispensable in modern dentistry.

A simple opaque virtual object overlay can occlude critical information from the real-world scenario, and even using semi-transparent overlays can misrepresent real-world data. Additionally, basic image fusion techniques, like overlays, often need more depth perception, which is particularly challenging for CBCT visualizations. In such cases, users must perceive the augmented content as being embedded within real objects, and the absence of clear depth cues can undermine

this integration, making it difficult to interpret the augmented information accurately. To achieve this, it relies on several key technologies that work together to enhance user experience and the effectiveness of AR and MR in practical dental applications.

1) *3D Rendering*: The dynamic navigation systems allow real-time monitoring of the drill position and movements during dental implantology [32]. This enables clinicians to visualize the patient 3D data obtained from CBCT scans. These dynamic virtual objects must accurately mimic the physical properties of real surgical environments, such as texture, lighting, and movement. The 3D rendering during the dynamic navigation reduces the gap between virtual planning and physical scenarios by transforming the complex 3D models derived from CBCT scans into detailed, interactive visualizations that clinicians can use in real-time. These visualizations must be highly accurate to reflect the intricate anatomical structures of the patient, such as bone density, nerve pathways, and soft tissues. This creates high-resolution, real-time patient dental anatomy visualization and continuously updates to reflect the precise movements during the dental procedure, ensuring the 3D model aligns with real-time patient [33]. Moreover, the rendered models accurately simulate physical properties like texture, lighting, and motion, creating a visually coherent surgical environment. Also, the system allows for interactive manipulation, enabling clinicians to zoom, rotate, and adjust the view for better surgical planning and decision-making.

2) *Occlusion Handling*: Occlusion is a vital depth cue in immersive technology [34]. This allows AR and MR technologies to depict virtual content in a way that aligns with a real-time clinical environment, improving the overall immersion experience. In dental procedures, a virtual 3D model of a tooth should be hidden or partially covered by a physical dental tool when it passes in front of it [35]. For instance, phantom rendering, initially proposed by Breen et al. [36], and related methodologies involve registering an invisible 3D model of a real-world occluder onto the virtual object, effectively preventing the rendering of virtual elements where physical objects block them. This concept can be extended by texturing the phantom object using data captured from the camera, allowing for the seamless integration of real and virtual information in overlapped areas, thereby improving the perception of spatial relationships. Typical approaches used for this purpose include cutaways, Focus-and-Context (F+C) visualization, and ghosting. Cutaways are achieved by creating an opening in the phantom object, which exposes the virtual object. In Focus-and-Context visualization, virtual objects are selectively occluded by prominent real-world features, such as edges, providing contextual cues from the physical environment [37]. Devices like HoloLens and Magic Leap achieve this through advanced depth sensing, such as TOF cameras, which accurately map the spatial relationships between real and virtual objects.

While occlusion provides valuable insight into the relative positioning of objects within a scene, it does not provide distance information between objects. The motion parallax and stereo disparity offer more precise data regarding relative

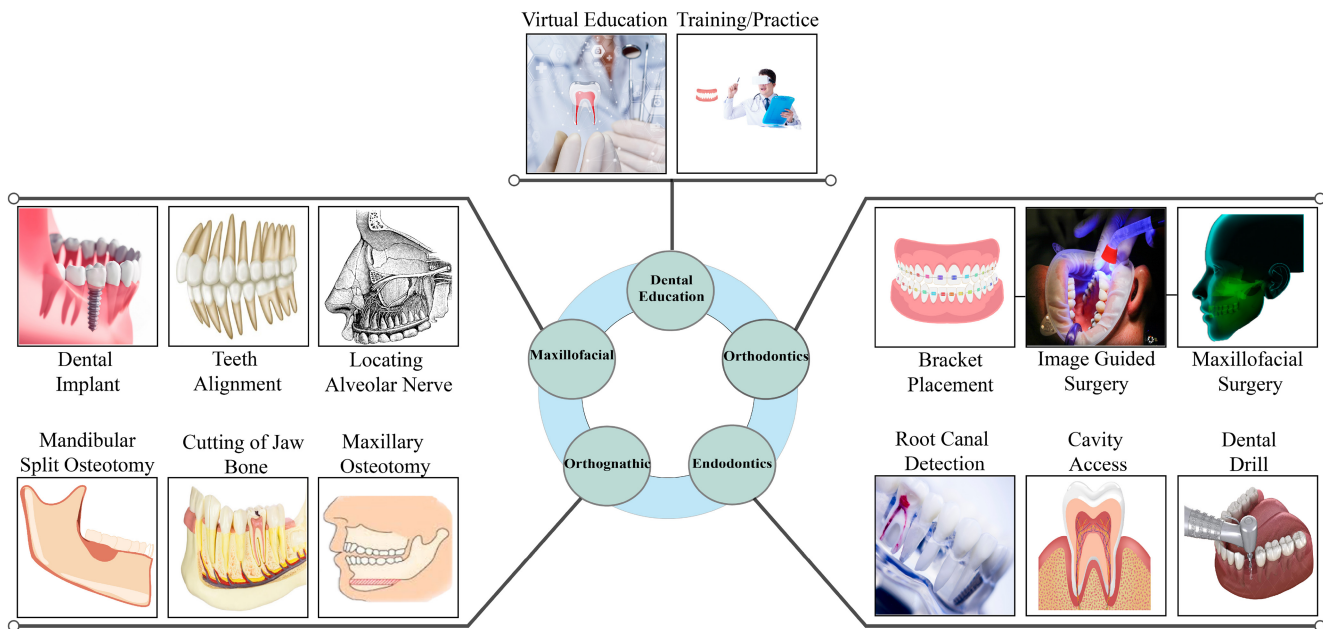


Fig. 3. AR and MR applications in different fields of dentistry.

and absolute distances. With stereoscopic HMDs, these cues can be naturally and effectively implemented. Illumination and shadowing are also critical elements in achieving visual coherence. In addition to enhancing depth perception, these cues are essential for accurately interpreting the shape of objects. By simulating real-world lighting conditions, for example, using light probes, virtual objects can be illuminated appropriately, and virtual shadows can be accurately cast onto real-world objects.

III. APPLICATIONS OF AR AND MR IN DIFFERENT FIELDS OF DENTISTRY

AR and MR applications focus on various dental treatments such as orthodontics, maxillofacial surgery, orthognathic surgery, dental implantology, bracket positioning, and cavity preparation [38], the Fig. 3 shows the use of AR and MR in different fields of dentistry. Additionally, certain tooth structures can be rendered translucent, allowing clinicians to look through them and navigate the root canal. Furthermore, AR and MR have the potential to become innovative educational tools that allow students to learn independently. Table II provides an overview of various dental fields that utilize the AR/MR technology.

A. Orthodontics

In orthodontics, AR and MR work by overlaying digital 3D models of dental structures onto the real-time view of a patient's mouth, allowing orthodontists to visualize and analyze tooth alignment and jaw structures. The application of AR and MR enable the simulation of tooth movements and planning of precise interventions, enhancing the accuracy of diagnosis and treatment plans, and ultimately improving patient outcomes and treatment efficiency. AR navigation systems can reduce surgical risk by providing real-time

intraoperative information directly on the surgical field, which shows interest in implementing AR in dentistry [39]. Therefore, dentists can apply AR in orthodontics for their patient check-ups, using AR graphics such as circle highlights and moving arrows to illustrate the mechanisms that work in functional appliances to add space between teeth, alter the angle of teeth, and move teeth closer to one another. Also, a smartphone-based AR application overlays digital orthodontic bracket plans onto patients teeth, eliminating the need for 3D imaging or physical guides [40]. The applications of XR in orthodontic education and clinical practice, improving training effectiveness, treatment planning, and patient experience. However, challenges still need to be addressed in widespread adoption due to high costs, technical limitations, and the need for further clinical validation through more extensive studies [41].

Thomas Fortin et al. [42] introduced the first system for dental implantology positioning that showed that a graphically superimposed suggested position on the patient can be a new technology to utilize CT to create a resin splint. Yamaguchi et al. [43] developed a surgical navigation system for surgeons to maintain a vision of the operative field without looking away during dental procedures that employ retinal imaging display in order to reduce re-projection errors by utilizing markers attached to the patient oral cavity. A surgical AR environment can perform the function of an automatic information filter, displaying only the most relevant information to surgeons, and allowing them to focus exclusively on implant placement, effectively minimizing time and additional costs [44]. Li et al. [45] utilized the OST-HMD-based orthodontic bracket placement for treatment guidance to simplify the AR-based treatment and avoid additional sensors and scanners. In bracket navigation systems, it is important to ensure both the accuracy and localization of AR systems. AR-assisted bracket navigation system enhanced

TABLE II
AR/MR DEVICES AND APPLICATIONS IN DIFFERENT FIELDS OF DENTISTRY

Dental fields	Scenarios	Devices	Findings	References
Orthodontics	Bracket placement in vivo	AR	Placement of brackets between direct bonding and AR-assisted navigation	[46]
	AR Navigation System	AR	Marker-based calibration reduces re-projection error	[43]
Endodontics	Detection of root canal orifices	AR	CAD is highly efficient for detection of root canal	[51]
	Automatic root canal detection	AR	Real-time detection and storage of canal locations	[52]
	Endodontic therapy	MR	Audiovisual warnings to dentists to accurately adjusting tools during cavity access	[53]
Dental Implantology	Dental implantology surgery	MR	Distances measurement between anatomical structures and the dental drill	[69]
	AR guided	AR	Reduces the operation time by eliminating the hand-eye coordination problem.	[63]
	3D AR guided	AR	3D AR navigation system is more accurate, applicable, and efficient than a 2D	[62]
	Stereo image	AR	Real-time optical tracking prevents nerve damage in dental implantology surgery	[65]
	Image-guided	AR	Image-guided surgery enhances the accuracy using static and dynamic navigation systems	[67]
Maxillofacial Surgery	Bone repositioning	MR	Waferless maxillary repositioning enhances accuracy in LeFort-I orthognathic surgery	[72]
	3D dental casts	MR	3D navigation provides direct, and improved visualization of patient regions of interest	[73]
	Surgical navigation	MR	Markerless registration is non-invasive, auto-updating, and simple to use in clinic	[74]
	Registration	MR	Practical maxillofacial surgery that overcomes the patient movement problems	[75]
	AR system	AR	Enhanced visualization improves overlay accuracy and reduces image registration time	[76]
	Spatial consistency	AR	Removing occlusions and artifacts enhances video accuracy and reduces processing time	[77]
Orthognathic Surgery	Video monitoring system	AR	ARToolKit prevents maxillary translocation in mandibular angle oblique split osteotomy	[78]
	Waferless maxillary positioning	AR	Precise technique to use arbitrary splints and 2D orthognathic surgical planning	[79]
	Mixed-reality simulation	MR	ManMoS orthognathic surgery effectively treats skeletal and dental asymmetrie	[80]
	Mandibular angle hypertrophy	AR	AR is effective, reliable, and user-friendly in orthognathic surgery	[81]
	Drilling or cutting of jaw bone	AR	Tracking and detection can be improve by removing noise from the video frame	[82]
	3D surgical instruments tracking	MR	Precise navigation of deep anatomical can improve surgical instrument positioning	[83]
	AR navigation	AR	EM tracking and skin-attached dynamic reference is highly accurate and reliable	[84]

the accuracy of the expert orthodontist in the incisogingival direction and the novice's ability to guide the bracket position within an acceptable clinical error. Lo et al. [46] proposed a prototype of an AR-based system to enhance the accuracy of orthodontic bracket placement. This study tested an AR system on 31 incisor teeth for orthodontic bracket placement, revealing improved vertical accuracy, especially for novices.

However, the horizontal placement accuracy remained consistent regardless of the method or orthodontist's experience. Suenaga et al. [47] combine AR and stereo vision technologies to project real-time intravenous (IV) images from preoperative CBCT data onto the surgical site without using markers. The proposed image-guided AR technique aims to superimpose region-specific 3D jawbone representations on the real operating area. This method facilitates surgical treatment of

structures that are not directly visible in spatial positions. Another study reported two cases demonstrating the successful application of CT-based computer-assisted design and an intra-operative, markerless AR-guided see-through video system for removing impacted supernumerary teeth. By combining these cutting-edge technologies, surgeons can improve the precision and safety of their procedures, reduce the risk of complications, and improve patient outcomes. AR pinpoints the tooth location and guides during surgery, which offers a promising advancement in dental surgery techniques, allowing for more accurate and efficient removal of impacted teeth [48]. Tran et al. [49] introduce an AR system for oral and maxillo-facial surgery that directly projects 3D virtual images of bone and soft tissue structures onto the patient. This provides depth information for high-risk areas and offers a wide viewing area with a motion parallax. The intuitive, real-time 3D interface is content-rich and hardware-accelerated, helping surgeons avoid high-risk areas, including hole drilling and screw fixation, and demonstrating a positional accuracy of less than 1 mm. The feasibility of the system was confirmed by a human volunteer test. Aichert et al. [50] presents an image-based tracking method for monitoring tooth movement in video images relative to a CT scan of the jaw. This method is based on a novel lightweight AR system for orthodontics, particularly for guided bracket placement. Despite challenging lighting conditions, the tracking algorithm effectively balances robustness, accuracy, and performance, allowing for successful tracking in real treatment procedures.

B. Endodontics

In Endodontics, AR and MR technologies are used to treat teeth with infected root canal systems. Preparing an adequate access cavity is critical for successful treatment, as it allows proper cleaning and shaping of the root canal system. However, complications, such as perforation, gouging, ledge formation, and canal transportation, can arise from improperly designed access cavities. AR systems offer significant improvements in addressing these issues by providing enhanced visualization and guidance and ensuring more accurate and effective treatment outcomes.

Brüllmann et al. [51] proposed a computer-aided recognition system for root canal orifices using a video camera during endodontic treatment. Canal orifices can be visualized on a video screen while considering patient treatment and detecting root canal orifices with a sensitivity of 90.1%. These findings suggest that the use of video cameras for the computer-aided detection of root canal orifices is feasible. Bruellmann et al. [52] presented a feasibility study on AR-based root canal detection from video, which automatically classifies and localizes the root canal orifices and stores the location and size of the structure. The developed algorithm detects teeth in video images and then segments the root canal orifices based on Euclidean distance measurements. The algorithm was tested on 126 human teeth and revealed that the software correctly identified 94% of 305 root canals, with varying accuracy rates depending on the type of tooth. Song et al. [53] introduce an HMD-based MR application

that can provide feedback to the dentist during root canal treatment, thereby eliminating the head moment problem and improving treatment outcomes. Dastan et al. [54] co-designed and evaluated MR drill positioning widgets for dental procedures. They compared static and dynamic widget designs in a user study with 35 dentists, finding that dynamic widgets improved precision but increased task load. At the same time, younger participants and those with gaming experience performed better with complex dynamic widgets. The dynamic widgets improved precision of $9.96^\circ \pm 9.72$ rotational, and $2.58 \text{ mm} \pm 1.69$ positional were recorded, but it increased the task time of 23.03 ± 10.32 sec compared to static widgets. Another study by Chen et al. [55] compared augmented reality-guided (ARG) and freehand endodontic microsurgery on 3D-printed models, finding that ARG improved precision and operator confidence but increased surgical time. They developed a low-cost AR application for endodontic microsurgery using customized 3D-printed models with artificial periapical lesions. Farronato et al. [56] focuses on evaluating the accuracy of AR in guiding access cavity preparation in endodontics, using custom-made 3D AR systems on 3D-printed jaws. This method transforms clinical practice by allowing clinicians to perform minimally invasive access cavities with AR guidance and improve treatment outcomes. The study showed an average deviation of 0.51 mm and 0.77 mm in frontal teeth and premolars, respectively. Furthermore, the system employs user-friendly software that eliminates the need for additional visits or printed guides, thereby making it a practical solution for dental professionals. Li et al. [57] investigated the feasibility of using mixed reality technology for root canal therapy by developing an application that offers real-time anatomical feedback through a head-mounted display. They conducted preliminary experiments on a phantom model and found that this approach significantly improved the accuracy of the procedure, reducing targeting errors from 1.4 mm to 0.4 mm. Dołęga-Dołęgowski et al. [58] developed an application for root canal treatment using MR technology. The results show that 3D holograms displayed on HoloLens 2 can reduce diagnosis and treatment planning time by 52% compared to traditional CT scan analysis methods. Martinho et al. [59] investigates the integration of AR with 3D dynamic navigation systems (3D-DNS) for osteotomy and root-end resection, comparing its accuracy and efficiency to traditional 3D-DNS. Results show that AR + 3D-DNS is more accurate and time-efficient than 3D-DNS; the finding suggests the potential for safe and reliable integration of HMD AR into 3D-DNS for endodontic microsurgery.

C. Dental Implantology

In dental implantology, AR and MR technologies enhance precision by superimposing virtual guides onto the patient's jawbone, thereby providing real-time 3D visualization of implant positions. This advanced guidance allows clinicians to align and place implants accurately, ensure optimal positioning, and reduce the risk of complications [60], [61]. Jiang et al. [62] proposed a 3D augmented reality navigation method to improve the accuracy and efficiency of

dental implantology positioning using point cloud-based image patient registration that can assist the dental implantology process by superimposing virtual images on the real environment. The study utilized 12 3D-printed mandibular models and divided them into two groups: guided by the 3D AR method and the traditional 2D image method. The results showed that the 3D AR method had higher accuracy in implant positioning, with smaller errors in both linear and angular measurements, especially in the central incisor and canine regions. In addition, surgeries using the 3D AR method were significantly faster. Ma et al. [63] developed an AR-guided navigation system with an accurate cone-beam computed tomography (CBCT) image registration approach to enhance the precision of dental implantology placements. This technique uses a registration device outside the patient's mouth to match the preoperative data. Once synchronized, the device was affixed to the patient's teeth for tracking purposes. During the procedure, 3D visualizations of the planned implant path and vital structures, such as the mandibular nerve, were superimposed directly onto the patient's real anatomy to create an AR view. Liu et al. [64] developed a novel MR-based dental implantology navigation system using 3D-CBCT images, incorporating a HoloLens HMD and optical tracking. The system demonstrated significantly better precision and feasibility compared to the free-hand (FH) approach, with lower entry deviation (MR: 0.6914 ± 0.2507 mm, FH: 1.571 ± 0.5004 mm, $P = 0.000$), middle deviation (MR: 0.7156 ± 0.2127 mm, FH: 1.170 ± 0.3448 mm, $P = 0.000$), and angular deviation (MR: $1.849 \pm 0.6120^\circ$, FH: $4.933 \pm 1.650^\circ$, $P = 0.000$), while the apex deviation showed no significant difference (MR: 0.7869 ± 0.2298 mm, FH: 0.9190 ± 0.3319 mm, $P = 0.1082$). The system achieved 3D reconstruction, real-time tracking, and holographic display, proving its potential for accurate and feasible dental implantology surgery.

Furthermore, Shrestha et al. [65] introduced an enhanced iterative closest point algorithm to improve the accuracy between CT-derived teeth models and the actual view of the patient teeth, thereby minimizing errors from mismatched points. Compared to existing methods with 0.44 mm accuracy, the new approach improved accuracy to 0.33 mm and increased the 9 fps to 14 fps. Kivovics et al. [66] assessed the precision of dental implantology placement using three methods: AR-based dynamic navigation, freehand technique, and static computer-assisted implant surgery (CAIS). Using 3D printed models, 48 implants were placed across the groups. The results showed that the AR-based navigation accuracy was similar to that of the static CAIS, but better than that of the freehand method. Specifically, there was no significant difference between AR and static CAIS in terms of angular deviation or coronal and apical global deviations. However, the deviations were notably lower with the AR method than with the freehand method. The study suggests that AR-based navigation offers a promising alternative to traditional methods, with comparable accuracy to static CAIS and improved accuracy over freehand placement. Further clinical investigations are required to confirm its practical applications. However, dynamic navigation with AR showed no significant difference from static CAIS. Static and dynamic navigation techniques

can be combined to improve the efficiency of reconstruction workflow in oncology using virtual surgical planning, patient-specific 3D printing models, dynamic guidance using real-time optical tracking, and AR visualization [67]. Lin et al. [68] focused on developing an AR-based dental implantology system to enhance implant placement accuracy. By integrating a surgical template with AR technology, dentists can visualize 3D virtual structures, thereby significantly reducing deviations from the planned position. Moreover, HMD models offer intraoperative visual assistance, ensuring optimal implant positioning and minimizing iatrogenic injury risk. Katić et al. [69] proposed a context-aware AR system for dental implantology surgery, aiming to stream information and enhance surgical guidance. This system demonstrated its ability to dynamically monitor surgical stages, intelligently adapt visualizations, and present only pertinent information, thereby fostering an efficient and precise surgical environment for dental professionals. The system enhanced surgical ease, ergonomics, and calibration accuracy with implant deviations of less than 2.5 mm. Dong et al. [70] proposes a marker-less AR image guidance method for dental implantology, achieving a registration error of 0.731 ± 0.144 mm. The dental planting errors were 1.174 ± 0.241 mm at the neck, 1.433 ± 0.389 mm at the apex, and $5.566 \pm 2.102^\circ$ for the angle, were achieved. This shows the clinical requirements and effectively guiding dentists during surgery.

D. Maxillofacial Surgery

In maxillofacial surgery, AR technology enhances the treatment of craniofacial structures including mouth, jaw, face, head, and neck. Specialists in this field perform intricate procedures involving delicate anatomical structures. Before surgery, patients undergo a CT scan to provide detailed digital imaging data. Surgeons use these data to design and plan an optimal course of therapy, including precise drilling positions, implant placements, resection margins, and reconstruction planning. AR overlays digital information onto the surgical field, significantly improving accuracy and surgical outcomes. Several new techniques and instruments have been developed to allow surgeons to view and manipulate surgical site directly, such as image-guided navigation systems [71].

Badiali et al. [72] introduced an HMD AR system specifically for maxillofacial bone surgery, negating the need for a localizer. The system displays a virtual plan that overlays on a real patient and assists surgeons in waferless maxillary repositioning. Using the LeFort I osteotomy as the test surgery, in vitro on a skull replica showed a mean error of 1.70 ± 0.51 mm when repositioning the maxilla. Zhu et al. [73] worked on the accuracy of treatment outcomes by integrating a novel registration and tracking method with an AR-based navigation system to superimpose the virtual image, constructed from CT scans, onto the real patient. A novel registration technique uses an occlusal splint combined with a fiducial marker to align virtual and real images. Once aligned, they form an "integrated image" displayed on a semi-transparent glass. The system position error is 0.96 ± 0.51 mm. In addition, to improve the response time, a real-time markerless image registration method by integrating

a shape-matching algorithm into a 2D tracking system for a video see-through AR-based approach has been developed by Wang et al. [74]. The system displayed an overlay error of approximately 1 mm and operated at 3-5 fps with a 4K camera. Similarly, another markerless image registration approach was developed for AR-guided surgery using a novel 3D stereo matching algorithm [75]. As a result, anatomical models and virtual implants can be superimposed on the camera view to enhance AR surgical navigation. The system was tested on a jaw phantom and showed a registration error of less than 0.50 mm, with a time of approximately 0.5 seconds. Markerless approaches do not rely on external fiducial markers but rather perform registration automatically to avoid misalignment difficulties caused by the movement of the patient and surgeon. Therefore, it will increase the overall system accuracy, and the processing time of AR-based systems plays an imperative role in the overall system efficiency. The iterative closest point (ICP) algorithm improves visualization accuracy and minimizes overlay error, reducing system processing time [76]. To ensure the spatial and temporal consistency of an augmented video, a mean value cloning algorithm was applied, which helped produce the composite video by combining the augmented video of the surgical site with the virtual hand of the remote expert surgeon. This technique is intended to decrease the processing time and improve the accuracy of the merged video by reducing overlay and visualization errors and eliminating occlusions and artifacts [77].

E. Orthognathic Surgery

In Orthognathic surgery, AR technology enhances precision by providing 3D visualization and real-time alignment of the jaw structures. This advanced guidance allows surgeons to accurately cut, reposition, and fix the jaw, thereby significantly improving surgical outcomes and reducing complications. By overlaying digital data onto the patient's anatomy, AR ensures optimal precision, thereby effectively improving jaw morphology and interocclusal relationships. 3D diagnosis and simulation of skeletal and occlusal problems are vital for patients with jaw deformities. Zhu et al. [78] used ARToolKit for the registration technique and successfully applied it to 15 patients in the study in accordance with the surgical plan to precisely define the cutting planes for the mandibular angle oblique split osteotomy. Zinser et al. [79] introduces an occlusal splint for the dental cast to fix the marker. Through computer-assisted orthognathic surgical navigation, an interactive image-guided visualization display (IGVD) enables the surgical process to be performed in a completely immersive environment by superimposing the virtually planned maxilla on top of the patient using a video graphic array (VGA) camera. This approach allows surgeons to precisely overlay the virtually planned position of the maxilla onto its real position during surgery using a VGA camera, thereby enhancing the surgeon's 3D perception. When tested on 16 adult class III patients undergoing bi-maxillary osteotomy, the method displayed high precision in transferring virtual surgical planning to real-world surgical outcomes.

Fushima and Kobayashi [80] developed a mandibular motion tracking system (ManMoS) for orthognathic surgery using MR-based simulation to verify effectiveness in the case of complicated skeletal and dental asymmetries. The overall error rate for the system was less than 0.32 mm, suggesting its high accuracy and suitability for clinical applications. The system can enhance collaboration between orthodontists and surgeons. Zhu et al. [81] introduce the ManMoS system that satisfies clinical needs and facilitates communication between orthodontists and surgeons. A retrospective study was conducted on 93 patients with mandibular angle hypertrophy. 41 patients were treated using the AR-based navigation system, 28 were treated using individualized templates (IT group), and the remaining patients received freehand osteotomy (freehand group). Based on study findings, the AR-based navigation technique was found to be more accurate, reliable, and practical for clinical use. When placing an implant near the jaw bone to be cut or drilled, a weighting-based de-noise filter can help to improve the accuracy of AR-based navigation systems by removing noise from real-time video and occluding objects such as surgical tools, surgical body parts, and blood [82]. Moreover, overlaying only the operational area with a 2D/3D AR navigation system can reduce positional error during jaw surgery. Therefore, it increases precision in positioning surgical instruments during navigation of deep anatomical corridors by applying multiple feature descriptions to accurately track and estimate the 3D position of the surgical instrument [83].

Kim et al. [84] proposed an AR-assisted method for freehand orthognathic surgery based on electromagnetic tracking (EM) and a skin-attached dynamic reference system. The system uses a noninvasive dynamic reference frame and a markerless optical tracking system. Preoperatively, two registrations (one between the physical EM tracking and CT image spaces and the other between the physical and AR camera spaces) were performed using the registration body complex and 3D depth camera. The maxillary bone segmentation (MBS) model was superimposed on a live video image of the patient, and the simulated model was displayed on a flat panel. Simultaneously, the MBS was freely repositioned in relation to a skin-attached dynamic reference tool (SRT), with quantitative visualization of the landmarks of interest using only EM tracking. The mean discrepancies for SRT in landmark positioning were minimal, 0.20 mm, 0.34 mm, 0.29 mm, and 0.55 mm in x (left lateral, right lateral), y (setback, advance), z (impaction, elongation) directions, and RMS, respectively. In comparison, those obtained by the BRT were 0.23 mm, 0.37 mm, 0.30 mm, and 0.60 mm. This indicates that the technique is precise and reliable for freehand orthognathic surgery. Liu et al. [85] proposed an AR system based on contour registration for jaw surgery, demonstrating feasibility and accuracy comparable to traditional surgical guides in model and animal trials, with distance and angular deviations of 1.62 ± 0.38 mm and $3.68^\circ \pm 0.71$, respectively for osteotomy surfaces. This system enables surgeons to observe and interact with surgical plans intraoperatively, enhancing real-time surgical guidance.

F. Dental Education

In dental education, AR and MR technologies are used to create advanced simulation training programs that provide immersive and interactive 3D interfaces. These technologies enable students to practice a wide range of dental procedures with enhanced realism and precision [86]. The interactive capabilities of AR and MR significantly improve learning experience and make dental education more effective. Dental schools use patient simulators with dental models to simulate dental treatments. Dental students must achieve an acceptable level of competence because most dental procedures (such as cavity preparation, endodontic therapy, and oral surgical interventions) are irreversible, and learning these skills solely on patients is not an acceptable practice [87]. However, in one study, 3D-printed and AR tooth models for reconstructing occlusal surfaces during cavity fillings were utilized, and it was found that 3D-printed models provided more accurate but slower results. While AR models are useful for dental education, they are not suitable replacements for physical models in clinical practice [88].

Suvinen et al. [89] discusses the growing interest in clinical simulation as an educational tool in preclinical dental education. Over the three-year period, student feedback collected through questionnaires was overwhelmingly positive, indicating a preference for the simulated learning environment over conventional preclinical training. Further research into methods of dental preclinical education proposed by Arigbede et al. [90] and findings suggest that, while the use of simulators in dental education is established, improvements can be made in providing continuous and constructive feedback to enhance the learning experience. Li et al. [91] replicates both soft and hard oral tissues as well as provides a clinical diagnosis and treatment environment through an AR dental simulator. Future advancements in big data, cloud computing, 5G, and deep learning are expected to refine simulators, provide personalized learning experiences, and improve the functionality for preclinical training. Traditional preclinical dental skills training based on a phantom head, extracted teeth, or plastic teeth [92] is generally used for practicing tooth preparation [93], for which the processes are irreversible. Kihara et al. [94] developed an AR system using HMD to assist dentists during tooth preparation by providing real-time visualization and navigation, particularly with cross-sectional views. User studies showed that the AR-assisted approach improved accuracy, reduced time, and made the procedure less complicated than traditional methods. The acquisition of extracted teeth has become increasingly complex, and the sensory feedback of preparing plastic teeth is different from that of natural teeth. Furthermore, AR-based wire bending training systems for orthodontics can improve the accuracy of orthodontic treatment by allowing students to work in artificial environments [95], [96]. Sukotjo et al. [97] AR (e-typodont) significantly improved patients understanding of dental implantology procedures compared to traditional typodont models. The participants found the AR application more engaging and educational, indicating its potential to enhance dental health literacy.

Escobar-Castillejos et al. [98] presents a comprehensive review of medical simulators with haptic devices, which are tools that enhance the realism of medical training by providing tactile via AR and MR for force feedback. These advanced devices making training reversible, repeatable, and environmental friendly [86], [99], [100], [101]. The study suggests a positive attitude of dental students toward AR, which is significantly influenced by infrastructure and prior knowledge readiness. Together, these factors enhance the potential of AR technologies in dental education for hands-on training and feedback [102].

IV. POTENTIAL TECHNOLOGICAL DEVELOPMENT AND FUTURE APPLICATIONS

AR and MR have been applied in various fields of dentistry and have been experimented with by clinicians during surgeries [103]. However, the most recent AR systems used in dentistry mainly provide immersive visualization of static tissue structures generated preoperatively. These are versatile technologies with infinite possibilities; however, it is also essential to recognize their limitations and challenges. First, the most critical step is to compare the cost-effectiveness of the systems (cost, time, satisfaction, and clinical outcomes) because traditional AR-based navigation systems lack to provide substantial data on efficacy and efficiency. Second, the navigation system has problems specific to early technologies: fluctuation in accuracy, low resolution, image delay, poor brightness and contrast issues, image registration and calibration, workflow in the operating room, and training staff. One of the major problems with 3D holograms is the mismatch between virtual models and real-time patients, which needs to be corrected. Therefore, 3D holograms are yet to be widely adopted in the surgical field as navigation tools, despite being valid for guidance. In addition, patient or clinician movement reduces the accuracy of dental procedures and increases the surgical risk. To overcome these challenges, it is necessary to ensure that digital technologies are continuously improved because this is the key to positive outcomes [96]. Technical and clinical research is a possible future research trend for AR and MR in digital dentistry, as shown in Fig. 4.

A. OST-HMD Optimization Technology

In digital dentistry, OST-HMD-based AR plays a crucial role in achieving precise real-virtual patient image registration. This technology enhances the diagnostic and treatment accuracy by accurately overlaying digital models onto real patient images. Hu et al. [96] utilized OST-HMD-based AR for orthodontic bracket placement, providing precise treatment guidance. Several AR glasses-based applications for dental education have been proposed to guide clinicians in correcting their pose during tooth extraction [104]. These surgical training applications involve mentorship by expert surgeons during actual procedures rather than outside the operating room. Both student and teacher surgeons can view a composite surgical field, simultaneously seeing each other's hands and surgical tools. The development of OST-HMD applications

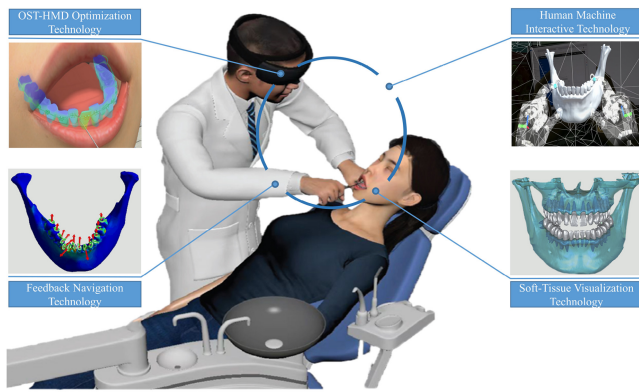


Fig. 4. Future prospects of AR and MR in Dentistry: Revolutionizing the future of dental practice through head-mounted displays, human-machine interaction, feedback navigation, and advanced tissue visualization. Each of these advancements can play a crucial role in the development of AR and MR technologies in digital dentistry, improving diagnostics and surgical precision and guiding future research.

is critical in dentistry, as it enables real-time overlay of digital information onto the dentist's field of view, enhancing accuracy and training efficacy.

1) *Enhanced Visualization*: The OST-HMD technology has significant potential for enhanced visualization in dental applications. This technology can project high-resolution 3D models directly onto a patient's mouth, offering a clear and detailed view of dental structures in real time. Such enhanced visualization allows dentists to accurately see through soft tissues to the underlying bones, nerves, and roots, facilitating precise diagnostics and treatment planning. Future advancements may include integration with AI for predictive insights, improved ergonomic designs for prolonged use, and cost reduction for broader accessibility. Overall, the OST-HMD technology promises to revolutionize dental care by enhancing visualization, reducing errors, and improving patient outcomes.

2) *User Comfort and Ergonomics*: Current developments aim to create lightweight and balanced OST-HMD headsets that reduce discomfort during prolonged use, making them more comfortable and ergonomic. These improvements are essential for wide adoption of technology. Ergonomically designed OST-HMDs enhance user comfort by evenly distributing weight, reducing neck and head fatigue, and allowing for adjustable fits tailored to individual practitioners. Improved user interfaces and intuitive controls further streamline the experience, making it easier for dentists to seamlessly navigate complex visual data. The potential for these ergonomic enhancements ensures that dental professionals can maintain high precision and efficiency during lengthy procedures. Rojas-Muñoz et al. [105] used HoloLens mentoring system in which an expert surgeon can view virtual 3D annotations (surgical tools and incision guidance lines), which the student surgeon sees in real-time. The authors reported improved information exchange between students and mentors, reduced number of focus shifts, and reduced placement error. A similar study was presented in [106], where trainees performed leg fasciotomy and reported improved surgical confidence. Therefore, OST-HMDs are the best choice for intraoperative

assistance because of their natural hand-eye coordination. However, the currently available systems are bulky and uncomfortable to wear during long surgeries. Also, the battery timing is another issue that needs to be addressed for a smooth and continuous procedure. Additionally, current AR systems used for daily practice in dental clinics are still expensive. The development of HMDs with a lightweight design and low cost is another direction to extend the applications of AR in dentistry.

B. Feedback Navigation Technology

In digital dentistry, intraoperative navigation is particularly valuable in complex treatment procedures or when operating on sensitive structures because it utilizes systems and devices to provide real-time feedback and guidance during surgery. This technology enhances surgical precision by offering continuous, on-screen updates of anatomical structures and also provides the surgeon with real-time updates, enabling necessary adjustments to the surgical plan during the procedure if unexpected situations arise [107].

1) *Real-Time Guidance*: Real-time guidance during surgical procedures for structural visualization has the potential to overlay complex data onto the surgical field, providing dentists with continuous and precise visual cues during treatment. Real-time guidance enhances accuracy by dynamically adjusting overlays to reflect dentist movements, reduce the risk of errors, and improve surgical outcomes. It facilitates complex procedures, such as implant placement and root canals, by clearly delineating anatomical structures and suggesting optimal paths. Continuous feedback ensures that dental interventions are precise and minimally invasive.

2) *Enhanced Precision*: Dynamic updating of visual fields with precise data allows accurate navigation of complex dental structures, significantly improving the precision of implant placement and the drilling path. Additionally, AR facilitates the careful avoidance of critical anatomical structures, such as nerves and blood vessels. The resulting enhanced precision reduces surgical risk, shortens operative times, and improves patient outcomes, thereby establishing AR as a pivotal tool in contemporary dental practice.

AR navigation systems with intraoperative feedback can significantly enhance the accuracy and efficiency of dental procedures by providing real-time guidance and monitoring. In orthodontics, for instance, the force applied to teeth by orthodontic appliances directly affects the treatment outcomes. An AR-based navigation system designed to measure orthodontic force relies on precise image reconstruction and registration techniques to superimpose a 3D model onto a real-time patient during clinical procedures. This system, with real-time feedback during appliance loading, ensures that dentists apply an accurate force without damaging the patient's teeth from excessive pressure. Similarly, in dental implantology, AR technology provides real-time visualization of drilling positions relative to the planned implant path, along with monitoring of the implant temperature to prevent tissue burns [108]. This ensures both stability and safety of dental implantology by providing immediate feedback. Furthermore,

TABLE III
THE COMPREHENSIVE OVERVIEW OF FUTURE RESEARCH DIRECTIONS AIMED AT OPTIMIZING THE APPLICATION
OF AR AND MR TECHNOLOGIES IN DIGITAL DENTISTRY

Future Technology Advancement	Key Directions	Potential Applications
OST-HMD Optimization	<ul style="list-style-type: none"> Enhanced visualization User comfort and ergonomics Cost reduction Integration with AI Improved battery life 	<ul style="list-style-type: none"> Real-time overlay of digital information Improved surgical training and mentorship Enhanced diagnostic and treatment accuracy Precise orthodontic bracket placement Hand-eye coordination during procedures
Feedback Navigation	<ul style="list-style-type: none"> Real-time guidance systems Enhanced precision in navigation Intraoperative feedback systems Real-time force measurement sensors 	<ul style="list-style-type: none"> Implantology and drilling path optimization Orthodontic force measurement and control Real-time surgical plan adjustments Implantology temperature Monitoring
Human-machine Interactive	<ul style="list-style-type: none"> Adaptive systems using machine learning Predictive analysis for treatment planning Efficient HMI methods for intraoperative control Balancing virtual and user information 	<ul style="list-style-type: none"> Personalized AR experiences for dentists Proactive treatment planning and risk reduction Improved workflow optimization Real-time alerts for potential complications Spatial awareness during complex procedures
Soft Tissue Visualization	<ul style="list-style-type: none"> Advanced preoperative planning tools Enhanced real-time 3D imaging of soft tissues Real-time soft tissue reconstruction techniques Integration with minimally invasive techniques 	<ul style="list-style-type: none"> Detailed soft tissue analysis without incisions Improved diagnosis of hidden dental nerves Enhanced safety in complex procedures Better patient education and treatment planning

incorporating real-time feedback on painful sensations into AR systems can play a crucial role in dental education. This allows dental students to develop practical skills in a realistic and controlled environment, thereby improving their competency and confidence in performing dental procedures. However, capturing real-time feedback is challenging. To the best of our knowledge, there is currently no AR system with an intraoperative real-time feedback sensor that can measure the force applied on teeth in vitro. Biomechanics and other calculation-based methods can hardly achieve the accuracy and real-time requirements of clinical applications.

C. Human-Machine Interactive Technology

In digital dentistry, AR systems enhance intraoperative surgery by integrating virtual scenes such as internal anatomical structures with real-world views, thereby facilitating more precise and informed surgical procedures. These virtual overlays significantly improve treatment outcomes by providing detailed visual guidance. However, excessive virtual elements can lead to visual fatigue and distract dentists, thereby reducing the accuracy and efficiency of intraoperative manipulation. To mitigate this issue, human-machine interface (HMI) APIs can be designed to create interactive AR displays that are user-friendly and minimize visual strain. The user experience of 3D immersive interfaces differs markedly from traditional 2D “desktop metaphors” interfaces, offering more intuitive interactions and enhanced spatial awareness, which are crucial for performing intricate surgical procedures. By integrating advanced AR systems with well-designed HMI, digital dentistry can balance the provision of essential virtual information with a comfortable user experience, ultimately leading to improved surgical outcomes and enhanced practitioner performance. However, not all virtual scenes must

be visualized during the intraoperative manipulation. For instance, during the bracket bonding procedure, only the position information of the target bracket is necessary, and the visualization of other information, such as the internal teeth and alveolar bone, is useless and may interfere with dentist manipulation. Similarly, for the archwire loading procedure, the internal teeth and alveolar bone and their force information are essential, and the position information of the brackets should be invisible.

1) *Adaptive System*: Adaptive systems learn from user interactions and customize the AR experience according to individual dentist preferences and techniques. By integrating machine learning algorithms, adaptive systems can provide personalized recommendations and real-time adjustments during procedures, thereby enhancing precision and efficiency. Adaptability ensures that AR tools remain intuitive and user-friendly, even when they handle increasingly complex tasks. As the system offers tailored support, optimizes workflow, reduces errors, and improves patient outcomes, AR is an indispensable component of modern dental practice.

2) *Predictive Analysis*: Machine learning algorithms and AR systems can be used to analyze historical and real-time data to forecast potential dental issues and procedural outcomes. This predictive capability allows proactive treatment planning, reduces the risk of complications, and enhances the precision of dental interventions. Dentists can receive real-time alerts regarding possible problems, such as nerve proximity during drilling or unexpected tissue resistance. This foresight not only improves procedural efficiency, but also enhances patient safety and outcomes, making predictive analysis a vital component of advanced dental care.

Therefore, it is necessary to develop an efficient HMI method that allows dentists to flexibly control the AR system

during intraoperative treatment. HMI in dentistry aims to bridge the gap between the physical and digital worlds, enhancing dentists capabilities while improving the patient's experience and outcomes. As these technologies continue to evolve, they are likely to become more integrated into routine dental practice, offering new levels of precision and efficiency in dental care.

D. Soft Tissue Visualization Technology

In digital dentistry, visualization of soft tissues is of paramount importance, and AR plays a crucial role in enhancing this capability. This technology enables dentists to visualize soft tissues, providing critical insights into blood flow, tissue depth, and underlying anatomical structures, without requiring incisions. This advanced visualization is vital for managing soft tissues that are susceptible to localized deformation and movement during dental treatment, particularly structures such as blood vessels and nerves. Accurate visualization of these tissues is essential during complex procedures including dental implantology and orthognathic surgery to prevent significant complications.

1) *Preoperative Planning*: By providing detailed information about the surgical plan and 3D models of soft tissues, AR allows dentists to thoroughly analyze the patient's oral anatomy before surgery. It helps in the precise visualization and identification of critical structures of dental areas, facilitates meticulous planning, and minimizes risks during procedures. Enhanced preoperative planning ensures that surgical approaches are tailored to the individual-specific anatomy, improving accuracy and outcomes. This technology not only enhances dentist confidence, but also increases patient safety and satisfaction, making it a pivotal development in dental care.

2) *Enhanced Imaging*: AR provides unprecedented clarity and detail by overlaying high-resolution, real-time 3D images of soft tissues onto a patient. This allows dentists to view beyond the surface and accurately identify and assess the condition of the gums, nerves, and blood vessels. Such precision aids in diagnosing issues that are not visible using traditional imaging techniques. The ability to visualize soft tissues in detail ensures more accurate treatment planning and execution, reduces the risk of complications, and improves patient outcome. Therefore, enhanced imaging presents a transformative potential for dental diagnostics. AR-based real-time soft tissue visualization and navigation systems integrate these dynamics and would provide helpful guidance for safety control and online planning of dental surgeries. However, real-time reconstruction remains challenging due to the limitations of the current intraoperative imaging techniques. AR and MR for soft tissue visualization in dentistry are part of a broader movement towards minimally invasive techniques and precision dentistry. This technology promises to improve treatment outcomes, enhance patient understanding and satisfaction, and advance dental education and training. However, integrating such advanced technologies requires significant investment in equipment, training, and workflow adjustments in dental practice.

V. DISCUSSION

The release of Google Glass, along with its open-source development platforms, has attracted significant interest in AR and MR technologies, and encourages inventor participation [109]. These technologies integrate tracking sensors, display devices, operating systems, and computational systems, collectively providing a more immersive user experience by overlaying additional real-world information. This integration makes AR and MR more beneficial than VR because it enhances the user's perception of their actual environment rather than creating a completely separate environment. Technological advancements have led to the emergence of numerous AR and MR applications that are increasingly able to meet user expectations, thereby expanding their potential audience. HMDs are among the most significant examples of MR systems that offer immersive and user-friendly interactive environments. These devices have become more precise and accurate through advanced registration and tracking techniques, which are essential for restorative dentistry applications. In restorative dentistry, precise image registration is crucial, because even micrometer-scale errors or gaps can cause significant damage or lead to poor outcomes. Thus, the development of sophisticated tracking and registration methods has been a focal point for ensuring accuracy and reliability in clinical settings. Moreover, the efficiency of AR and MR systems in digital dentistry, particularly in orthodontics and dental implantology, depends heavily on the speed and capability of computer devices and supporting software. Surgical images must be displayed in 3D without lag to ensure that surgeons who move freely with their display devices can maintain proper orientation and depth perception. This is particularly critical in dental procedures, where patients are often under local anesthesia and may move their head abruptly. The ability to adapt to such movements in real-time without losing accuracy is essential for preventing complications and ensuring successful outcomes.

In the future, the integration of AR and MR technologies in dental applications, especially through the use of HMDs, has revolutionized the way procedures are performed. These technologies provide enhanced precision, orientation, and improved patient safety. As these technologies continue to evolve, they are expected to play an increasingly vital role in various medical fields, driving further innovation and improvement in patient care.

VI. CONCLUSION

In this review, we demonstrate the features, applications, and potential of AR and MR technologies in various fields of digital dentistry. The advent of contemporary digital technologies has the potential to radically transform both clinical and educational aspects of dentistry. For instance, students can independently enhance their practical skills and knowledge, facilitating a seamless transition from preclinical training to clinical practice. Dentists can leverage these technologies to improve their daily practices, offering the flexibility to access these tools anywhere and at any time. Despite the rapid development of AR and MR in digital dentistry, their

application remains primarily experimental owing to several limitations, such as the mobility and bulkiness of HMDs, challenges in fostering effective communication between dentists and patients, concerns over privacy, and a general lack of familiarity with these technologies among clinicians. Future research in healthcare, particularly dentistry, should focus on overcoming these limitations to fully harness the benefits of AR and MR. Advancements in these technologies represent modern strategic approaches that can significantly enhance the efficiency and quality of dental care. By addressing these challenges, AR and MR can move beyond experimental stages and become an integral part of everyday dental practice, ensuring improved patient outcomes and a streamlined clinical workflow.

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