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AUGMENTED, VIRTUAL AND MIXED REALITY IN ORAL AND MAXILLOFACIAL SURGERY: A REVIEW OF SURGICAL TRAINING, NAVIGATION AND PATIENT-CENTERED APPLICATIONS

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ABSTRACT

Objectives. Augmented reality (AR), virtual reality (VR), and mixed reality (MR)-collectively termed extended reality (XR)-are increasingly applied in oral and maxillofacial surgery (OMFS), a discipline that combines anatomical complexity with high demands for precision and aesthetics. This review synthesises the current applications, reported performance, and limitations of AR, VR, and MR across four domains of OMFS: surgical training and simulation, preoperative planning, intraoperative navigation, and patient communication.

Methods. A narrative, thematically structured review of peer-reviewed studies applying AR, VR, or MR to OMFS and closely related surgical fields was conducted, with findings organised by application domain and appraised against the metrics most often reported.

Results. In training, immersive VR and haptic simulators provide risk-free, repeatable, objectively assessed practice and yield outcomes that are non-inferior and often superior to conventional methods. In planning, immersive three-dimensional visualisation improves spatial understanding and supports waferless, guide-based, and patient-specific workflows. In navigation, AR and MR overlay the surgical plan onto the operative field, with reported overlay or registration errors typically in the sub-millimetre to low-millimetre range. In patient communication, patient-specific VR, AR, and MR visualisations improve understanding and satisfaction and reduce anxiety during informed consent.

Conclusions. XR offers tangible benefits across the OMFS pathway, yet evidence is constrained by small heterogeneous studies, registration and ergonomic challenges, novelty bias, and limited long-term clinical data. Robust validation, cost-effectiveness analysis, and standardised reporting are needed before routine adoption.

KEYWORDS

Augmented Reality, Virtual Reality, Mixed Reality, Oral and Maxillofacial Surgery, Surgical Navigation, Surgical Education

CITATION

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1. Introduction

Oral and maxillofacial surgery (OMFS) addresses pathology and deformity of the mouth, jaws, face, and neck, a region that contains numerous delicate and functionally important structures in a small, anatomically intricate space. Procedures in this field must respect critical anatomy such as the inferior alveolar nerve and the maxillary sinuses while simultaneously satisfying functional and aesthetic goals, so that even small errors can have significant consequences. These demands have made OMFS an early and enthusiastic adopter of digital technology.

The stakes in this region are unusually high. A maxillary osteotomy passes close to the descending palatine vessels and the maxillary sinus; a sagittal split of the mandible places the inferior alveolar nerve at risk; implant placement must respect the nerve canal, the sinus floor, and adjacent roots; and reconstruction after trauma or tumour resection must restore both the skeletal framework and the overlying facial form. The clinician must therefore integrate a mental three-dimensional model of bone, soft tissue, dentition, and neurovascular structures, and then transfer a plan formed in that mental space to the patient on the operating table. Immersive technologies are attractive precisely because they externalise this three-dimensional reasoning, presenting the relevant anatomy and plan in three dimensions for learning, rehearsal, execution, and explanation.

Over the past two decades the discipline has been transformed by cone-beam computed tomography, three-dimensional surface imaging, virtual surgical planning (VSP), computer-aided design and manufacturing, and three-dimensional printing of guides and patient-specific implants. Against this digital backdrop, immersive visualisation technologies have emerged as a natural next step. Augmented reality (AR), virtual reality (VR), and mixed reality (MR)-together often referred to as extended reality (XR)-promise to move

three-dimensional patient data off the flat screen and into the surgeon's, trainee's, or patient's direct field of view (Stucki et al., 2024).

These terms describe points along a reality–virtuality continuum. VR immerses the user in a fully computer-generated environment, typically through a head-mounted display, replacing the real world entirely. AR overlays digital information onto the real world, viewed through smart glasses, a tablet, or a smartphone, while leaving the real environment dominant. MR goes further, anchoring virtual objects to the physical world so that holograms and real anatomy coexist and can be manipulated together in the same space. Haptic interfaces add force feedback, allowing users to feel virtual tissues and instruments, and are frequently combined with VR for skills training (Maes et al., 2026).

The clinical value of each modality differs accordingly. VR is best suited to immersive rehearsal and education, where a fully synthetic environment can be controlled, repeated, and instrumented; AR and MR come into their own when virtual information must be combined with the real patient, for example by projecting a plan onto the operative field or onto the patient during a consultation. Underlying all of these uses is image fusion—the combination of preoperative imaging such as cone-beam computed tomography with the live scene—and the registration and tracking that keep the two aligned. The quality of this alignment, more than the choice of headset, ultimately determines whether an application is a visually impressive demonstration or a clinically dependable tool.

The anatomical complexity and precision requirements of OMFS make it particularly suited to benefit from these technologies, and the literature has expanded rapidly as affordable, capable headsets such as the Microsoft HoloLens 2 and consumer VR systems have become available. Applications cluster into four broad domains: the training and assessment of surgical skills; preoperative planning and VSP; intraoperative navigation and guidance; and the education of, and communication with, patients. Earlier overviews mapped the breadth of this activity and noted that dental implantology and orthognathic surgery were among the most frequent applications, with intraoperative navigation and prediction planning prominent (Ayoub & Pulijala, 2019).

The breadth of this activity is considerable. Early surveys of VR and AR in OMFS already identified scores of relevant studies spanning education, haptic training, image fusion, planning, and navigation, with dental implantology and orthognathic surgery emerging as the most frequent clinical applications (Ayoub & Pulijala, 2019). More recent scoping and systematic reviews, employing formal reporting frameworks, have catalogued dozens of studies across training, planning, and intraoperative guidance and have begun to compare the commercial headsets in routine use. This rapid accumulation of literature, much of it published within the last few years, makes a synthesising overview timely, but it also reflects a field in which technology and evidence are advancing in parallel and not always in step.

The available studies are, however, methodologically heterogeneous, differing in technology, study design, reference standards, and outcome measures, which makes it difficult for clinicians and educators to judge where XR delivers genuine value and where enthusiasm has outpaced evidence. The aim of this review is to provide a structured, clinically and educationally oriented synthesis of AR, VR, and MR applications across the OMFS pathway, summarising the methods used, the performance reported, and the limitations that currently constrain routine adoption, and thereby to support a critical appraisal of the technology and to identify priorities for future research.

2. Methodology

This work is a narrative, thematically structured review rather than a systematic review or meta-analysis. Relevant literature was identified through searches of the PubMed, Scopus, Embase, and Web of Science databases, supplemented by hand-searching the reference lists of pertinent reviews and primary studies. Search terms combined concepts describing the technologies (“augmented reality,” “virtual reality,” “mixed reality,” “extended reality,” “head-mounted display,” “haptic”) with terms describing the clinical domain (“oral and maxillofacial surgery,” “orthognathic,” “dental implant,” “surgical navigation,” “surgical training,” “informed consent”).

Studies were considered relevant if they applied AR, VR, or MR to one or more of the following in OMFS or closely related surgical fields: the training and assessment of surgical skills, preoperative planning and VSP, intraoperative navigation and guidance, and patient education and communication. Only English-language, peer-reviewed publications were included, and editorials and non-peer-reviewed sources were excluded. Because the purpose of the review is interpretive and oriented towards clinical and educational

practice, no formal risk-of-bias scoring or quantitative pooling was undertaken; the strengths and limitations of the evidence are instead discussed narratively.

Findings were organised into the application domains shown in Figure 1. Within each domain the principal technologies and approaches are described together with the outcome measures most often reported in the source studies. These include registration, overlay, or target-registration error expressed in millimetres for navigation; validated skill or preparation scores, procedure time, and error counts for training; and patient understanding, satisfaction, and anxiety for communication. Throughout, a deliberate distinction is drawn between technical performance, such as a sub-millimetre overlay error, and clinical or educational usefulness, such as a demonstrated improvement in surgical outcome, learning, or patient experience; the two are related but not equivalent, and most current evidence speaks to the former.

The scope was kept deliberately broad in terms of procedure type, encompassing orthognathic surgery, dental implantology, trauma and orbital reconstruction, and tumour surgery, because the same immersive tools are frequently applied across these procedures and because evidence from one often informs the others. Where direct OMFS evidence was sparse-most notably for patient communication-closely related surgical literature was drawn upon and identified as such, so that conclusions for OMFS are clearly distinguished from extrapolation.

3. Results

Applications of immersive technologies in OMFS were grouped into four domains spanning the surgical pathway: (1) surgical training and simulation; (2) preoperative planning and virtual surgical planning; (3) intraoperative navigation and guidance; and (4) patient communication and informed consent. Figure 1 places these domains on the reality–virtuality continuum and summarises representative tasks and the cross-cutting requirements that condition their clinical use; Table 1 defines the principal technologies, and Table 2 summarises representative applications and reported performance.

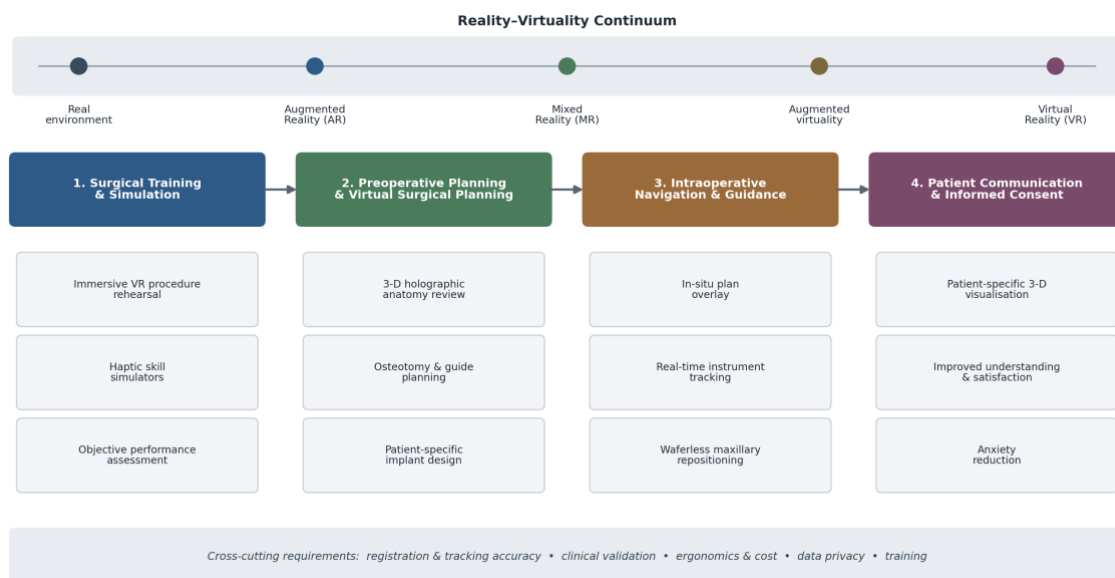


Fig. 1. Augmented, virtual, and mixed reality across the oral and maxillofacial surgery pathway. The upper band shows the reality–virtuality continuum; the four pillars list representative tasks; the lower band highlights cross-cutting requirements for safe clinical translation.

3.1. Foundational Concepts and Enabling Technologies

A clear vocabulary is essential because the terms AR, VR, and MR are frequently conflated. As summarised in Table 1, VR replaces the real environment with a fully synthetic one and is delivered through immersive head-mounted displays; AR superimposes digital content onto a predominantly real scene through optical or video see-through glasses, tablets, or smartphones; and MR registers virtual objects to the physical world so that the user perceives and interacts with both simultaneously, typically through a self-contained headset. The umbrella term XR spans this continuum. Each modality can be augmented with haptic feedback, which conveys pressure, vibration, and resistance and is central to realistic skills simulation.

Table 1. Definitions of the principal immersive technologies, typical hardware, and primary applications in oral and maxillofacial surgery.

Modality	Definition	Typical hardware	Primary OMFS use
Virtual reality (VR)	Fully computer-generated environment that replaces the real world	Immersive head-mounted display, hand controllers	Training, simulation, patient education
Augmented reality (AR)	Digital content overlaid onto a predominantly real scene	Optical/video see-through glasses, tablet, smartphone	Navigation, planning, consent
Mixed reality (MR)	Virtual objects registered to and interactive with the physical world	Self-contained headset (e.g. HoloLens 2)	Navigation, planning, hands-free 3-D review
Haptics	Force/tactile feedback added to VR or AR	Force-feedback handpieces or controllers	Psychomotor skills training

Two technical capabilities underpin most clinical applications. The first is registration-the alignment of virtual models to the real anatomy-which may be marker-based, using fiducials or splints, or markerless, using surface or feature recognition. The second is tracking, the continuous updating of that alignment as the patient, instrument, or observer moves, achieved with optical, electromagnetic, or headset-integrated sensors. The accuracy of registration and tracking largely determines whether a system is fit for clinical use, and it is the dominant theme in the navigation literature discussed below.

The hardware supporting these modalities has evolved considerably. Early maxillofacial AR relied on autostereoscopic or integral-videography displays and bespoke optics to present three-dimensional images in situ, whereas current systems increasingly use self-contained headsets with integrated cameras and depth sensors, of which the Microsoft HoloLens 2 has become the most widely reported. AR can be delivered through optical see-through displays, in which the user views the real world directly through transparent optics overlaid with graphics, or through video see-through approaches, in which a camera feed of the surgical field is merged with the virtual plan and shown on a screen; each has trade-offs in latency, brightness, and depth perception. Lower-cost AR using tablets and smartphones, and projector-based or semi-transparent-mirror displays, has also been explored, broadening access at the expense of immersion. Whichever display is used, the preoperative plan must first be fused with the patient's imaging, making CBCT or CT segmentation and three-dimensional reconstruction a shared prerequisite across all of the applications considered below.

In practice, deploying any of these systems begins with the same workflow: the patient's cross-sectional imaging is segmented to isolate the relevant structures, a three-dimensional model is reconstructed, and that model is exported in a suitable format and transferred to the display device. Recent systems have streamlined this pipeline to the point that a single operator with brief training can complete it, lowering a barrier that previously confined such technology to specialised centres. The quality of the segmentation, however, propagates through every subsequent use, so that an inaccurate or poorly reconstructed model will compromise training fidelity, planning, navigation, and patient communication alike-another reason that reliable, ideally automated, image processing is a foundational rather than a peripheral concern.

3.2. Surgical Training and Simulation

Surgical education has traditionally followed an apprenticeship model in which trainees acquire skills by operating on real patients under supervision. Reduced training hours, increasing scrutiny of patient safety, and limited caseloads have all placed this model under strain, motivating a search for high-fidelity simulation. Immersive VR and haptic simulators address this need by offering standardised scenarios, the opportunity for unlimited repetition without risk to patients, immediate and objective performance feedback, and a reduction in consumable materials (Maes et al., 2026).

The evidence base for training is the strongest of the four domains. A systematic review of AR and VR in dental and OMFS education that drew on twenty-five randomised controlled trials, and classified the available tools into haptic simulators, head-mounted devices, and software platforms, concluded that these technologies deliver training outcomes that are non-inferior to, and often better than, conventional methods, with an overall body of evidence judged to be at low risk of bias (Maes et al., 2026). Earlier work in OMFS specifically demonstrated, in a single-blind randomised controlled trial, that a VR surgery application improved the performance of novices and supported the development of non-technical skills such as decision-making and communication (Ayoub & Pulijala, 2019). Haptic VR simulators have been applied across a range of preclinical and surgical tasks, allowing trainees to feel instruments and tissues while their technique is recorded and scored against validated rubrics.

The range of training applications is wide. Immersive VR has been used to rehearse whole procedures and to develop spatial and cognitive skills, and dedicated cognitive simulators have been validated for specific reconstructive tasks such as orbital floor repair. Haptic platforms allow trainees to practise cutting, drilling, and preparation while feeling realistic resistance, a feature that is especially relevant to bone work, where the tactile cue of breaching a cortex is an important safety signal. A notable strength of these systems is objective, automated assessment: performance can be graded against validated rubrics covering preparation quality, residual error, and procedure time, and, in implant training, the positional and angular deviation of the simulated placement can be measured directly. This converts subjective supervisory judgement into reproducible metrics and supports deliberate, feedback-driven practice. The accumulated evidence indicates that such training improves technical performance regardless of prior clinical experience, with both students and residents benefiting from repeated simulator practice (Maes et al., 2026; Stucki et al., 2024).

Despite these encouraging results, important caveats remain. Many individual studies are small and heterogeneous, outcome measures are not standardised, and the realism of simulated oral environments-gingival dynamics, salivary flow, and physiological reflexes-remains imperfect. Practical issues such as simulator cost, occasional technical failures, and motion sickness with immersive headsets also temper enthusiasm. The literature increasingly recommends that future work comprise larger, longer randomised trials with standardised outcomes and cost-effectiveness analysis, and that it assess not only technical skill acquisition but also knowledge retention, transfer to the operating room, and learner satisfaction (Maes et al., 2026; Stucki et al., 2024).

Beyond individual skill, immersive training carries implications for how surgical education is organised. By decoupling early skill acquisition from the availability of patients and cadaveric material, VR and haptic simulators can expand practice opportunities and standardise the early learning curve, and they lend themselves to remote and self-directed use. This is particularly relevant where access to expert supervision or to physical training resources is limited, raising the prospect of more equitable training, although the cost of hardware and the absence of agreed curricula and assessment standards currently temper that promise. The consensus emerging from the literature is that XR is best positioned as a structured complement to, rather than a replacement for, supervised clinical experience and established bench training.

3.3. Preoperative Planning and Virtual Surgical Planning

Virtual surgical planning is now a standard component of complex OMFS, allowing osteotomies, segment movements, and reconstructions to be designed digitally and transferred to surgery through printed splints, cutting guides, and patient-specific implants. Conventional VSP is performed on two-dimensional screens, which require the surgeon to reconstruct three-dimensional relationships mentally. Immersive AR, VR, and MR address this limitation by presenting the plan as a manipulable three-dimensional hologram or scene, improving appreciation of spatial relationships and, in MR, allowing the surgeon to rotate, slice, and scale models directly through hand gestures without touching a screen (Stucki et al., 2024).

In orthognathic surgery, planning increasingly aims to dispense with intermediate occlusal wafers in favour of guide- or navigation-based maxillary positioning. Splint-less approaches using personalised surgical guide systems have been described and shown to transfer the plan accurately (Li et al., 2017), and image-guided visualisation displays have been used for waferless maxillary positioning with reported accuracy supporting clinical use (Zinser et al., 2013). More recently, AR has been compared directly with conventional computer-aided design and manufacturing for orthognathic plate and guide workflows, with development and accuracy evaluations indicating that AR-based approaches can achieve clinically acceptable precision (Civita et al., 2025). Beyond the jaws, AR and VR have been systematically reviewed for preoperative planning in craniomaxillofacial trauma, including orbital reconstruction, where three-dimensional visualisation aids appreciation of complex defects (Dubron et al., 2023). Across these applications the recurring benefit is improved spatial understanding; the recurring limitation is that most reports remain technical feasibility or accuracy studies rather than trials demonstrating improved patient outcomes.

Immersive planning is not confined to orthognathic surgery. In oncological and reconstructive OMFS, holographic three-dimensional models allow the surgeon to study tumour extent, plan resection margins, and design reconstruction before operating, and mixed-reality models can be combined with conventional navigation so that osteotomy lines are visualised through a headset while frozen-section control ensures clear margins. A recurring observation across surgical specialties is that visualising volumetric imaging as a three-dimensional hologram, rather than as cross-sectional slices on a flat monitor, improves the understanding of complex spatial relationships and can speed diagnostic and planning tasks. For OMFS, where the geometry of the facial skeleton and its relationship to airway, orbit, and dentition is intricate, this advantage is intuitively valuable. The principal caveat is that, as in the orthognathic literature, most reports establish feasibility, surgeon preference, or technical accuracy rather than measuring whether immersive planning changes the surgical result, and well-designed comparative studies remain scarce (Dubron et al., 2023; Stucki et al., 2024).

Planning and training also overlap. An immersive plan can double as a rehearsal: a surgeon may step through a complex or unusual case in virtual reality before performing it, anticipating difficulties and refining the sequence of steps. This is most valuable for rare presentations and high-stakes reconstructions, where conventional experience accumulates slowly and where the opportunity to practise the specific case is otherwise absent. The same patient-specific model that informs the plan can thus support deliberate preparation, blurring the boundary between preoperative planning and individualised training, and illustrating how a single three-dimensional dataset can serve several purposes along the surgical pathway.

3.4. Intraoperative Navigation and Guidance

The purpose of intraoperative navigation is to execute the preoperative plan accurately, and it is here that AR and MR are most distinctive. Conventional surgical navigation displays the plan and instrument position on an external two-dimensional monitor, forcing the surgeon to look away from the operative field and to map mentally between screen and patient. AR and MR instead overlay the plan in situ, directly onto or alongside the surgical field, and MR additionally allows hands-free, sterile interaction with the holographic models during the operation, which several authors regard as a meaningful ergonomic advance over monitor-based systems.

Reported accuracy is encouraging. Early pilot work demonstrated the feasibility of in-situ three-dimensional integral videography with surgical navigation in maxillofacial surgery (Suenaga et al., 2013), and a wearable AR system was validated specifically for maxillary repositioning in orthognathic surgery (Badiali et al., 2014). Overviews of computer-assisted navigation in OMFS have reported mean discrepancies between planned and achieved results of the order of one to one-and-a-half millimetres across a range of procedures (Ayoub & Pulijala, 2019). More recent engineering has narrowed these figures further: a portable, all-in-one AR navigation system that merges a live video stream of the surgical field with the preoperative plan achieved an overall overlap error of approximately half a millimetre in a skull-model study (Li et al., 2024), and AR approaches have been shown to reach precision comparable to established CAD/CAM workflows in orthognathic applications (Civita et al., 2025). Table 2 summarises representative systems and their reported performance.

The accuracy of an AR or MR navigation system depends heavily on how it is registered to the patient. Marker-based strategies, such as an occlusal splint carrying a fiducial array or reference spheres, provide reproducible and accurate alignment and have supported reported positional deviations of roughly one to two and a half millimetres between planned and navigated points, with angular deviations of a few degrees.

Markerless strategies that register to the patient's facial surface or profile are more convenient and avoid additional appliances, but are generally less robust and more sensitive to lighting and movement. Specialised applications illustrate what well-registered systems can achieve: AR displays that superimpose the course of the inferior alveolar nerve onto the surgical field, for example, have reported position errors below one millimetre, offering a means of protecting a structure whose injury is a common and serious complication. These figures must be read with care, however, because each study uses its own phantom or clinical reference standard, and bench accuracy on a skull model does not guarantee equivalent performance in the moving, bleeding surgical field.

Table 2. Representative applications of augmented, virtual, and mixed reality across oral and maxillofacial surgery domains and their reported performance.

Domain	Representative application	Reported performance / finding
Training & simulation	Immersive VR and haptic skills simulators	Outcomes non-inferior to or better than conventional training; low risk of bias across 25 RCTs (Maes et al., 2026)
Planning / VSP	Splint-less and waferless maxillary positioning; AR vs CAD/CAM	Accurate plan transfer; clinically acceptable precision (Li et al., 2017; Zinser et al., 2013; Civita et al., 2025)
Intraoperative navigation	In-situ AR/MR overlay of the surgical plan	Mean discrepancy ~1–1.5 mm; portable AR overlay error ~0.5 mm (Ayoub & Pulijala, 2019; Li et al., 2024)
Patient communication	Patient-specific VR/AR/MR for informed consent	Improved understanding and satisfaction; reduced anxiety (Wehrkamp et al., 2025; Evans et al., 2025)

Several challenges nonetheless distinguish OMFS navigation from that in more rigid anatomical regions. The maxilla and mandible move relative to one another, the head is often not rigidly fixed, and soft tissues deform during surgery, all of which complicate registration and its maintenance. Marker-based registration using splints or fiducials is accurate but adds invasiveness and workflow steps, whereas markerless registration is more convenient but generally less robust. Practical concerns include the potential for attention shift away from the field, system latency, the limited field of view and comfort of current headsets, and the additional time that set-up and registration can add to an operation. These factors explain why, despite strong technical results, routine intraoperative use remains limited.

A clear trend in recent work is the move towards portable, self-contained systems. Mixed-reality platforms built on a single headset exploit the device's integrated cameras and tracking to dispense with external optical hardware, and a recent portable MR navigation system for OMFS that combined headset-based marker tracking with a non-invasive patient-specific dental bracket reported a mean intraoperative registration error of roughly one and a half millimetres in a prospective clinical series, an accuracy considered sufficient for many OMFS tasks where sub-millimetre precision is not mandatory. Such systems trade a small amount of accuracy for substantial gains in mobility, simplicity, and sterility, and they exemplify the practical compromise that is likely to govern clinical adoption: a system that is good enough, hands-free, and easy to set up may be preferred over a marginally more accurate but cumbersome alternative. For the highest-precision tasks, such as implant placement with strict angulation requirements, the accuracy of current portable systems may nonetheless remain insufficient.

The case for AR and MR in navigation rests not only on accuracy but also on cognitive ergonomics. Conventional navigation requires the surgeon to divide attention between the operative field and a separate monitor, and to perform a continual mental transformation between the two coordinate frames. By presenting the plan in situ, immersive systems aim to remove this indirection, keeping the surgeon's gaze and attention on the patient and reducing the cognitive load of the operation. Whether this translates into measurable improvements in accuracy, speed, or safety, rather than merely a preferable experience, is a question that the current literature-dominated by feasibility and phantom-accuracy studies-has not yet answered convincingly. Demonstrating such clinical benefit, in adequately powered comparative studies against conventional navigation, is among the most important tasks for the field.

3.5. Patient Communication, Education, and Informed Consent

Informed consent requires that patients understand their condition, the proposed procedure, and its risks and alternatives, yet comprehension is frequently limited by health literacy and by the anxiety that a surgical consultation provokes. Because OMFS procedures often produce visible changes to the face and jaws, the ability to show patients a clear, patient-specific three-dimensional representation of their own anatomy and planned treatment is especially valuable. Immersive technologies offer exactly this capability, replacing abstract verbal descriptions and two-dimensional radiographs with interactive models.

The evidence, drawn largely from surgery in general rather than OMFS alone, is consistent in direction. A systematic review of VR, AR, and MR head-mounted displays during preoperative informed consent, encompassing sixteen studies and more than one thousand patients, found that these technologies improved patient understanding and satisfaction and reduced anxiety, with the most consistent benefits seen for VR and more variable results for AR and MR (Wehrkamp et al., 2025). A separate systematic review focused on AR for surgical consent and patient education similarly reported improvements in patient satisfaction and understanding, while cautioning that several studies were at high risk of bias and prone to a “novelty” effect that may overstate the benefit of an unfamiliar technology (Evans et al., 2025). For OMFS, the implication is that XR can strengthen shared decision-making and help to align patient expectations with realistic outcomes, provided that visualisations are presented honestly, with their uncertainty made explicit, and are not allowed to function as an implied guarantee of result.

Several mechanisms plausibly underlie these benefits. Seeing one’s own anatomy in three dimensions makes abstract risks concrete; interacting with a model promotes active rather than passive learning; and immersive experiences can occupy attention in a way that reduces procedural anxiety. In OMFS these mechanisms map onto common clinical scenarios: showing an orthognathic patient how their facial profile and occlusion will change, demonstrating the proximity of an implant to the nerve canal or sinus, or explaining the staged nature of reconstruction. Immersive distraction has also been used to reduce anxiety during procedures such as extractions. A further, often-overlooked benefit is documentary: a record that a patient viewed and engaged with a patient-specific visualisation may strengthen the evidential basis of consent. The same power to persuade, however, demands restraint. Because OMFS outcomes are influenced by biological variation, healing, and surgical execution, visualisations should be framed as expected rather than guaranteed results, and the novelty of the medium should not be allowed to inflate either patient expectation or perceived benefit (Wehrkamp et al., 2025; Evans et al., 2025).

4. Discussion

4.1. Clinical and Educational Implications and Current Maturity

Across the four domains, immersive technologies have reached different levels of maturity. Training is the most mature application: the supporting evidence includes multiple randomised controlled trials, and the case for VR and haptic simulation as effective, safe, and resource-efficient complements to conventional teaching is well established. Intraoperative navigation is technically advanced, with reported overlay and registration accuracies that are clinically attractive, but its routine clinical adoption lags behind its technical performance. Planning and patient communication occupy an intermediate position, with strong feasibility evidence and consistent, if largely subjective, benefits. The clearest gains across the pathway are improved spatial understanding, safer and more measurable skills acquisition, potentially more accurate plan execution, and better-informed, less anxious patients.

A unifying observation is that these four domains are not isolated. The same patient-specific three-dimensional dataset, derived from CBCT and surface imaging, can be reused along a single digital thread: to rehearse the case in VR, to plan it immersively, to navigate its execution in AR or MR, and to explain it to the patient. This continuity is one of the most compelling arguments for immersive technologies in OMFS, because the marginal cost of extending an existing three-dimensional plan into each successive use is modest once the data and infrastructure exist. It also means that improvements in one domain, such as more accurate segmentation or registration, propagate benefits across the others.

4.2. Limitations of the Evidence and Technical Challenges

These benefits must be weighed against substantial limitations. Much of the evidence comprises small, single-centre, feasibility or accuracy studies with heterogeneous designs and outcome measures, and comparatively few trials demonstrate improvements in hard clinical outcomes rather than in technical metrics or subjective impressions. The novelty of the technology is itself a source of bias, since enthusiastic early users may overstate benefits (Evans et al., 2025). Technically, OMFS poses specific difficulties for navigation: the

mobility of the mandible relative to the maxilla, the frequent absence of rigid head fixation, and intraoperative soft-tissue deformation all threaten the accuracy and stability of registration, while markerless methods that would simplify the workflow remain less robust than marker-based ones. For training, the imperfect realism of simulated oral tissues and physiological responses limits transfer to the clinical setting.

A further obstacle to interpreting the evidence is the absence of standardisation. Studies report different accuracy metrics-fiducial, target, and overlay errors are not interchangeable-and use different phantoms, reference standards, and clinical endpoints, so that headline figures cannot be compared directly. Training studies likewise vary in their assessment rubrics and rarely measure transfer to the operating room. Agreed reporting standards, common benchmark datasets and phantoms, and clear definitions of the reference “ground truth” would allow meaningful comparison between systems and accelerate the identification of those worth adopting.

4.3. Cost, Integration, and Ergonomics

Translation depends on factors beyond accuracy. Current head-mounted displays remain costly once bespoke software development is included, and the financial case-whether improved training, planning, or execution justifies the investment and its maintenance-is rarely quantified. Ergonomic limitations of present hardware, including a restricted field of view, headset weight and comfort, and the risk of attention shift away from the operative field, constrain prolonged intraoperative use. Integration into existing clinical pipelines is equally important: systems that export into established VSP and manufacturing environments, and that add discrete, checkable steps rather than replacing validated workflows, are more likely to be adopted. The learning curve for surgeons and the additional operative time that set-up and registration can introduce must also be accounted for.

The human factors of adoption are easily underestimated. Surgeons and their teams require time to become proficient with an unfamiliar interface, and during that learning period an immersive system may slow rather than speed an operation; indeed, some reports describe longer preparation times when AR is introduced. Set-up, registration, and verification add steps that must be justified by a commensurate benefit, and the technology must be reliable enough that a failure mid-procedure does not jeopardise the case. These considerations favour a measured, stepwise introduction-beginning with lower-risk uses such as training and patient communication-over an abrupt move to immersive intraoperative guidance.

4.4. Ethics, Safety, and Regulation

Software that guides surgical decisions or actions is generally regulated as a medical device, and clinical deployment therefore requires formal validation, clearance, and post-market surveillance, with transparent documentation of intended use and performance limits. Many of the systems reported in the literature are research prototypes that have not undergone such evaluation. Ethical considerations include patient safety should a navigation overlay be inaccurate or misleading, the protection of the three-dimensional imaging data on which these systems depend, honest communication during XR-assisted consent so that simulations are not mistaken for guarantees, and equitable access, since the cost of the technology may widen rather than narrow disparities in care.

The data dimension of these technologies deserves particular emphasis. Immersive systems depend on detailed three-dimensional reconstructions of a patient’s face and skull, which are highly identifying, and on their storage and transfer between imaging, planning, and headset platforms; each step raises questions of privacy, security, and consent for data use that are easily overlooked amid the focus on accuracy. Accountability is equally important: when a navigation overlay contributes to an intraoperative decision, responsibility for an error must remain clearly with the surgical team rather than diffusing into the technology, which argues for systems that support, and visibly defer to, human judgement.

4.5. Future Directions

The most promising developments are likely to combine improved engineering with rigorous evaluation. Markerless and artificial-intelligence-driven registration, together with deformation modelling that compensates for tissue movement, would address the central technical weakness of OMFS navigation. Lighter, wider-field, more comfortable headsets would ease intraoperative use, and tighter integration with VSP, robotics, and manufacturing would embed XR within existing workflows. Remote, XR-enabled mentoring and tele-proctoring could extend expert training to under-resourced settings. Above all, the field needs larger, multicentre, prospective studies with standardised outcome reporting that measure clinical and educational impact rather than technical accuracy alone, and that include cost-effectiveness analysis.

Convergence with artificial intelligence is likely to be especially consequential. Automated segmentation and landmarking can supply the three-dimensional models that immersive systems depend on more quickly and consistently than manual methods, while learning-based registration and deformation modelling could make markerless navigation both convenient and robust. Looking further ahead, the integration of imaging, planning, and intraoperative data into a continuously updated patient-specific model—a surgical “digital twin”—would allow immersive interfaces to display not only static anatomy but predicted outcomes and intraoperative changes. These directions reinforce the view that the future value of XR in OMFS lies less in the novelty of the display than in the quality, integration, and validation of the data behind it.

4.6. Limitations of This Review

This review is narrative rather than systematic; studies were selected for relevance and illustrative value rather than through an exhaustive, pre-registered protocol, and no formal quality scoring or quantitative pooling was performed. The performance figures cited are drawn from heterogeneous studies and are intended to convey the order of magnitude of current capability rather than to support direct comparison. Because the field is evolving quickly, specific results will date, although the broad conclusions regarding relative maturity, evidentiary gaps, and translational requirements are likely to remain valid in the near term.

5. Conclusions

Augmented, virtual, and mixed reality offer tangible benefits across the oral and maxillofacial surgery pathway. Immersive VR and haptic simulation provide effective, safe, and measurable surgical training; immersive planning improves the appreciation of complex three-dimensional anatomy; AR and MR navigation can overlay the surgical plan onto the operative field with sub-millimetre to low-millimetre accuracy; and patient-specific XR visualisation improves understanding and satisfaction and reduces anxiety during informed consent. Training is the most mature of these applications, while navigation is technically advanced but not yet routinely adopted.

At present, XR is best regarded as a powerful adjunct rather than a replacement for established techniques and clinical judgement. The supporting evidence is constrained by small, heterogeneous studies, registration and ergonomic challenges, novelty bias, cost, and a scarcity of data on long-term clinical outcomes. Realising the potential of these technologies will require robust, multicentre, prospective validation, attention to cost-effectiveness and workflow integration, clear regulatory and ethical frameworks, and continued engineering advances in registration, tracking, and hardware. With these conditions met, immersive technologies are well placed to make oral and maxillofacial surgery safer to learn, more precise to perform, and more clearly communicated to patients.

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