

Shaping Smiles Through Time: The Revolution Of Augmented Reality In Prosthodontics

Rohit Raghavan¹, Shajahan PA², Feba C Tony³

¹Professor and Head, Department of Prosthodontics, Royal Dental College, Palakkad, Kerala

²Professor, Department of Prosthodontics, Royal Dental College, Palakkad, Kerala

³Post graduate student, Royal Dental College, Palakkad, Kerala

Corresponding Author: Feba C Tony; Postgraduate student, Royal Dental College, Palakkad, Kerala

Abstract Augmented reality (AR) is a technology that blends digital elements with the real-world environment by overlaying computer-generated images onto the user's view. This integration creates a hybrid visual experience and has become increasingly valuable in various domains, including dentistry and medicine. At present, the use of AR in dentistry is mainly confined to educational purposes, maxillofacial surgeries, and implant procedures. However, with continued advancements, its application is likely to expand into other essential areas of dental care. In prosthodontics, one of the key challenges is helping patients visualize the expected results of smile designs or prosthetic treatments. AR can bridge this gap by projecting the intended outcomes directly onto the patient's existing oral condition. This not only enhances patient understanding but also improves communication between the dental team and the patient, ensuring clearer treatment goals and expectations. As the technology becomes more mainstream, the possibilities for AR in dental practice especially in prosthodontics are expected to grow significantly. This article outlines a brief history of AR and highlights its emerging role and potential benefits in prosthodontic treatment.

Keywords: Augmented reality, Dental surgery, Virtual reality

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INTRODUCTION

Modern dentistry is increasingly defined by the integration of 3D digital technologies, computer-aided design (CAD), and computer-aided manufacturing (CAM). As digital advancements continue to shape the field, numerous innovations have emerged to improve both dental education and clinical practice. Among the most notable are technologies within the reality virtuality continuum, particularly augmented reality (AR) and virtual reality (VR).^[1] Traditional digital workflows in dentistry typically follow a three-step process: first, an image is captured using a scanning device; next, the operator digitally modifies the tooth's position or size; finally, the data is either converted back into a physical model or retained in digital form as a virtual wax-up.^[2] The introduction of augmented (AR) and virtual reality (VR) has streamlined and enhanced these procedures. AR and VR technologies rely on a combination of real and virtual data inputs, along with components such

as tracking systems, registration techniques, visualization processing, spatial perception, display types, and feedback mechanisms. While VR creates a fully immersive digital environment, AR overlays virtual elements onto the real world, enabling interaction between both physical and digital spaces. Augmented reality systems typically utilize a range of devices such as head-mounted displays, monocular systems, screen-based interfaces, and other hybrid technologies.^[3] Augmented reality (AR) emphasizes clinical applications by enabling the immediate display of clinical data directly on the patient, seamlessly integrating digital information with the real-world environment. In dentistry, AR is primarily used to "enhance reality" by superimposing digital content such as images, videos, and 3D models onto real-world objects. It also facilitates real-time communication between patients and dentists through these visual tools, improving understanding and collaboration.

CLINICAL APPLICATIONS

At present, augmented reality is utilized in fields such as plastic surgery, laparoscopic procedures, and neurosurgery. Within dentistry, its applications extend to oral and maxillofacial surgery, dental implant surgery, and orthognathic surgery.^[4] AR devices enable users to integrate medical information, data, and visuals directly into their real-world view. Unlike traditional image-guided surgery, where surgeons must divert their attention away from the operative field, AR guidance systems display real-time intraoperative data right within the surgeon's line of sight. This continuous access to information helps reduce surgical risks.^[5] Augmented reality has demonstrated its potential to enhance outcomes in dental implant procedures. As early as 1995, implant placement systems featuring realistic overlays of the suggested implant position directly on the patient were introduced. Additionally, AR surgery utilized retinal imaging displays to pioneer implant navigation technologies. During implant placement, AR can function as an automated data filter, allowing surgeons to concentrate solely on the procedure by presenting only the most essential information. This advanced technology also facilitates improved communication between dentists, technicians, and patients. Through detailed virtual simulations, patients can visualize the anticipated clinical results before treatment.

Furthermore, AR devices are capable of generating 3D models directly within the patient's mouth, enabling precise 3D aesthetic planning. These systems also allow operators to share their real-time view with dental technicians or other specialists, fostering collaborative treatment planning.

KEY MILESTONES IN THE DEVELOPMENT OF AUGMENTED REALITY

The journey to today's advanced augmented reality systems began with the groundbreaking work of numerous visionary individuals. Below are some of the most influential figures and pivotal events that shaped the evolution of AR. In 1962, cinematographer Morton Heilig created the Sensorama, a motorbike simulator that stands as one of the earliest known examples of immersive, multi-sensory technology.^[6] In 1968, Ivan Sutherland created the Sword of Damocles, considered the pioneering system in augmented reality. It was among the first devices to incorporate a six-degree-of-freedom tracker along with an optical see-through head-mounted display. In 1975, Myron Krueger, an artist, introduced Video Place, an augmented reality system that pioneered user interaction with virtual elements. In 1992, the term "Augmented Reality" was coined by Tom Caudell and David Mizell, who worked on Boeing's Computer Services' Adaptive Neural Systems Research and development project. Their research aimed to enhance Boeing's production and engineering workflows by developing software that visually displayed the locations of

various wires during assembly. In 1996, Jun Rekimoto developed the prototype NaviCam AR system. It used markers—physical or virtual objects or locations—that the computer identifies to position digital content. NaviCam was among the first marker-based systems to offer six-degree-of-freedom tracking, and this type of marker remains in use today. In 1999, Total Immersion was founded as the first company to offer augmented reality solutions, launching their cross-platform product, D'Fusion. In the same year, Hirokazu Kato released ARToolKit, a software toolkit that enables the integration of real-world video with virtual objects and 3D graphics across multiple operating systems. ARToolKit became the foundation for nearly all Flash-based augmented reality applications on the web. Developed by Hollerer, Feiner, and Pavlik, this technology also helped pave the way for AR browsers. In 2000, Simon Julier and his colleagues created the Battlefield Augmented Reality System (BARS), designed to deliver critical information to ground troops. BARS incorporated a head-mounted display, a wearable computer, and wireless networking to enhance battlefield awareness. That same year, Bruce Thomas and his team developed AR-Quake, an augmented reality version of the popular game Quake which featured six degrees of freedom (6DOF) tracking, GPS, a digital compass, and vision-based marker tracking. In 2004, Mathias Möhring showcased the first mobile 3D marker tracking system. This innovation enabled the detection, differentiation, and integration of 3D markers within live video feeds, marking the debut of augmented reality on mobile phones. In 2009, SPRXmobile launched Layar, an augmented reality browser that utilizes GPS and compass data for accurate positioning. It operates on an open client-server platform and features content layers similar to those of a traditional PC web browser.

DENTAL IMPLANT SURGERY PROCEDURES

Dental implants are increasingly used to treat patients with missing teeth. However, implant placement is a delicate procedure that demands thorough training and precise execution. Ensuring adequate bone thickness around the implant is crucial to minimize excessive exposure of the implant surface. Augmented reality (AR) technology has simplified treatment planning and accurate localization of the implant site, making the process less invasive and more comfortable for patients.^[7] Seipel and colleagues compared a low-cost stereoscopic display system offering six degrees of freedom in implant positioning to traditional virtual systems with only three degrees of contrasted the performance of a 6 DoF low cost spectroscopic display with traditional 3 DoF virtual systems to determine the impact on implant positioning accuracy. Using voxel-level computed

tomography (CT) image allows for real-time adjustments during treatment planning. Kusumoto and Ohtani developed systems that integrated CT images of the jawbone with virtual reality (VR) force-feedback haptic devices, providing realistic training experiences for novice dentists. Additionally, Xiaojun and his team introduced CAPPOIS, modular software designed to assist in preoperative planning. This technology can be tested on simulated jawbones before being applied in clinical settings.

CROWN PREPARATION

Most teeth that have undergone root canal treatment require a prosthetic crown to prevent further tooth loss. Consequently, crown preparation is a common dental procedure that demands precision to ensure the crown's durability and success. Preparing maxillary teeth is generally more complex than mandibular teeth, posing a significant challenge for those without preclinical training. Therefore, trainee dentists must practice and assess their tooth preparations to be well-prepared for clinical practice. At the University of Otago in New Zealand, a software called Prepr was developed to evaluate all-ceramic tooth preparations for mandibular molars. Integrated into dental simulators, this tool has been shown to enhance student performance compared to traditional training methods.^[7]

MAXILLOFACIAL PROSTHESIS

Maxillofacial prosthetics is a demanding specialty, particularly when treating patients with severe facial injuries and high expectations. Success in this field depends on a thorough understanding of oral anatomy, physiology, and prosthetic design. Because treatment often involves collaboration among multiple disciplines, effective digital data visualization is essential for planning and patient communication. Technologies like Vuforia and Unity 3D are commonly used to develop these AR applications, offering advanced features such as image and object recognition and real-time interaction with the environment. By using a built-in camera, the system captures live video streams and enhances them by overlaying 3D models onto the real-world view. To assist prosthodontists, an augmented reality application was created that allows users to drag, resize, and rearrange images and models to suit individual treatment plans. Interactive visual buttons control aspects like visibility, movement, rotation, and size adjustments. The customized scene can then be saved as a standalone Android app, complete with an icon, making it easy to access and share for clinical use.^[8] Currently there are numerous dental simulator systems available which ranges from traditional phantom head models to advanced virtual reality VR and augmented reality AR which are primarily used for dental education, training and treatment.^[2]

DentSim™ was released in 2004, DentSim™ was among the first dental simulators to combine augmented reality with a physical lab mannequin. It captures the movement of the student's handpiece and the typhodont teeth optically, providing real-time evaluation. Students can view the tracked images from multiple angles while working on the plastic teeth. According to Jasinevicius et al., using this dental simulator improved students' preparation skills and reduced the average time needed for each procedure.

Voxel-Man was originally designed for middle ear surgery, the Voxel-Man simulator was adapted for dental use, allowing students to practice with realistic teeth and force-feedback handpieces. It simulates different tooth tissues and offers a 3D display with a virtual dental mirror. An automatic evaluation tool provides instant feedback by comparing student work to standards. Studies by Pohlenz et al. and Sternberg et al. showed the simulator effectively improves skills, with simulator-trained students outperforming those trained on cadavers in apicectomy procedures.

BoneNavi is a bone navigation system developed by Ohtani et al. to assist in computer-aided implant surgery. It combines virtual reality force feedback with CT scans of the jawbone to aid in implant placement and surgical guide creation. These CT images enable personalized treatment planning and pre-surgical practice. However, there is currently no research validating its effectiveness.

SIMIMPLANTO

SimImplanto, developed by Pires et al. in 2016, is a keyboard-controlled Falcon haptic device designed for implant-based oral rehabilitation simulation. It calculates drilling resistance from CT scans of different bone densities and uses 3D jaw models from scanned dental casts. However, there is no further evidence regarding its effectiveness or clinical use.

DENTIST SIMODONT®

The Nissin Simodont®, developed by the Academic Centre for Dentistry in Amsterdam with Moog Industrial Group, is a dental simulator featuring a 3D display, virtual mirror, handpiece gimbal, and ergonomic design. Instructors can customize training and track student performance. Studies by Bakr, Al-Saud, and Zafar show it's an effective tool that enhances dental education when combined with traditional teaching.

VIRTEASY DENT

HRV (Changé, France) developed Virteasy Dent in collaboration with several universities, including Sheffield. It generates a comprehensive digital simulation featuring a virtual patient within a fully rendered clinical workspace. The platform encompasses a comprehensive range of dental disciplines, including restorative dentistry, endodontics, prosthodontics, implantology alongside integrated operator evaluation. Through the simulator editing tool users can import intra

oral images to design and implement custom pathologies. The simulator has shown promise in providing clinically useful qualitative input.^[9]

DENTAL EDUCATION ASSISTANT (IDEA)

The Dental Education Assistant (IDEA), launched in 2011, is a cavity preparation simulator using a 6-degree stylus and PHANTOM® haptic device. It features modules like Manual Dexterity™ and Scaling & Root-Planning™. Using 3D shapes instead of real tooth images, it provides feedback on time, tissue removal, and accuracy. Gal *et al.* found it useful for both students and professionals, though sensory simulation and feedback could be improved.

FUTURE POSSIBILITIES

Marker-based augmented reality (AR) systems currently enable scaling of real images. In the future, marker-less AR and head-mounted devices are expected to reduce visual distortions. Additionally, there is a need to develop specialized algorithms for oral surgery and prosthetic applications.^[2]

Other technologies like photon emission tomography, near-infrared spectroscopy, and dyes such as indocyanine can be combined with current AR systems to better identify complex anatomy and vital structures. Additionally, integrating haptic force feedback and robotics shows great promise. However, more clinical trials on real patients are needed to assess the accuracy and effectiveness of these systems. Future research should focus on virtual simulations combined with AR-guided surgeries to identify system limitations, reduce errors, and improve precision.^[10]

CONCLUSION

Augmented Reality (AR) offers significant benefits in dentistry by improving treatment planning, enhancing surgical precision, and serving as an effective educational tool. It enables clinicians to visualize outcomes and supports procedures like dental implant placement through advanced navigation systems.

Despite its advantages, AR adoption is limited by high costs and legal concerns. However, as technology evolves, integrating tools like 3D imaging, indocyanine dyes, and

haptic robotics may improve accuracy and accessibility. With ongoing advancements, AR and computer-guided systems are set to become essential in implantology, offering more precise planning and a valuable hands-on learning experience for clinicians.

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