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Scoping Review Mixed Reality

The role of extended reality in oral and maxillofacial surgery: a scoping review

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F. Nonis, A. Novaresio, S. Moos, E. Vezzetti: The role of extended reality in oral and maxillofacial surgery: a scoping review. Int. J. Oral Maxillofac. Surg. 2026; 55: 599–614. © 2025 International Association of Oral and Maxillofacial Surgeons. Published by Elsevier Inc. All rights are reserved, including those for text and data mining, AI training, and similar technologies.

Abstract. Extended reality (XR) technologies, including augmented reality (AR), mixed reality (MR), and virtual reality (VR), are increasingly transforming surgical disciplines. Oral and maxillofacial surgery, given the anatomical complexity and precision required, is particularly suited to benefit from these innovations. The aim of this scoping review was to map the clinical applications of XR in oral and maxillofacial surgery and compare the most commonly used commercial headsets. A comprehensive literature search was performed across the PubMed, Scopus, and Web of Science databases, covering studies published between January 2018 and June 2025. The PRISMA-ScR guidelines were followed. Overall, 759 records were identified in the database and subsequent citation search, of which 90 met the predefined inclusion criteria. The studies were categorized based on the type of application: training, preoperative planning, virtual surgical planning (VSP), and intraoperative guidance. The analysis revealed that AR and MR are predominantly employed in intraoperative procedures, enhancing surgical navigation and precision. In contrast, fully immersive VR is primarily employed in training, preoperative simulation, and VSP, while its adoption in the postoperative phase remains a promising area for future exploration. XR technologies hold significant potential in oral and maxillofacial surgery and are evolving rapidly and diversifying in their applications. Further research and regulatory validation are needed to support clinical integration and evaluate long-term outcomes.

Keywords: Augmented reality; Mixed reality; Virtual reality; Oral surgery; Maxillofacial surgery.

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Extended reality (XR) is an umbrella term encompassing virtual reality (VR), augmented reality (AR), and mixed reality (MR)¹. These technologies provide varying levels of immersion and interaction, blending the physical and digital

worlds to create novel, interactive experiences. While the classification of VR, AR, and MR into distinct categories is widely accepted, their boundaries can sometimes blur due to overlapping functionalities and applications².

Similarly to multimedia, which integrates text, images, audio, video, and interactive content to dynamically convey information, XR merges digital and real-world elements to create an interactive and immersive spectrum of

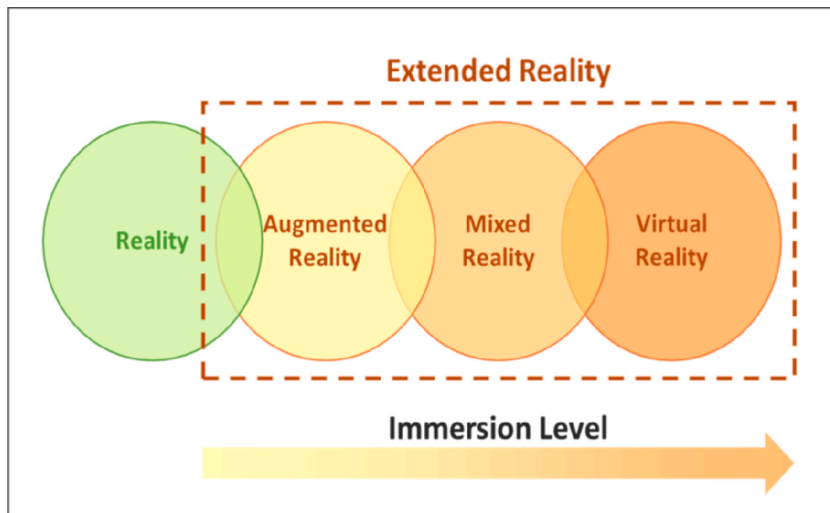


Fig. 1. Visual representation of virtual reality (VR), augmented reality (AR), and mixed reality (MR) positioned along the reality to virtuality continuum, illustrating their respective levels of immersion.

experiences (Fig. 1). Each XR technology serves a unique yet complementary role, enhancing perception, understanding, and engagement in diverse fields, from entertainment and education to industrial applications and healthcare. In further detail, VR is a fully immersive experience in which the user is placed in a completely virtual environment. VR enables total immersion, allowing users to interact within simulated settings for training, education, and procedural rehearsal. With AR, digital content overlaps the real world, enhancing the user's perception of reality. AR enhances real-world experiences without fully replacing them, making it ideal for guidance, visualization, and real-time decision-making. MR combines elements of both VR and AR, integrating virtual objects into the real world in a way that they interact with each other and the real environment. MR allows for more advanced

manipulation and engagement, bridging the gap between digital enhancement and full immersion.

XR technologies are rapidly transforming various industries, including gaming, entertainment, education, manufacturing, and healthcare^{3,4}. Among these, medicine has increasingly adopted XR technologies to improve surgical precision, visualization, and outcomes⁵. Among the surgical disciplines, oral and maxillofacial surgery (OMS) is a highly complex surgical specialty that requires meticulous planning and execution due to the intricate anatomical structures involved. The integration of XR technologies provides novel solutions across all phases of the surgical process, from preoperative to postoperative, for the planning of surgeries, teaching patients, educating residents, and assisting in performing surgeries^{5,6}. However, the incorporation of digital tools in OMS is

not entirely new. Computer-aided design and manufacturing (CAD/CAM) technologies have already revolutionized preoperative planning, prosthetic fabrication, and custom implant design, enhancing precision and reducing surgical times^{7,8}. These advancements have paved the way for the seamless integration of XR technologies, which further enhance spatial visualization, real-time guidance, and intraoperative navigation^{5,6}.

Despite the growing interest in XR applications in OMS, a comprehensive understanding of how, in which phases of the surgical process, and for what purpose these technologies have been adopted remains limited. The aim of this literature review was to provide an updated overview and analysis of the current adoption of AR, MR, and VR in OMS, categorizing their applications across the different surgical phases. The benefits of conducting this literature review on XR applications in OMS include highlighting the advantages of XR in improving procedural accuracy, training, and patient outcomes and understanding the real-world applications and effectiveness of XR. It is anticipated that this review will be a valuable resource for academics, clinicians, and technology developers, guiding future innovation and adoption in surgical practice.

Materials and methods

This review was performed in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses extension for Scoping Reviews (PRISMA-ScR) guidelines⁹. This scoping review was conducted without prior registration of a review protocol.

A systematic search, complemented by a manual search, was performed. First, the Scopus and Web of Science databases were searched using the following parameters, taking into account plural forms and truncation: ("Virtual Reality") OR ("Mixed Reality") OR ("Augmented Reality") AND (("Maxill*") OR ("Oral Surgery")). The search was completed in the PubMed database using the same parameters and including the following medical subject heading (MeSH) terms for a rigorous review: "Surgery, Oral", "Oral Surgery Procedures", "Virtual Reality", and "Augmented Reality". Before proceeding to the screening,

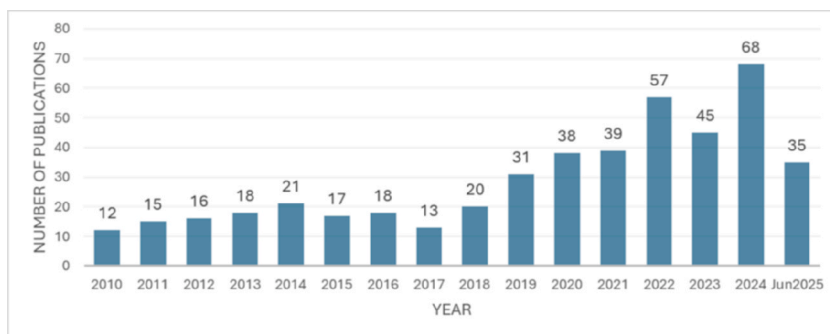


Fig. 2. Frequency distribution histogram showing the trend in publications on extended reality in maxillofacial surgery over the years, in the Scopus database. A change in trend can be observed, starting from 2018.

literature reviews, book chapters, theses, and articles not written in English were excluded, resulting in 753 articles published in the last 7.5 years, between January 2018 and June 2025. This timeframe was selected to capture the most recent developments in the field and because a marked increase in publications has been observed since 2018, indicating a growing research interest. These articles were then evaluated by title to identify and exclude duplicates. Fig. 2 shows the trend in publications on XR in OMS over the years based on the Scopus results.

During the screening stage, the title and abstract of each study were analysed to discard those that did not meet the inclusion criteria. Specifically, studies were included if they presented original research describing the use, development, or evaluation of AR, MR, or VR applications in OMS. Additional exclusion criteria included studies without sufficient methodological detail, papers focused solely on general dentistry or other medical specialties, and publications not accessible in full text. Fig. 3 describes the selection process according to the PRISMA guidelines.

All articles meeting the inclusion criteria were read carefully with respect to the following research questions: (1) What are the main applications of XR technologies in oral and maxillofacial

surgery? (2) In what phase of the surgical process are VR, AR, and MR applied?

Results

A total of 90 relevant papers were identified in the selection process. [Supplementary material Table S1](#) lists the studies by year of publication and first author, and provides a description of each study, the display used to render XR, the corresponding XR technology, the phase of its application, and the source database^{10–99}. The taxonomic framework mapped by Al Hamad et al.² and shown in Fig. 4 was followed in this work, considering both the method of display, i.e. full display using a head-mounted display (HMD) or partial display using a see-through screen, and the reality class, i.e. VR, AR, or MR.

As shown in Table 1, 41.9% of the applications in the studies fell into the AR class, with 29.0% being full display via an HMD and 12.9% being partial display via a transparent screen. The other 58.1% of applications involved MR (32.3%) and VR (25.8%), the vast majority with the full display method. This subdivision into full and partial display methods is reflected in the distribution of XR devices used, which are listed in Table 2. Several different

commercial HMD devices have been applied for maxillofacial surgery applications, plus some developed internally for research purposes (e.g., VOSTARS^{19,32}).

HoloLens 1 and 2 were the most used HMD in the included studies (46.2% of applications), due to their technical characteristics, which make them suitable for OMS. HoloLens is a MR headset developed and manufactured by Microsoft Corp.; the first HoloLens headset was discontinued in 2019 in favour of HoloLens 2, which offers significant improvements over its predecessor, including a larger field of view, better resolution, and more advanced hand-tracking capabilities. It is worth noting that in October 2024, Microsoft announced the discontinuation of HoloLens 2, with official support scheduled to end in 2027, and no successor device has yet been announced. This development may influence the future availability and adoption of MR technologies in OMS. The second most used devices were Oculus Rift (7.5%) and the Meta Quest headsets (2, Pro, and 3; 7.6%); these headsets were developed by Oculus (Meta) and differ slightly in terms of design and technical characteristics. Oculus Rift, a VR headset, was released in 2016 and then discontinued in favour of Meta Quest 2 (also a VR headset), which was released in 2020. Meta then

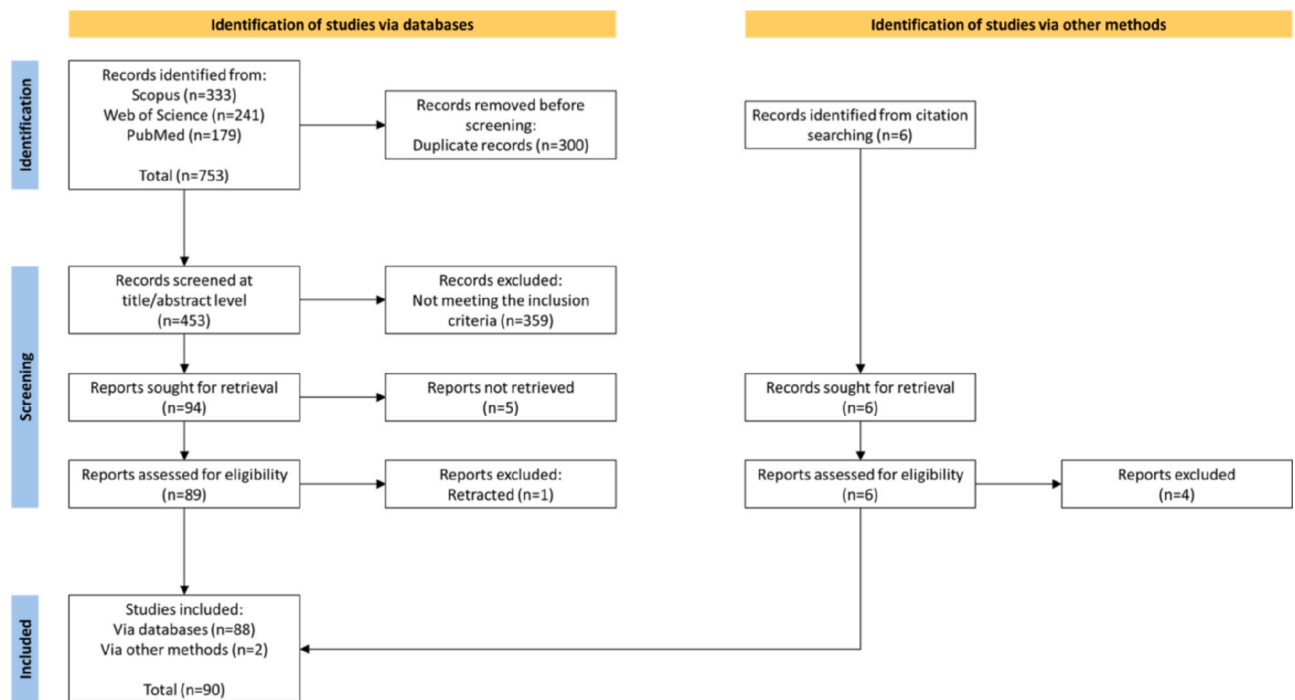


Fig. 3. PRISMA flowchart showing the search and selection process for this review.

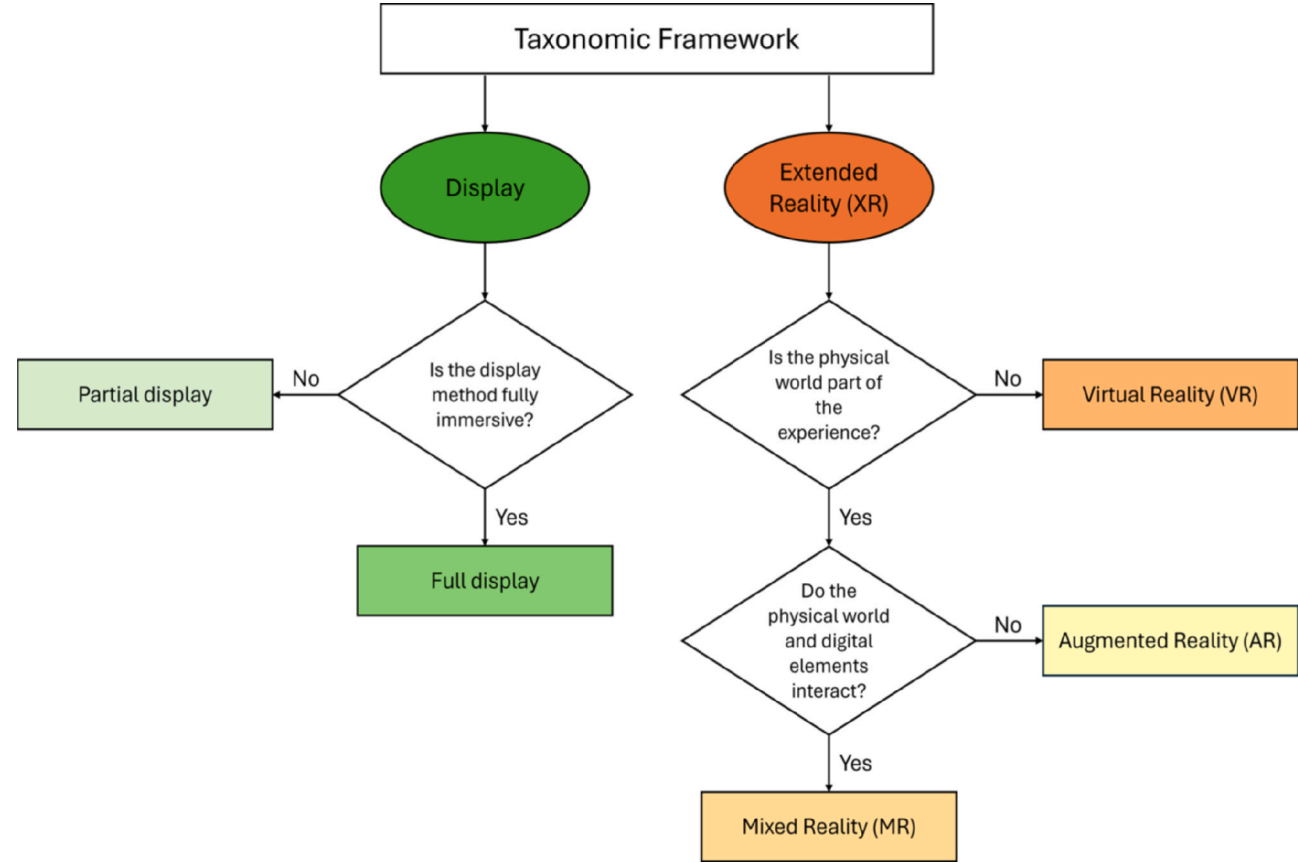


Fig. 4. Taxonomic framework adopted in the current literature review, distinguishing between partial and full display and between virtual, mixed, and augmented reality.

Table 1. Distribution of the extended reality (XR) technologies among the studies in the current review. Three studies presented two applications, for a total of 93 applications in 90 studies.

XR technology	Number of applications	Percentage
Partial display AR	12	12.9%
Partial display MR	1	1.1%
Full display AR	27	29.0%
Full display MR	29	31.2%
Full display VR	24	25.8%

AR, augmented reality; MR, mixed reality; VR, virtual reality.

launched Meta Quest Pro (2022) and Meta Quest 3 (2023), two MR viewers that include VR. Another VR headset to mention is HTC VIVE and its improved version, HTC VIVE Pro. Five studies reported the use of HTC devices for developing VR applications (5.4% of applications). Other types of display included AR smart glasses (9.7%) such as Moverio BT 200 and 300, HiAR G200, and Magic Leap 1 and 2.

Table 3 lists the commercial devices, their year of release, and the main technical characteristics. Most of the considered devices were released between 2014 and 2020. The most recent

ones include Meta Quest Pro (2022), Magic Leap 2 (2022), and Meta Quest 3 (2023). Although the Apple Vision Pro (2024) was not used in any of the studies analysed and is not currently classified as a medical device, its advanced hardware and software capabilities suggest strong potential for future applications in surgery and precision medicine.

AR devices like HoloLens and Magic Leap have generally been more expensive than VR ones, featuring advanced displays like holographic or photonic chip technology with built-in processors. The VR devices, including

Meta Quest 2, HTC VIVE, and Oculus Rift, have tended to be more affordable, with gradual improvements in display quality over time. The most recent models, such as the Meta Quest 3 (2064 × 2208 per eye), show a noticeable increase in resolution compared with earlier generations. Regarding the display type, VR headsets have often relied on OLED, offering deep blacks and vibrant colours, or LCD, which has been more common in newer devices for cost efficiency. AR headsets offer lower resolution displays but add complex spatial computing capabilities. Some VR headsets require external PCs for high-end performance, while others, like the Meta Quest 2, are standalone and self-powered by Qualcomm Snapdragon chipsets.

Table 4 shows the distribution of the various XR technologies according to the type of application related to OMS (phase of surgery). Based on this categorization, the 90 selected papers were grouped and analysed as follows: training, preoperative, virtual surgical planning (VSP), and intraoperative.

Table 2. Distribution of the devices adopted in the extended reality applications evaluated in the current study. Three studies presented two applications, for a total of 93 applications in 90 studies.

Type of display	Number of applications	Percentage
Full display		
Oculus Rift	7	7.5%
Meta Quest 2	4	4.3%
Meta Quest 3	1	1.1%
Meta Quest Pro	2	2.2%
HTC VIVE/Pro	5	5.4%
HoloLens	19	20.4%
HoloLens 2	24	25.8%
Moverio BT 200/300	3	3.2%
HiAR G200	2	2.2%
Magic Leap 1/2	4	4.3%
Pico G2	1	1.1%
VOSTARS	2	2.2%
Other ^a	6	6.5%
Partial display		
Other ^b	13	14.0%

^aIncluding semi-transparent helmet, haptic device, panoramic camera, glasses, smartphone, and self-developed applications.

^bIncluding tablet, smartphone, camera, projector, half-silvered mirror, and custom/self-developed applications.

Training

Training is a critical component of OMS, providing novice and experienced surgeons with the theoretical knowledge and practical skills to perform complex procedures with precision and safety. Traditional training methods, such as cadaver dissections and mentorship-based apprenticeships, remain essential but are increasingly being complemented by technology-based approaches. In recent years, the increasing spread and adoption of immersive and three-dimensional (3D) printing technologies have transformed the surgical training landscape, offering new possibilities and allowing young surgeons to acquire practical skills in a safe, controlled, and risk-free environment.

In the recent literature, both VR and AR/MR have been used to enhance the training phase. Pulijala et al.^{11,12}

Table 3. Comparison of commercial headsets based on year of release, price at launch, display type, resolution per eye or total, and computing power.

Device	Year released	Price at launch	Display type	Resolution	Computing power
HoloLens 1	2016	\$3000	Holographic lens	1268 × 720 per eye	Intel Atom CPU + HPU
HoloLens 2	2019	\$3500	Holographic lens	1440 × 936 per eye	Qualcomm Snapdragon 850 + 2nd Gen HPU
Oculus Rift	2016	\$599	OLED	1080 × 1200 per eye	PC-powered
Meta Quest 2	2020	\$299–399	LCD	1832 × 1920 per eye	Qualcomm Snapdragon XR2
Meta Quest Pro	2022	\$1499	LCD	1800 × 1920 per eye	Qualcomm Snapdragon XR2+ with 12 GB RAM
Meta Quest 3	2023	\$499–649	LCD	2064 × 2208 per eye	Qualcomm Snapdragon XR2 Gen 2 with 8 GB RAM
HTC VIVE	2016	\$799	OLED	1080 × 1200 per eye	PC-powered
HTC VIVE Pro	2018	\$799	AMOLED	1440 × 1600 per eye	PC-powered, dual front facing cameras
Magic Leap 1	2018	\$2295	Waveguide (Photonic Lightfield)	1280 × 960 per eye	Nvidia Parker SoC + Nvidia Pascal GPU
Magic Leap 2	2022	\$3299	Waveguide with dynamic dimming	1440 × 1760 per eye	AMD Zen 2 Quad-core + AMD GCN GPU
Moverio BT 200	2014	\$699	LCD	960 × 540	Dual-core 1.2 GHz (ARM Cortex A9), Android-based
Moverio BT 300	2016	\$799	OLED	1280 × 720	Intel Atom x5 1.44 GHz
HiAR G200	2020	NA	OLED	1920 × 1080 per eye	Qualcomm Snapdragon 835
Pico G2	2019	\$399–449	LCD	1920 × 2160 per eye	Qualcomm Snapdragon 835 with 4 GB RAM
Apple Vision Pro ^a	2024	\$3499	Micro-OLED	3660 × 3200 per eye	Apple M2 (8-core CPU, 10-core GPU, 16-core Neural Engine) + Apple R1

AMOLED, active matrix organic light-emitting diode; CPU, central processing unit; GPU, graphics processing unit; HPU, holographic processing unit; LCD, liquid crystal display; NA, not available; OLED, organic light-emitting diode; RAM, random-access memory; SoC, system-on-a-chip.

^aNot used in any of the studies analysed and not currently classified as a medical device; however, its advanced hardware and software capabilities suggest strong potential for future applications in surgery and precision medicine.

Table 4. Distribution of the phase of the planning process related to the use of extended reality (XR) in the studies included in this review. Three studies presented two applications, for a total of 93 applications in 90 studies.

Application	Number of applications	Percentage	Dominant XR technology
Training	16	17.2%	VR
Preoperative	3	3.2%	AR and VR
VSP	17	18.3%	VR
Intraoperative	56	60.2%	AR and MR
Postoperative	1	1.1%	VR

AR, augmented reality; MR, mixed reality; VR, virtual reality; VSP, virtual surgical planning.

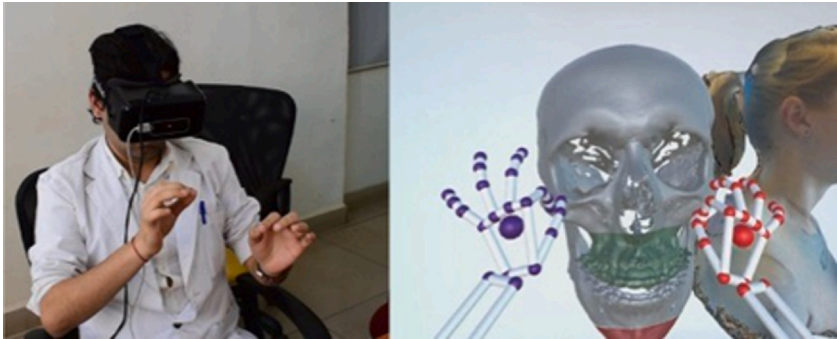


Fig. 5. Illustration of a virtual reality (VR) application for training purposes, showing 3D interaction with CBCT data. Data from CBCT scans, stereophotogrammetry, and soft tissue prediction planning could be used in the application. Reproduced, with permission, from Pulijala et al.¹¹.

designed, validated, and evaluated a novel Le Fort I osteotomy training tool, shown in Fig. 5, based on immersive VR using Oculus Rift. Similarly, Choi et al.⁶⁸ used 360° video and an HMD (Meta Quest 2) to allow students to have the same clinical experience as in reality, which proved to be an effective teaching method if used along with conventional clinical observation. Fan et al.³⁵ developed and evaluated a VR teaching platform for OMS education. In the training phase, VR demonstrated potential for improving OMS education, enhancing residents' learning interest, efficiency, theoretical knowledge, practical skills, and satisfaction.

While VR has been used for advanced surgical simulation and observation, AR/MR has been used for anatomy visualization. For example, Neri et al.⁸⁰ developed AeducAR (Fig. 6), an innovative tool for human anatomy education that combines virtual information projected using AR with real, tangible 3D-printed anatomical models. This tool significantly enhanced the anatomy learning process and improved learning outcomes, with students expressing positive feedback regarding the interactive features.

Preoperative

The preoperative phase is the initial phase of patient-specific planning and is essential to develop a personalized surgical approach that aligns with the patient's needs and clinical indications. This may include a patient consultation, during which the surgeon discusses the patient's medical history, symptoms, and surgical goals to understand their expectations and any underlying health conditions that may impact the procedure. A detailed physical examination will then be performed to evaluate key anatomical features such as facial symmetry, occlusion, soft tissue characteristics, and the skeletal structure to identify functional or aesthetic concerns. Advanced imaging techniques, including computed tomography (CT), magnetic resonance imaging (MRI), and 3D scans, can be used to obtain precise anatomical data, aiding in the creation of personalized surgical plans. Additionally, digital tools and VSP can improve decision-making by allowing the surgeon to simulate different surgical approaches, enhancing accuracy and predictability. This phase serves as the foundation for successful surgical

outcomes, ensuring that treatment strategies are carefully tailored to each patient's unique anatomical and functional requirements.

Cercenelli et al.⁵⁰ developed an AR application to track and display the anatomical structures of interest in superimposition for evaluating temporomandibular joint (TMJ) kinematics. The AR-derived TMJ movements were then compared with standard kinesiographic acquisitions to prove the feasibility of the proposed application aimed at facilitating the diagnostic evaluation for the surgeon. The AR application successfully superimposed a 3D visualization of the joint onto the patient's head thereby facilitating diagnostic evaluation, and AR-derived jaw movement trajectories were consistent with kinesiography curves.

Lee et al.⁷⁵ evaluated whether a mobile-based AR model improves diagnostic accuracy, spatial understanding, and cognitive load during craniofacial fracture assessment. The AR model was preferred by 83% of clinicians, especially less experienced ones.

Another interesting application of VR was proposed by Ganry et al.¹⁰, who offered an innovative strategy to manage preoperative anxiety and stress in patients undergoing skin cancer surgery (Fig. 7). Salivary cortisol levels were significantly reduced after VR exposure, proving its effectiveness, while heart coherence scores showed no significant change. Although not reported in Supplementary material Table S1, similar studies have been conducted to determine whether the use of VR can reduce anxiety in adults, with mixed results^{100–105}. Gurbuz and Gurbuz¹⁰⁵, in fact, observed that VR did not affect anxiety and pain levels in patients, contrary to what other researchers claimed. As highlighted by the reported studies, both fully and partially immersive technologies can be useful during the preoperative phase for different purposes.

VSP

VSP follows the preoperative phase and allows surgeons to plan surgeries before entering the operating room. The primary goal of VSP is to improve the clinical workflow, reduce the surgery time, and increase accuracy, transferring the digital plan to the operating room via accurate, 3D-printed, patient-specific models and instrumentation.

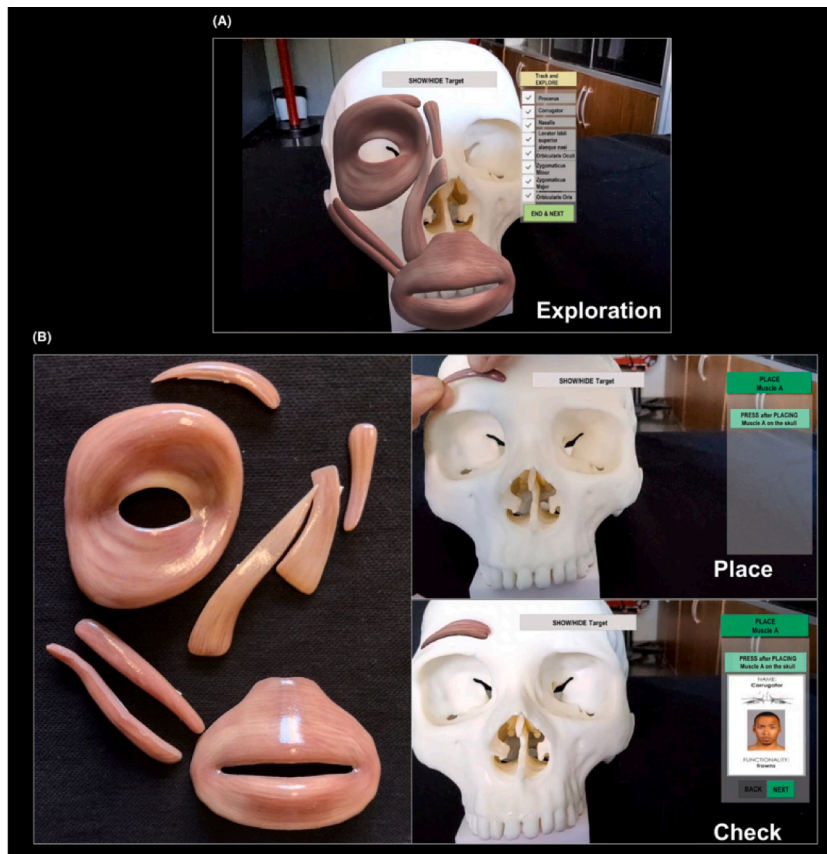


Fig. 6. Illustration of an augmented reality (AR) application for training purposes, showing representative images of the learning experience on facial mimic muscles. It requires placing 3D-printed muscles on the skull phantom and then checking them in AR view.

Reproduced, with permission, from Neri et al.⁸⁰.

Together with 3D printing, XR applications in VSP have grown significantly in the last year, with a

prevalent use of VR. Indeed, compared to AR and MR, VR lends itself best to enhanced surgical simulation, and



Fig. 7. Illustration of a virtual reality (VR) application for preoperative purposes, showing a patient using the virtual reality system to control preoperative anxiety. Reproduced, with permission, from Ganry et al.¹⁰.

surgeons can use VR to manipulate 3D models of the patient's facial anatomy, simulating different surgical approaches and predicting outcomes. Arias-Amezquita et al.⁶⁵ reported that VR is an effective and intuitive surgical planning and 3D visualization tool. In their study, they outlined the development of the world's first VR planning platform and workflow for segmentation, preoperative planning, and digital design. Further examples are reported in the studies of Bartella et al.¹⁴, Gruber et al.⁷¹, and Kangas et al.⁷³. In the first of these, the authors presented a clinical application of software that addressed real-time data importation, the use of DICOM datasets, moderate demand for graphical and computational power, affordable hardware, and intuitive control¹⁴. In the second, 10 mandibles were segmented in VR using the HTC VIVE Pro HMD, on a desktop screen, by five experts and via five AI models. The results highlighted the VR method as the preferred one, showing high accuracy and precision overall while saving time⁷¹. Lastly, Kangas et al.⁷³ developed a multi-user VR environment for orthognathic surgical planning.

Although VR has been the most widely used technology for VSP, the recent literature reports some AR and MR applications. For example, Liu et al.⁵⁴ reported AR-guided osteotomies in mandibular resection and defect reconstruction, and Wilkat et al.⁶² used MR for setting the virtual occlusion during orthognathic surgery (Fig. 8). The MR tool offered enhanced accuracy and efficiency in occlusion planning, addressing limitations of traditional methods.

Intraoperative

Unlike the earlier phases of the surgical process, where AR, MR, and VR can be integrated depending on the final objective, the intraoperative phase primarily involves the integration of AR or MR, with VR being excluded due to its detachment from the real environment. The adoption of AR and MR headsets or glasses is crucial in this context, as they allow the surgeon to visualize the virtual surgical plan while operating, without the need to divert their sight and attention to external monitors.

Augmented surgery, defined as the integration of AR and MR technologies into the surgical environment to

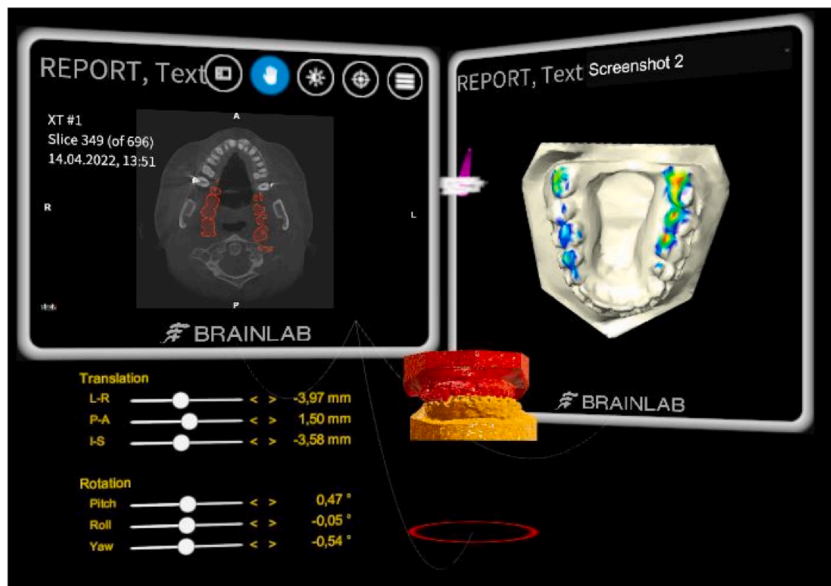


Fig. 8. Illustration of a mixed reality (MR) application for virtual surgical planning (VSP) purposes, showing an MR working space for occlusion detection. Reproduced from Wilkat et al.⁶² (open access article under a Creative Commons Attribution (CC BY) license).

enhance precision, accuracy, and confidence in performing procedures, has become increasingly accessible in recent years, as noted by Remschmidt et al.⁵⁸ and illustrated in [Supplementary material Table S1](#). Among the most widely adopted devices are HoloLens and HoloLens 2, which have been utilized to overlay 3D navigation information within the surgeon's field of vision. These devices allow the display of virtual models of the patient's anatomical structures^{46,48}, osteotomies^{49,64}, tumour margins^{45,77}, and other critical surgical information. Brunzini et al.⁴⁹ developed and proposed an MR application deployed on HoloLens 2 to perform osteotomies without the need for customized physical cutting guides, which currently represent the gold standard¹⁰⁶. Similarly, Tang et al.⁴⁵ demonstrated the feasibility, safety, and effectiveness of combining XR technology with surgical navigation for tumour resection in the oral and maxillofacial region. In their study, Remschmidt et al.⁵⁸ evaluated the intraoperative feasibility and usability of HoloLens 2 for apicoectomies, advocating for its routine use. As shown in [Fig. 9](#), the image guidance systems integrated into the HoloLens 2 eliminate the need for the surgeon to focus alternately on the computer workstations and the surgical field, allowing all relevant image data to be projected directly into their field of view.

While most intraoperative applications involve full-display technology, Li et al.⁷⁶ proposed an AR surgical navigation system that integrates the VSP into the real surgical field using a tablet for guidance, representing a partial-display AR application ([Fig. 10](#)). Additionally, Sugahara et al.⁶⁰, in a study from Tokyo Dental College, presented a case report in which HoloLens was used to ascertain the positions of the iliac bone graft and repositioned maxillary bone after Le Fort I osteotomy.

Performance benchmarks

As well as proposing an application of XR technology in OMS, some studies included in this review focused specifically on performance benchmarks, such as spatial guidance and osteotomy accuracy, providing important quantitative insights into the technical capabilities of XR systems. In 2019, Pietruski et al.¹⁷ published the results of a proof-of-concept study to compare the accuracy of simulated mandibular osteotomies performed with cutting guides and two AR intraoperative navigation systems. In 2023, they published a similar study on skull models⁵⁶, demonstrating that the accuracy achieved with both AR-based strategies was within the threshold of clinical tolerance. Cerenelli et al.¹⁹ reported the results of phantom tests with VOSTARS aimed at evaluating its

feasibility and accuracy in performing maxillofacial surgical tasks, and showed excellent tracking robustness under operating room lighting. Accuracy tests showed that 100% of Le Fort I trajectories were traced with an accuracy of ± 1.0 mm, and on average, 88% of the trajectory length was within ± 0.5 mm accuracy. Koyachi et al.²⁵ verified the reproducibility and accuracy of preoperative planning in maxilla repositioning surgery performed with the use of CAD/CAM technologies and MR surgical navigation. The median absolute value deviation of seven maxillary points resulted in a repositioning error of 0.38 mm, indicating that the method used was able to reproduce the maxilla position with high accuracy. In a technical note, Zoabi et al.⁴⁸ discussed the use of AR to evaluate and guide the insertion and positioning of a patient-specific implant (PSI) for orbital floor reconstruction following blow-out fracture. The post-operative CT scan showed remarkable precision, with a placement accuracy under 0.3 mm. Bussink et al.³¹ presented an AR-based approach to assist in condylectomy. The 3D registration of planned and postoperative mandibular models showed a positioning error under 1 mm. Carbone et al.³² tested VOSTARS on phantoms and real patients in a clinical trial to aid the surgeon while performing Le Fort I osteotomy, demonstrating the value of the hybrid approach and the safety and usability of the navigation platform. On average, 86% of the VOSTARS guided osteotomies reproduced the preoperative plan with an accuracy level of ± 0.5 mm. Chan et al.³⁴ employed a projector-based AR method to guide osteotomies and improve margin delineation. One hundred and fifteen virtual osteotomies were analysed in terms of intra-tumour cuts, close, adequate, and excessive distances from the tumour, resulting in 0.0% cuts inside the tumour area under AR guidance versus 1.9% without any guidance. Li et al.⁷⁶ developed a portable, all-in-one surgical navigation system using AR, and investigated its feasibility and accuracy. This AR surgical navigation system demonstrated precise AR visualization, with an overall overlap error of 0.53 ± 0.21 mm.

Although immersive technologies have shown promise in the intraoperative phase, the current literature is characterized by a predominance of feasibility studies, technical



Fig. 9. Illustration of a full display augmented reality (AR) application for intraoperative purposes, showing surgeons focusing on the operating field. Reproduced from Remschmidt et al.⁵⁸ (open access article under a Creative Commons Attribution (CC BY) license).

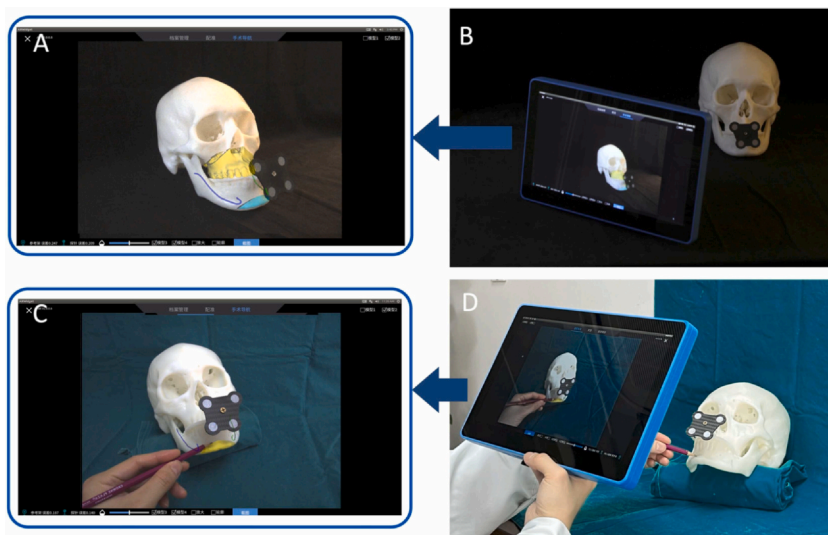


Fig. 10. Illustration of a partial display augmented reality (AR) application for intraoperative purposes, showing virtual imaging superimposed on the skull model to guide the operation. Reproduced, with permission, from Li et al.⁷⁶

validations, and case reports, with a general lack of randomized controlled trials or high-level clinical evidence¹⁰⁷. Future research aimed at addressing this gap by adopting standardized outcome measures, including accuracy benchmarks, usability metrics, and patient outcomes, is needed.

Experimental validation

To better contextualize the level of maturity and clinical applicability of

XR systems in OMS, the intraoperative studies were categorized based on their validation setting: in vitro, in vivo, or pre-clinical. In vitro studies typically involve simulated procedures using 3D-printed models or phantoms. These settings allow controlled evaluation of specific parameters such as spatial accuracy, usability, and workflow integration without the complexity of live surgery. In vivo studies refer to the actual use of XR systems in human patients during real surgical

interventions. Although often limited in number and scale, these provide valuable insights into clinical feasibility, surgeon perception, and safety outcomes. Pre-clinical validation, including cadaveric or animal-based studies, serves as an intermediate step, enabling the evaluation of device performance in anatomically realistic conditions without patient risk.

This classification provides a practical proxy for the technology readiness of XR systems within the surgical workflow, especially in the absence of standardized TRL (technology readiness level) reporting in the included studies. Fig. 11 illustrates the distribution of experimental settings used in the intraoperative XR studies: in vivo ($n = 29$), in vitro ($n = 24$), and pre-clinical ($n = 6$). Three studies included two validation settings^{32,81,82}, for a total of 59 in 56 included intraoperative studies.

This distribution offers an insight into the technological readiness of XR systems in surgery and helps contextualize their current stage of clinical integration. The predominance of in vivo studies suggests that XR technologies are increasingly being applied directly in clinical environments, reflecting growing confidence in their safety and utility. The substantial number of in vitro studies highlights their importance in early-phase testing and iterative development. The lower number of pre-clinical studies may be due to ethical, logistical, and cost-related constraints typically associated with cadaveric or animal models.

Discussion

XR technologies, including AR, MR, and VR, have been applied increasingly in OMS in the last few years, demonstrating their contribution to surgical precision, planning, training, and

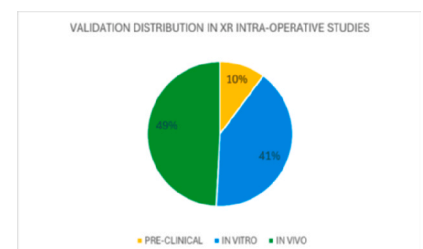


Fig. 11. Distribution of experimental settings used in intraoperative extended reality (XR) studies, categorized into in vivo ($n = 29$), in vitro ($n = 24$), and pre-clinical ($n = 6$).

education. This scoping review focused on the implementation of these technologies at different stages of the surgical process in OMS, highlighting their advantages and limitations. Furthermore, this review provides clarity on the taxonomy in this research area².

Surgical phase

AR has demonstrated considerable utility during the intraoperative phase, where its ability to enhance the surgeon's visual field is critical¹⁰⁸. By overlaying digital images or anatomical models reconstructed from medical imaging, such as MRI or CT scans, AR provides the surgeon with augmented views of the operative field, enabling real-time guidance and improving accuracy and efficiency¹³. Studies have shown that AR enhances surgical performance, particularly in procedures involving delicate structures such as in orbital floor reconstruction⁴⁸ and osteotomies⁶⁰. In such cases, precise navigation is essential, and AR enables the surgeon to perform highly accurate operations with minimal invasiveness, reducing the need for additional imaging or re-positioning during surgery. Therefore, the advantages of AR in OMS are multifaceted for both surgeons and patients¹⁰⁹. On the one hand, the surgeon benefits from enhanced spatial awareness, improved accuracy, and reduced cognitive load through the provision of continuous access to imaging data within their field of vision and reducing the time spent on image interpretation. On the other hand, using AR systems minimizes the invasiveness of procedures, reduces the risk of complications, and shortens patient recovery times. Furthermore, traditional methods often require multiple imaging scans to guide the surgeon, which can lead to increased radiation exposure for both the medical team and the patient. In contrast, AR navigation relies on pre-existing imaging data, which can be integrated directly into the AR environment.

However, the limitations of AR remain significant. While its potential to improve outcomes is well-documented, issues such as the misalignment of virtual images with the patient's actual anatomy can lead to errors in navigation, mainly when there are intraoperative changes in tissue position or patient movement. AR systems also suffer from limited field of view and

suboptimal resolution, which can impair the visibility of small or intricate structures, particularly in microsurgical applications. Finally, the high cost of AR systems and the steep learning curve associated with their integration into surgical workflows limit their widespread adoption in smaller or resource-constrained medical centres.

AR has been adopted in all stages of the surgical process, including preoperative planning, VSP, and intraoperative navigation. Its versatility in OMS is demonstrated by applications in the preoperative phase to evaluate mandible kinematics⁵⁰, in the VSP phase to set the virtual occlusion during orthognathic surgery planning⁶², and in the training phase to learn human anatomy⁸⁰.

MR builds on the functionality of AR² by offering more immersive and interactive experiences, allowing users to engage with virtual objects in real time. As emerged from the literature review, MR is particularly valuable during intraoperative navigation^{56,58,60,64}. Unlike AR, which primarily overlays images, MR allows the surgeon to interact directly with 3D reconstructions of the patient anatomy, improving spatial awareness and enhancing decision-making during complex surgeries. This interactive capability enables the surgeon to adjust and manipulate 3D models of bones, soft tissues, or surgical plans as if they are part of the real-world environment. The surgeon no longer needs to switch between physical and virtual worlds by consulting external imaging screens, as the digital models are seamlessly integrated into their view. The advantages of MR in intraoperative guidance are especially notable in procedures that demand high precision and extensive navigation, such as facial trauma repairs, reconstructive surgeries, and orthognathic procedures. By maintaining a holistic view of the surgical site, MR helps to reduce operative times and improve patient outcomes, particularly in complex or lengthy procedures where continual visual feedback is essential.

Despite these benefits, MR also presents challenges. First, the technology requires precise calibration and robust tracking systems to ensure that virtual objects align perfectly with the patient's anatomy. Any misalignment or latency in processing can undermine surgical accuracy. Additionally, MR systems are still developing in terms of

ergonomics; the headsets are often bulky, and their use during extended surgeries can cause discomfort for the surgeon. Moreover, like AR, the high cost of MR systems limits their accessibility in smaller hospitals or clinics, where cost-effectiveness is a critical concern. Although MR has shown promise in various clinical applications, further refinement of the technology is needed to overcome these barriers and expand its clinical utility.

Unlike AR and MR, which have been used primarily in the intraoperative phase, VR has found its most significant applications in training, preoperative planning, and VSP. VR is highly immersive, providing users with the ability to interact with fully virtual environments, making it an excellent tool for simulating surgical procedures and allowing surgeons to rehearse complex surgeries without risk to patients^{11,12}. Its role in surgical training is particularly valuable, enabling both novice and experienced surgeons to refine their skills and enhance their understanding of complex anatomy and procedures. VR has also emerged as an effective and intuitive surgical planning and 3D visualization tool⁶⁵, showing the promising applicability and efficiency of VR in clinical planning and management. Additionally, VR has been shown to have beneficial effects on reducing patient anxiety before surgery¹⁰, providing patients with an immersive environment, alleviating fear and improving overall patient satisfaction.

Despite its many benefits, VR has some evident limitations. Indeed, due to its immersive nature, VR is not practical for use in real-time surgical procedures, as it isolates the surgeon from the physical environment. This disconnection restricts the use of VR primarily to the preoperative and training phases, limiting its real-time clinical applications compared to AR and MR. Additionally, while VR offers significant educational and planning benefits, the cost of developing and maintaining VR environments and the time-consuming nature of creating detailed 3D models are current challenges for its widespread adoption.

Regulatory affairs

As presented and detailed in this scoping review, XR technologies can potentially transform health care, specifically OMS, delivering new types of

treatments and diagnostics and changing how and where care is delivered. Central to their potential in diagnosis and treatment is their ability to deliver both standard and entirely new types of content in highly immersive and realistic ways, remotely, and tailored to a variety of clinical contexts. However, their clinical use is subject to medical device regulation, which must be considered when evaluating their safety, effectiveness, and readiness for translation into routine practice.

In the United States, XR systems intended for diagnosis, treatment, or intraoperative use are generally classified as medical devices and fall under the jurisdiction of the US Food and Drug Administration (FDA)¹¹⁰. In the European Union, similar technologies fall under the Medical Device Regulation (MDR 2017/745)¹¹¹. This regulation classifies devices based on risk and sets high standards of quality and safety for medical devices in order to meet common safety concerns as regards such products. Clinical investigation with pre-market medical devices is permitted and is a prerequisite for obtaining CE certification. To perform pre-market clinical investigations in compliance with the MDR, approval by the Ethics Committee is required.

In 2018, the FDA gave 510(k) clearance to the OpenSight Augmented Reality System¹¹², the first AR medical solution for Microsoft HoloLens cleared for use in preoperative surgical planning. As explicitly stated by Microsoft, HoloLens and HoloLens 2 are general-purpose computing devices and are not, by themselves, certified as medical devices. However, they can serve as hardware components within certified medical systems, as exemplified by FDA-cleared applications. Based on the last update of September 2024, the FDA has authorized 69 medical devices that incorporate AR and VR for marketing based on data and information that demonstrate their safety and effectiveness. There is currently no centralized public list, similar to that of the FDA, that collects XR devices certified under the European MDR, but medical devices are submitted in EUDAMED, the IT system established by Regulation 2017/745.

Among the studies analysed in this scoping review, Cai et al.⁶⁷ used Virtual Surgery Intelligence (VSI) HoloMedicine¹¹³ for registration and superimposition. The medical software,

designed and distributed by apoQlar, is intended to visualize 3D imaging holograms of the patient for preoperative planning outside and/or inside the surgical room. It has been certified as a medical device in 33 countries (EU, Singapore, USA).

Despite the growing interest in XR applications, many of the reviewed studies did not report whether the systems used were certified medical devices or experimental prototypes. This limits the ability to assess their clinical applicability and regulatory compliance. Future studies should clearly state whether the XR system has received regulatory clearance and under which jurisdiction, as this has direct implications for clinical translation and patient safety.

Limitations and future directions

In conclusion, a scoping review of recent studies on the adoption of XR applications in OMS, published between 2018 and June 2025, was performed. This review is novel in grouping the selected studies by stage of the surgical process, focusing on training, preoperative, VSP, and intraoperative, to clarify how AR, MR, and VR are currently used in OMS, in order to help researchers identify gaps in the current literature and suggest areas for future studies, and inform surgeons on the potential of XR technologies.

AR excels in providing real-time intraoperative guidance, improving surgical precision and workflow efficiency. MR enhances intraoperative navigation and preoperative planning through its immersive and interactive capabilities, offering surgeons a more dynamic and versatile tool for engaging with patient data. VR, although limited to preoperative, eliciting positive and relaxing emotions¹¹⁴, and training applications, plays a crucial role in improving surgical planning and advancing surgeon training.

In addition to its current uses, VR holds potential in the postoperative phase⁸⁵, where immersive 3D environments could assist in post-surgical assessments and rehabilitation. Surgeons could use VR to compare preoperative plans with actual outcomes, while patients could engage in virtual rehabilitation programmes that simulate physical exercises in a controlled and motivating environment.

Beyond traditional XR technologies, diminished reality (DR) is worth mentioning as an emerging concept that could serve as a complementary approach¹¹⁵. Unlike AR, which adds digital elements to the real world, DR is a subset of XR that specifically addresses real-time occlusion, removal, and transparency of objects in the environment^{116,117}. This could help both in the training and intraoperative phases, by removing distractions in a learning environment or highlighting specific items to focus on, and reducing visual overload during complex surgical procedures, respectively. While still in the early stages of development, DR may represent a valuable future direction, particularly in high-density visual environments such as those encountered in OMS.

Nevertheless, significant limitations, including regulatory compliance, high costs, technical challenges, and the need for more clinical validation, continue to hinder the widespread adoption of extended reality technologies in oral and maxillofacial surgery. Further research and technological advancements are required to overcome these barriers, refine the integration of extended reality into existing workflows, and fully realise the potential of these technologies to transform oral and maxillofacial surgery.

Ethical approval

Not applicable.

Patient consent

Not applicable.

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None.

Competing interests

None.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at [doi:10.1016/j.ijom.2025.12.006](https://doi.org/10.1016/j.ijom.2025.12.006).

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