Journal of Dental Sciences 19 (2024) S91—S101

Available online at www.sciencedirect.com

ScienceDirect

journal homepage: www.e-jds.com

Review Article

The use of augmented reality (AR) and virtual reality (VR) in dental surgery education and practice: A narrative review

Ping-Yi Lin [a,b,c], Ting-Chen Chen [a,c,d], Chien-Ju Lin [e], Cheng-Chieh Huang [a,c], Yi-Hsuan Tsai [f], Yi-Ling Tsai [a,e], Chen-Ying Wang [a,e*]

[a] *School of Dentistry, National Taiwan University, Taipei, Taiwan*
[b] *Department of Dentistry, Far Eastern Memorial Hospital, New Taipei City, Taiwan*
[c] *Graduate Institute of Clinical Dentistry, National Taiwan University, Taiwan*
[d] *Department of Oral Health, Ministry of Health and Welfare, Taipei, Taiwan*
[e] *Department of Dentistry, National Taiwan University Hospital, Taipei, Taiwan*
[f] *Graduate Institute of Oral Biology, National Taiwan University, Taipei, Taiwan*

Received 24 September 2024; Final revision received 11 October 2024
Available online 28 October 2024

KEYWORDS
Augmented reality;
Virtual reality;
Dental education;
Dental surgery

Abstract Integrating augmented reality (AR) and virtual reality (VR) into dental surgery education and practice has significantly advanced the precision and interactivity of dental training and patient care. This narrative review summarizes findings from extensive literature searches conducted in PubMed, Cochrane Library, and Embase, highlighting AR and VR technologies transformative impact and current applications. Research shows that AR improves surgical precision by offering real-time data overlays during procedures, leading to better outcomes in operations like dental implant placements. On the other hand, VR has revolutionized training environments by offering detailed, immersive simulations that significantly improve the retention of surgical skills. This was demonstrated through VR applications in orthognathic surgery in 2023. Despite their advantages, these technologies encounter adoption challenges, such as high implementation costs and the complexity of integrating advanced simulations into standard training curricula. The prospects for AR and VR in dental surgery are promising. Ongoing developments aim to enhance realism through improved haptic feedback and integrate artificial intelligence to tailor learning experiences. Continued innovation and research are crucial to overcome current limitations, expand applications, and fully realize the potential of AR and VR in improving dental education and clinical practice.

* Corresponding author. School of Dentistry, National Taiwan University, No. 1, Chang-de Street, Taipei 10048, Taiwan.
E-mail address: jywang8919@ntu.edu.tw (C.-Y. Wang).

https://doi.org/10.1016/j.jds.2024.10.011

Introduction

The landscape of dental education and clinical practice is undergoing a profound transformation with the integration of augmented reality (AR) and virtual reality (VR). These innovative technologies, heralding a new era in medical training and patient care, are increasingly recognized for their potential to enhance learning and clinical outcomes.

The primary focus of dental surgical education is clinical training. Teaching methods include lectures and demonstrations in the classroom and practical exercises using manikins, physical models, and instruments in the laboratory. Additionally, computer-aided simulation is used for practice. Assessment after the training includes multiple-choice questionnaires (MCQs), simulated pre-clinical operation skill tests (PCOST), and the objective structured clinical examination (OSCE).[1] The training and assessment above may show that interactive simulation plays a significant role in dental surgical education. Augmented reality (AR) and virtual reality (VR), which may enhance interactive simulation, have transitioned from their origins in gaming and entertainment to become pivotal technologies in dental education and practice. These technologies enhance traditional educational methods and revolutionize how dentistry teaches and practices procedural skills.[2] Beyond dental surgery, AR and VR are extensively used for training in various dental procedures, including diagnostics,[3,4] and restorative dentistry,[5] particularly in the visualization and understanding of complex anatomical structures.[6–8] In educational settings, AR and VR provide an immersive platform where students can interact with three-dimensional models of teeth and supporting structures,[6,7] performing everything from routine cleanings to more complex procedures such as root canal therapy and crown preparation. This hands-on approach facilitates a deeper understanding of dental anatomy and procedures, enhancing students' cognitive and psychomotor skills. These technologies offer simulations in dental surgery that provide realistic, scalable, and controlled environments.[9] This allows for detailed visualization of complex anatomical structures and surgical procedures, facilitating a deeper understanding and retention of surgical skills.[10]

The adoption of AR and VR in dental surgery is not just a technological upgrade but a necessary evolution to meet the increasing demands for precision and safety in surgical procedures. For instance, VR platforms like those used in orthognathic surgery education have significantly improved surgical planning and execution, enhancing procedural outcomes and patient safety.[9,11] Meanwhile, AR applications provide real-time overlay information during surgeries, improving the surgeon's accuracy and reducing intraoperative risks.[12,13]

This narrative review aims to critically examine the current applications of AR and VR in dental surgery education and practice. It discusses the technological advancements, evaluates the benefits and challenges of these tools, and explores their future potential. Special attention is given to integrating these technologies in training settings, their impact on patient outcomes, and the readiness of the dental profession to embrace these changes.

Furthermore, despite considerable advancements in areas such as tooth restoration and preclinical training using AR and VR, their application in more complex surgical training still needs improvement. Integrating a comprehensive range of surgical instruments and techniques into these virtual systems poses significant hurdles. However, the ongoing development and refinement of these technologies promises to bridge these gaps, offering more sophisticated training tools that could revolutionize dental surgical education.[14]

In summary, this review will delve into how AR and VR shape the future of dental surgery education, focusing on their current utilities, limitations, and the vistas they open for future advancements.

Materials and methods

Data sources

For this narrative review, extensive literature searches were conducted in three primary databases: PubMed, the Cochrane Library, and Embase. These databases were selected for their comprehensive medical and dental research coverage, providing a rich source of scientific articles and clinical studies.

Search strategy

The literature search was structured around predefined keywords to ensure a focused retrieval of relevant studies. The keywords used included "dental," "virtual reality," "augmented reality," "dental surgery," "dental education," and "surgery practice." These terms were combined using Boolean operators to maximize the search scope, targeting studies that discuss the intersection of these technologies with dental surgery education.

Selection criteria

The search was limited to studies published from 2000 to the present to focus on the most current technologies and methodologies. The initial search yielded a total of 106 records: 51 from PubMed, 31 from Embase, and 24 from Cochrane Library. After removing 35 duplicate records, 71 studies were reviewed. Two authors (PY Lin and YH Tsai) independently examined the titles and abstracts, resulting in the exclusion of 41 studies that were not directly related to the use of virtual or augmented reality technologies in dental surgery education or practice. Subsequently, the full texts of the remaining 30 articles were carefully examined. An additional 23 studies were excluded as they did not align with the objectives of this review. These exclusions were based on the studies relevance to the specific application of virtual or augmented reality in dental surgery education and practice. Finally, 7 studies were selected for inclusion in this review, as they met all the inclusion criteria and provided relevant data for discussion (Fig. 1).

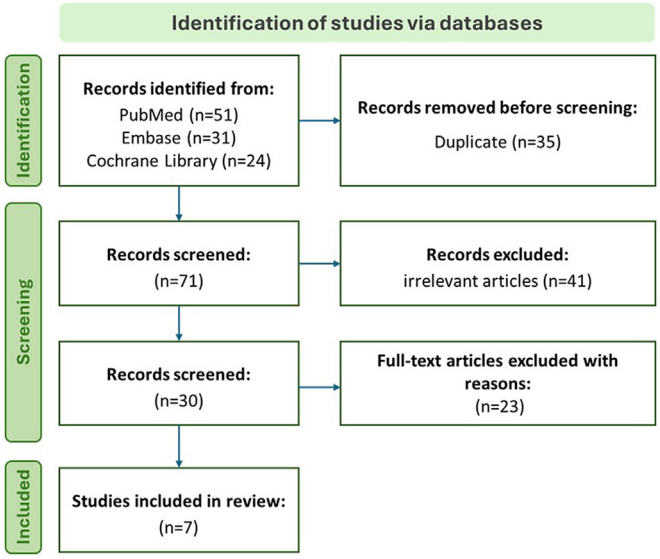

Figure 1 Flow chart of selection process.

Data extraction and organization

The data extraction focused on studies that specifically addressed the use of AR and VR in dental surgery training. Each study was assessed for its relevance, methodology, outcomes, and the potential benefits it provided. This process involved detailed note-taking and thematic organization to effectively synthesize the findings across different studies (Table 1).

Results

Development of augmented reality and virtual reality technologies

Historical development

The evolution of augmented reality (AR) and virtual reality (VR) technologies has been transformative across various sectors, with significant strides made in healthcare and education. Initially conceptualized in the early 20th century, the real breakthrough came with Ivan Sutherland's invention of the "Ultimate Display" in 1965,[19] laying the groundwork for virtual reality. Over the decades, these technologies have progressed from rudimentary forms to sophisticated systems in complex fields such as aviation and healthcare.

In the context of dental education, AR and VR began gaining traction in the late 1990s as computing power increased, allowing for more detailed and realistic simulations. Early applications were focused on anatomical education and basic procedural training, providing a foundation that would lead to more advanced uses in surgical training and practice. This historical progression has enhanced educational methods and improved the precision and effectiveness of dental treatments.

Technological advancements

The last two decades have witnessed vital technological advancements that have profoundly impacted dental surgery. Notably, integrating haptic feedback into VR systems has allowed dental students and professionals to experience realistic tactile sensations during virtual training sessions. This technology simulates the feel of various dental procedures, such as drilling or applying pressure, which is crucial for developing the hand-eye coordination and fine-scale motor skills needed in dental surgery.[18]

Augmented reality has also made significant inroads in dental practice through real-time data visualization. AR systems can project digital images and information directly onto the patient's anatomical structures, providing dentists with unparalleled accuracy during procedures.[20] For instance, AR navigation systems enhance the placement of dental implants by showing precise locations and angles directly in the surgeon's field of view, reducing the risk of errors and improving patient outcomes.[12]

An excellent example of these advancements can be found in the work presented by Wan et al.,[10] which showed how immersive VR environments can significantly improve learning outcomes in orthognathic surgery education. This is achieved by providing detailed, realistic simulations of surgical procedures. Furthermore, the development of a new cognitive simulator for orbital floor reconstruction, as discussed by Khelemsky et al.,[21] highlights the role of VR in improving surgical planning and execution through complex anatomical and procedural visualizations.

These advancements underscore a pivotal shift in dental education and surgery, moving away from traditional learning paradigms and towards an integrated, technology-enhanced approach. As AR and VR technologies evolve; they are set to redefine dental training and practice standards, making complex surgical procedures more accessible and accurate.

Application in dental surgery education

Fig. 2 below illustrates the multifaceted benefits of AR and VR in dental surgery education and practice, categorized

Table 1 Comparative analysis of selected studies.

Authors (Publish year)	Area	Population	Intervention	Outcome	Results	Potentials
Casap et al.[15] (2011)	VR in dental education (implantation)	Forty final-year undergraduate dentistry students without previous experience in dental implantation surgery	Comparison of traditional freehand protocols with a virtual reality navigation system for training in dental implantation.	Accuracy of implant placement and procedural efficiency	1. Improved accuracy in marking implant sites with the navigation system 2. Similar performance in basic drilling tasks across both methods 3. Faster completion times with traditional methods 4. Mixed results in self-assessment accuracy	The study suggests that while the navigation system improves accuracy in specific tasks, the overall added value of training with virtual reality navigation is minimal. It points out the necessity for a balanced approach combining traditional and innovative methods to maximize training effectiveness and efficiency.
Suebnukarn et al.[9] (2012)	VR in endodontic microsurgery training	Ten junior endodontic postgraduate trainees with limited surgical experience	1. Utilization of a VR simulation integrated with cone-beam computed tomography (CBCT) data for pre-surgical training in endodontic microsurgery. 2. Participants practiced surgical procedures using a VR simulator equipped with micro-instruments and volumetric data from a CBCT scan of a cadaveric porcine mandible.	1. Assessment of surgical competency through an endodontic competency rating scale. 2. Comparison of performance scores between surgeries performed with and without VR pre-surgical practice.	1. Significant improvement in surgical scores for procedures practiced using VR compared to those without VR. 2. Median scores for osteotomy on a molar tooth were higher with VR practice (median 4.5) compared to without VR (median 3), showing statistically significant differences ($P = 0.042$).	1. The study underscores the potential of integrating VR and CBCT for enhancing surgical precision and training efficiency in dental education. 2. VR pre-surgical practice could become a standard component of training, potentially increasing the safety and efficacy of endodontic surgeries.
Pulijala et al.[16] (2018)	VR in surgical training (orthognathic surgery)	Novice surgical residents from seven dental schools	Use of immersive virtual reality (iVR) via Oculus Rift and Leap Motion devices for surgical training, compared to traditional training methods using PowerPoint presentations.	Self-confidence levels and cognitive skills of the surgical residents.	Participants in the iVR group reported significantly higher self-confidence levels post-intervention compared to those in the control group. This suggests that iVR could be more effective in enhancing	The study underscores the potential of VR technologies in improving surgical training by providing a realistic, immersive environment that enhances learning and self-confidence,

					self-confidence among novice surgeons.	potentially leading to better preparedness for actual surgical procedures.
Sytek et al.[17] (2021)	VR in orthodontics and orthognathic surgery	20 graduate-level orthodontic residents.	Simulation methods: 1. 2D digital simulation: Traditional digital methods using cephalometric tracings. 2. 3D digital simulation: More advanced digital methods allowing manipulation of CBCT segmented skeletal structures. 3. Virtual reality (VR) simulation: Immersive simulation using a head-mounted device (Oculus Rift) to manipulate a 3D virtual patient model.	The study assessed residents' ability to diagnose, plan treatment, and their attitudes towards each simulation method. Specific outcomes included the number of surgical movements planned, the time taken to complete tasks, and the types of questions asked during training and testing.	1. Increased complexity with higher fidelity tools: Residents prescribed more surgical movements using 3D and VR tools compared to 2D methods. 2. Time and interaction: VR took the most time to complete tasks and required more interactions due to the novelty and immersive nature of the technology. 3. Performance: There were no significant differences in overall performance across the methods, but 3D and VR methods were preferred for their enhanced visualization and manipulation capabilities. 4. Attitudes: Qualitative feedback indicated positive attitudes toward VR for its immersive and interactive experience, although there was a learning curve.	The study suggests that VR and high-fidelity simulation methods have the potential to enhance the education of orthodontic residents by providing more comprehensive and interactive tools for treatment planning. Despite the learning curve, residents showed readiness to adopt VR tools, indicating a potential shift towards more immersive and technologically advanced methods in dental education.
Vincent et al.[18] (2022)	VR in dental implantation training	88 first-year dental students	The study utilized the Virteasy® haptic simulator, which includes a 3D screen, plastic handpiece, and force feedback arm to	The study focused on various parameters including mesio-distal and bucco-lingual positioning, angulation, drilling	1. Improvement with virtual aids: The presence of virtual aids significantly improved the accuracy and safety of the	The study suggests that integrating haptic simulators with virtual aids in dental education could enhance the acquisition of clinical

(*continued on next page*)

Table 1 (*continued*)

Authors (Publish year)	Area	Population	Intervention	Outcome	Results	Potentials
			simulate tactile sensations during dental procedures. The intervention involved training students to prepare an implant site for a left first mandibular molar using this simulator. Group 1 Received training with virtual assistance (including aids like positioning, angulation, and depth indicators) in all their sessions. Group 2 Received initial training with assistance, but subsequent sessions were conducted without virtual assistance.	depth, and the occurrence of cortical bone perforation. The primary outcome was to assess whether virtual aids improved the students' performance in implant site preparation.	procedures, as evidenced by fewer cortical bone perforations and better overall performance metrics in Group 1 compared to Group 2. 2. Learning curve: Repeated practice, especially with virtual aids, helped students in Group 1 to acquire skills more effectively, as seen in the gradual improvement in performance over multiple sessions. 3. Time efficiency: Despite better outcomes with aids, the exercises took longer initially. However, with repetition, students were able to perform procedures more quickly.	skills, making it possible to train students more effectively and safely before they perform procedures on real patients. The findings highlight the importance of incorporating realistic virtual aids in the design of dental simulators. Continuous advancements in VR and AR technology can potentially lead to more immersive and effective training tools in dental education and practice.
Wan et al.[10] (2024)	VR in surgical education (orthognathic surgery)	Fifth year medical students	The intervention group used an immersive virtual reality (iVR) surgical training system, while the control group used traditional learning methods with technical manuals and operation videos.	The effectiveness of the iVR system was measured by scores in the assessment mode, time to complete the procedure, and accuracy in surgical tasks like instrument selection and angular adjustments.	1. Higher assessment scores and greater accuracy in the VR group. 2. Faster completion of procedures by VR-trained students.	The study highlights the potential of iVR as an effective tool for enhancing complex surgical training, suggesting its utility in replacing or supplementing traditional methods.

Yari et al.[13] (2024)	AR in dental education (local anesthesia)	Fourth year dental students	Use of an augmented reality book for local anesthesia training versus traditional textbook methods.	Proficiency in administering local anesthesia, including theoretical knowledge and practical skills.	1. Students using the AR book showed significantly higher levels of concentration and practical skills. 2. Time required for administering anesthesia was less in the AR group. 3. No significant difference in the success rate of local anesthesia administration between the two groups.	The study suggests AR books can enhance the learning experience by increasing student engagement and improving practical skills, making them a valuable tool for dental education.

Abbreviations: VR, virtual reality; AR, augmented reality.

into collaborative learning, personalized learning, and patient education.

AR and VR are transforming dental education by enhancing both personalized and collaborative learning experiences. These technologies offer a risk-free training environment, allowing students to practice complex procedures without the fear of harming patients. This approach reduces costs by minimizing the need for physical models and materials while supporting a dynamic learning process through real-time feedback. The immediate correction of mistakes and the refinement of techniques significantly enhance learning outcomes, build psychological preparedness, and boost student confidence by exposing them to realistic clinical scenarios. These immersive tools greatly improve information retention and skill acquisition.

Furthermore, AR and VR technologies support collaborative learning by fostering teamwork, knowledge sharing, and decision-making among dental professionals. They also enhance personalized learning by providing cost-effective training environments that offer real-time feedback and diverse scenarios, making these technologies highly accessible and effective. This, in turn, supports the development of federated learning models in dental practice.[22] In the domain of patient education, AR and VR offer visual explanations that aid in patient understanding and participation in shared decision-making.[23] Additionally, these technologies enhance team resource management, improve clinical outcomes, and increase safety in dental surgery, ultimately contributing to resilience in healthcare.[24,25]

Preclinical training

AR and VR are increasingly recognized for their transformative potential in preclinical dental education. These technologies allow students to engage in highly realistic simulations of dental procedures, thereby bridging the gap between theoretical knowledge and clinical practice. For instance, a scoping review by McAlpin et al.[11] highlights how VR has been utilized to simulate various dental procedures, providing students with a hands-on experience that is otherwise hard to replicate in a traditional classroom setting. Furthermore, recent studies,[6,26–30] have demonstrated that virtual reality haptic simulators significantly enhance the learning experience in pre-clinical restorative dentistry. The study reveals that students appreciate the hands-on practice these simulators provide. They feel that such immersive tools considerably improve their manual dexterity and procedural understanding. This feedback underscores the value of VR technologies in bridging the gap between theoretical knowledge and practical skills, making them an indispensable part of modern dental training curricula.

Skill acquisition and enhancement

Integrating AR and VR in dental education significantly enhances the acquisition and refinement of surgical skills. According to Serrano et al.,[30] VR and haptic technologies have improved the psychomotor skills required for complex dental surgeries. These technologies allow repeated practice in a controlled environment, reducing the learning curve and preparing students for real-life surgical tasks. Additionally, using AR to navigate complex dental

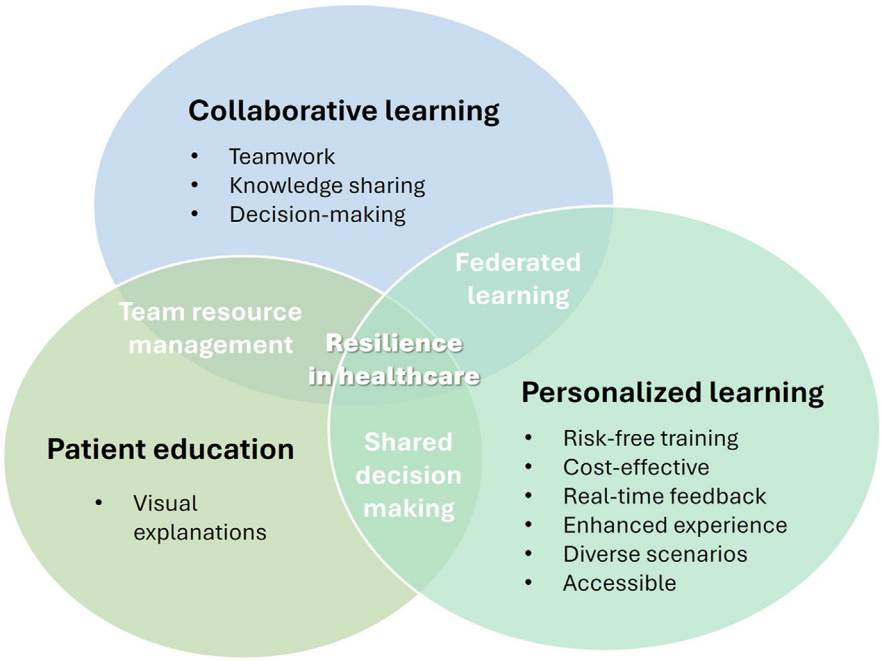

Figure 2 The multifaceted benefits of augmented reality (AR) and virtual reality (VR) in dental surgery education and practice, categorized into collaborative learning, personalized learning, and patient education.

procedures provides real-time feedback and guidance, enhancing both the learning process and the procedures' precision.

Interactive learning

The immersive nature of AR and VR creates an engaging and interactive learning environment that significantly improves student engagement and knowledge retention. These technologies offer a risk-free platform for students to practice complex procedures, allowing them to learn from their mistakes without fearing harming actual patients. The real-time feedback provided by AR and VR facilitates immediate correction of errors and refinement of techniques, which enhances learning outcomes and builds psychological preparedness. By exposing students to realistic clinical scenarios, AR and VR reduce anxiety and foster a deeper understanding of dental anatomy and procedures. Additionally, they enhance collaborative learning by enabling teamwork in virtual environments. Research, like the study conducted by Boer et al.,[27] indicates that dental students who use VR simulations for training perform better in practical tests and gain a deeper understanding of the complexities of dental procedures. This method enhances the effectiveness, enjoyment, and accessibility of learning, better-preparing students for real-world clinical practice.

Application in clinical dental practice

Surgical planning and navigation

Integrating AR and VR into surgical planning and navigation marks a significant advancement in dental clinical practices. These technologies enable dentists to perform complex procedures with greater confidence and precision. For example, VR's role in preoperative planning allows for a comprehensive visualization of the surgical site, helping clinicians meticulously plans each step before the actual procedure, significantly mitigating risks associated with invasive procedures.[17]

Patient education

AR and VR technologies significantly enhance how dental professionals communicate procedural information to patients, making complex dental surgeries understandable. Through immersive visuals, patients can better understand their anatomical issues and the surgical interventions planned for them. This is crucial for informed consent and for alleviating patient anxiety pre-surgery. Huang et al. highlight how AR applications in patient consultations improve the clarity of communication, leading to enhanced patient satisfaction and preparedness for upcoming dental procedures.[31]

Enhancing precision in surgical procedures

In the realm of improving precision in surgical procedures, AR has been particularly transformative. The study by Mladenovic et al.[28] demonstrates how AR can effectively guide local anesthesia administration with greater precision. The technology allows clinicians to visualize the exact location where the anesthesia should be administered, enhancing the procedure's efficacy and minimizing patient discomfort. Additionally, real-time AR navigation systems are used during dental implant surgeries to guide the exact placement of implants, which requires high precision to avoid critical anatomical structures and ensure optimal outcomes.[12]

These examples underscore the pivotal role of AR and VR technologies in modernizing dental clinical practices. They make complex procedures safer and more efficient and

improve the educational and communicative aspects of dental care. As these technologies evolve, their adoption in dental practices is expected to increase, further revolutionizing the field and setting new standards of excellence in dental care.

Augmented reality vs. virtual reality in dental surgery training

AR excels at enhancing precision during surgical procedures through real-time overlays that guide surgical actions.[9] This technology enables surgeons to visualize critical structures beneath the surface, aiding in precise incisions and implant placements.[14,15] Conversely, VR's strength lies in its ability to provide a fully immersive training environment where no real patient is at risk, making it ideal for extensive practice and mastery of complex surgical techniques.[9—11,15,16,21]

While VR currently lacks tactile feedback for a complete surgical feel, advances in haptic feedback enhance this aspect, making VR a more effective tool for training in delicate procedures.[26,27,29,30,32,33]

Augmented reality/virtual reality vs. traditional methods in dental surgery training

Both AR and VR represent significant improvements over traditional dental surgical training methods, particularly regarding patient safety. While invaluable for its real-life experience, traditional training often exposes patients to potential risks during novice training sessions. In contrast, AR and VR eliminate these risks by allowing trainees to practice and refine their skills in a safe, controlled environment without compromising patient well-being.[10,21,22]

Furthermore, the repetitive practice possible with VR simulations is crucial for skill acquisition and confidence building, which are sometimes limited in traditional settings due to the availability of suitable cases or ethical concerns about repeated interventions on patients. By integrating simulation technologies into the training curriculum, dental education can significantly reduce the risk to patients while enhancing the learning process for students.[9,11,13—15]

These technologies also address the logistical and financial constraints of traditional methods. While conventional training requires significant resources for setup and maintenance, virtual simulations are more scalable and can be updated easily to incorporate the latest surgical techniques and medical knowledge.

In summary, while AR and VR technologies enhance training efficiency and safety, they should complement rather than replace traditional hands-on training. The ideal educational approach in dental surgery would blend advanced simulations with practical experiences, ensuring that all training aspects—technical skills, clinical judgment, and patient interaction—are thoroughly addressed.

Discussion

As technology continues to advance, augmented reality (AR) and virtual reality (VR) are finding applications far beyond gaming and entertainment, making significant inroads into fields like dental education and clinical practice. This shift marks a transformative moment in dental education, signaling a new direction for training methodologies. Currently, dental simulators such as Simodont primarily focus on basic procedures like tooth preparation and restorative tasks.[34] However, developing more comprehensive models that encompass a wider range of dental surgical procedures would greatly enhance training outcomes. Expanding these simulations to include more complex surgeries, such as implant placements and periodontal treatments, would offer dental students a more well-rounded and practical learning experience.

While AR and VR provide highly realistic simulations that enhance learning and surgical skill development, their widespread adoption still faces several hurdles. Technological limitations impede the broader use of AR and VR in dental surgery. For instance, VR devices must offer high-resolution graphics and minimal latency to effectively simulate surgical procedures. AR, on the other hand, must seamlessly integrate digital information with the real-world environment, ensuring precise alignment without causing disorientation.[35] The high costs associated with implementing these technologies also pose a significant barrier, particularly for smaller dental practices.[36] Adoption is also hindered by educational challenges. Mastering AR and VR requires a steep learning curve, and training dental professionals to become proficient with these sophisticated tools is time-intensive, requiring ongoing education.[37] Resistance from more traditional sectors within dentistry can further slow the integration of AR and VR into both educational programs and clinical practice.[38] Moreover, the adoption of these technologies raises ethical concerns. Relying on AR and VR prompts questions about their reliability and the potential for technical malfunctions, which could lead to procedural errors. Data privacy and security are also critical issues, especially given the sensitive nature of patient information used in these systems.[39,40] Importantly, there is a moral obligation to ensure that AR and VR do not diminish the quality of patient care. While these technologies can significantly enhance training and procedural planning, hands-on experience remains essential for dental professionals to hone their skills effectively.[41] In addition, AR and VR technologies face limitations in replicating the full scope of real patient interactions in clinical settings. For example, they often cannot simulate patients' emotional or physical responses, such as anxiety or fear, which play a crucial role in shaping treatment approaches and outcomes.[42,43]

To fully leverage the potential of AR and VR, future research must address these challenges and explore broader clinical applications. Innovations like enhanced sensory feedback and the integration of artificial intelligence (AI) could further elevate AR and VR into powerful tools for personalized education. AI could dynamically adjust training scenarios and provide feedback tailored to the learner's pace and performance, thereby improving the overall educational experience.[44] AI can also reduce the workload for educators by automatically adjusting task difficulty in real-time and offering instant feedback, making training sessions more efficient.[45]

As these technologies continue to evolve, their applications in dental surgery could expand beyond education and procedural planning. For instance, AR might provide real-time diagnostic assistance during surgeries, overlaying

critical information—such as blood vessel or nerve locations—directly onto the surgical field.[46] VR could also play a role in patient rehabilitation by helping patients visualize their recovery progress, leading to improved engagement and satisfaction.[47] AI's role in simulating patient responses could offer dental professionals deeper insights into potential treatment outcomes. Extensive research is needed to fully unlock the potential of AR and VR in dental surgery. This includes comparative studies on the long-term effectiveness of these technologies compared to traditional methods, as well as exploring how they can be seamlessly integrated into everyday clinical practice. Collaboration between technology developers, dental professionals, and educational institutions will be vital to ensuring that these technologies are both practical and advanced enough to meet real-world needs.[48] Additionally, ethical and privacy concerns must be carefully addressed, and sound guidelines and regulations need to be established for their use in sensitive medical environments.[49]

In conclusion, AR and VR are rapidly revolutionizing dental surgery education and clinical practice. These technologies are not only reshaping the way we train dental students but are also enhancing the quality and efficiency of clinical treatments. As they continue to develop and gain broader acceptance, dental professionals will be better prepared to face clinical challenges, ultimately leading to improved patient care and professional expertise.

Declaration of competing interest

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

Acknowledgments

This study was supported by the National Taiwan University Hospital & Far Eastern Memorial Hospital joint research project; [grant number:108-FTN21, 109-FTN18] and Ministry of Health and Welfare [grant number:PCA225]. The authors would like to thank the National Taiwan University Medical Library, especially the medical librarian Chen-Jung Huang, for her valuable help in the literature search.

References

1. Tseng WY, Tsai YL, Lai EHH, et al. The analysis and feedback from the performance of pre-clinical operation skills tests for clerkship in school of dentistry, National Taiwan University in 2022. *J Dent Sci* 2023;18:775—80.
2. Mansoory MS, Azizi SM, Mirhosseini F, Yousefi D, Moradpoor H. A study to investigate the effectiveness of the application of virtual reality technology in dental education. *BMC Med Educ* 2022;22:457.
3. Dzyuba N, Jandu J, Yates J, Kushnerev E. Virtual and augmented reality in dental education: the good, the bad and the better. *Eur J Dent Educ* 2022;00:1—19.
4. Soltanimehr E, Bahrampour E, Imani MM, Rahimi F, Almasi B, Moattari M. Effect of virtual versus traditional education on theoretical knowledge and reporting skills of dental students in radiographic interpretation of bony lesions of the jaw. *BMC Med Educ* 2019;19:233.
5. Hattori A, Tonami Ki, Tsuruta J, et al. Effect of the haptic 3D virtual reality dental training simulator on assessment of tooth preparation. *J Dent Sci* 2022;17:514—20.
6. de Boer IR, Lagerweij MD, de Vries MW, Wesselink PR, Vervoorn JM. The effect of force feedback in a virtual learning environment on the performance and satisfaction of dental students. *Simulat HealthcSimulat* 2017;12:83—90.
7. Dwisaptarini AP, Suebnukarn S, Rhienmora P, Haddawy P, Koontongkaew S. Effectiveness of the multilayered caries model and visuo-tactile virtual reality simulator for minimally invasive caries removal: a randomized controlled trial. *Operat Dent* 2018;43:110—8.
8. Murbay S, Chang JWW, Yeung S, Neelakantan P. Evaluation of the introduction of a dental virtual simulator on the performance of undergraduate dental students in the pre-clinical operative dentistry course. *Eur J Dent Educ* 2020;24:5—16.
9. Suebnukarn S, Rhienmora P, Haddawy P. The use of cone-beam computed tomography and virtual reality simulation for presurgical practice in endodontic microsurgery. *Int Endod J* 2012;45:627—32.
10. Wan T, Liu K, Li B, Wang X. Effectiveness of immersive virtual reality in orthognathic surgical education: a randomized controlled trial. *J Dent Educ* 2024;88:109—17.
11. McAlpin E, Levine M, Brenner C, et al. Evaluating the effectiveness of a virtual reality simulation for preclinical local anesthesia dental education. *Eur J Dent Educ* 2022;00:1—12.
12. Kivovics M, Takács A, Pénzes D, Németh O, Mijiritsky E. Accuracy of dental implant placement using augmented reality-based navigation, static computer assisted implant surgery, and the free-hand method: an in vitro study. *J Dent* 2022;119:104070.
13. Yari A, Fasih P, Goodarzi A, Nouralishahi A, Nikeghbal D. The effect of augmented reality book on the proficiency of local anesthesia administration of the inferior alveolar nerve. *J Dent Educ* 2024;88:1000—8.
14. Zhou Y, Chen W, Zhao X, et al. Application evaluation of virtual reality technology in dental implant training: a new dental implant training system: a CONSORT-compliant trial. *Medicine (Baltim)* 2021;100:e27355.
15. Casap N, Nadel S, Tarazi E, Weiss EI. Evaluation of a navigation system for dental implantation as a tool to train novice dental practitioners. *J Oral Maxillofac Surg* 2011;69:2548—56.
16. Pulijala Y, Ma M, Pears M, Peebles D, Ayoub A. Effectiveness of immersive virtual reality in surgical training-A randomized control trial. *J Oral Maxillofac Surg* 2018;76:1065—72.
17. Sytek L, Inglehart MR, Ramaswamy V, Aronovich S, Edwards S, Kim-Berman H. Comparisons of orthodontic residents' performance and attitudes using 2D, 3D, and virtual reality surgical simulation methods. *J Dent Educ* 2021;85:1415—26.
18. Vincent M, Giess R, Balthazard R, Tran N, Mortier É, Joseph D. Virtual aids and students' performance with haptic simulation in implantology. *J Dent Educ* 2022;86:1015—22.
19. Sutherland IE. The ultimate display. In: *Proceedings from the proceedings of the IFIP congress*. Abstract, 1965.
20. Zhu M, Liu F, Chai G, et al. A novel augmented reality system for displaying inferior alveolar nerve bundles in maxillofacial surgery. *Sci Rep* 2017;7:42365.
21. Khelemsky R, Hill B, Buchbinder D. Validation of a novel cognitive simulator for orbital floor reconstruction. *J Oral Maxillofac Surg* 2017;75:775—85.
22. Rischke R, Schneider L, Müller K, Samek W, Schwendicke F, Krois J. Federated learning in dentistry: chances and challenges. *J Dent Res* 2022;101:1269—73.
23. Jayakumar P, Moore MG, Furlough KA, et al. Comparison of an artificial intelligence—enabled patient decision aid vs educational material on decision quality, shared decision-making, patient experience, and functional outcomes in adults with

knee osteoarthritis: a randomized clinical trial. *JAMA Netw Open* 2021;4:e2037107-e07.
24. Haraldseid-Driftland C, Billett S, Guise V, et al. The role of collaborative learning in resilience in healthcare—a thematic qualitative meta-synthesis of resilience narratives. *BMC Health Serv Res* 2022;22:1091.
25. Hsu YC, Jerng JS, Chang CW, et al. Integrating team resource management program into staff training improves staff's perception and patient safety in organ procurement and transplantation: the experience in a university-affiliated medical center in Taiwan. *BMC Surg* 2014;14:1—8.
26. de Boer IR, Lagerweij MD, Wesselink PR, Vervoorn JM. The effect of variations in force feedback in a virtual reality environment on the performance and satisfaction of dental students. *Simulat Healthc J Soc Med Simulat* 2019;14:169—74.
27. de Boer IR, Wesselink PR, Vervoorn JM. Student performance and appreciation using 3D vs. 2D vision in a virtual learning environment. *Eur J Dent Educ* 2016;20:142—7.
28. Mladenovic R, Dakovic D, Pereira L, Matvijenko V, Mladenovic K. Effect of augmented reality simulation on administration of local anaesthesia in paediatric patients. *Eur J Dent Educ* 2020;24:507—12.
29. Philip N, Ali K, Duggal M, Daas H, Nazzal H. Effectiveness and student perceptions of haptic virtual reality simulation training as an instructional tool in pre-clinical paediatric dentistry: a pilot pedagogical study. *Int J Environ Res Publ Health* 2023;20:4226.
30. Serrano CM, Bakker DR, Zamani M, et al. Virtual reality and haptics in dental education: implementation progress and lessons learned after a decade. *Eur J Dent Educ* 2023;27:833—40.
31. Huang TK, Yang CH, Hsieh YH, Wang JC, Hung CC. Augmented reality (AR) and virtual reality (VR) applied in dentistry. *Kaohsiung J Med Sci* 2018;34:243—8.
32. Al-Saud LM, Mushtaq F, Allsop MJ, et al. Feedback and motor skill acquisition using a haptic dental simulator. *Eur J Dent Educ* 2017;21:240—7.
33. Daud A, Matoug-Elwerfelli M, Daas H, Zahra D, Ali K. Enhancing learning experiences in pre-clinical restorative dentistry: the impact of virtual reality haptic simulators. *BMC Med Educ* 2023;23:948.
34. Leung ALS, Yeung C, Chu S, Wong AWY, Yu OY, Chu C-H. Use of computer simulation in dental training with special reference to simodont. *Dent J* 2021;9:125.
35. Li Y, Ye H, Ye F, et al. The current situation and future prospects of simulators in dental education. *J Med Internet Res* 2021;23:e23635.
36. Baniasadi T, Ayyoubzadeh SM, Mohammadzadeh N. Challenges and practical considerations in applying virtual reality in medical education and treatment. *Oman Med J* 2020;35:e125.
37. Mohamad Zainal NH, Wahid HH, Mahmud M, et al. The applications of augmented reality (AR) and virtual reality (VR) in teaching medical and dentistry students: a review on advantages and disadvantages. *Malays J Med Health Sci* 2023;19:65—78.
38. Kolade Adeyele T. *Revolutionizing health education: the dynamic shift of e-learning platforms*. IntechOpen, 2024.
39. Singh B, Vig K, Kaunert C, Modernizing Healthcare. Application of augmented reality and virtual reality in clinical practice and medical education. *Mod Technol Healthc Med Educ* 2024:1—21.
40. Steele P, Burleigh C, Kroposki M, Magabo M, Bailey L. Ethical considerations in designing virtual and augmented reality products-Virtual and augmented reality design with students in mind: designers' perceptions. *J Educ Technol Syst* 2020;49:219—38.
41. Sombilon EV, Rahmanov SS, Jachecki K, Rahmanov Z, Peisachovich E. Ethical considerations when designing and implementing immersive realities in nursing education. *Cureus* 2024;16:e64333.
42. Moussa R, Alghazaly A, Althagafi N, Eshky R, Borzangy S. Effectiveness of virtual reality and interactive simulators on dental education outcomes: systematic review. *Eur J Dent Educ* 2022;16:14—31.
43. Serrano CM, Wesselink PR, Vervoorn JM. First experiences with patient-centered training in virtual reality. *J Dent Educ* 2020;84:607—14.
44. Mladenovic R. *AI-powered and "augmented" dentistry: applications, implications and limitations*. Augment Real Artif Intell, 2023:211—26.
45. Bayrakdar IS, Orhan K, Jagtap R. Artificial intelligence in dental education. *Artif Intell Dent* 2024:223—34.
46. Ma L, Huang T, Wang J, Liao H. Visualization, registration and tracking techniques for augmented reality guided surgery: a review. *Phys Med Biol* 2023;68:04TR02.
47. Adeghe EP, Okolo CA, Ojeyinka OT. A review of the integration of virtual reality in healthcare: implications for patient education and treatment outcomes. *Int J Sci Technol Res Arch* 2024;6:79—88.
48. Herur-Raman A, Almeida ND, Greenleaf W, Williams D, Karshenas A, Sherman JH. Next-generation simulation-integrating extended reality technology into medical education. *Front Virtual Real* 2021;2:693399.
49. Ursin F, Timmermann C, Benzinger L, Salloch S, Tietze FA. Intraoperative application of mixed and augmented reality for digital surgery: a systematic review of ethical issues. *Front Surg* 2024;11:1287218.