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Digital Revolution in Dentistry and Oral Surgery: A Comprehensive Review of AI, 3D Printing, Robotics and Virtual Surgical Planning

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Abstract

Digital technologies are fundamentally reshaping dentistry and oral–maxillofacial surgery (OMFS), transitioning clinical workflows from analogue, experience-dependent processes toward data-driven, patient-specific paradigms. This comprehensive review synthesizes the most recent evidence (2023–2026) on six converging technological domains: (1) artificial intelligence (AI) in diagnostics and surgical navigation, (2) three-dimensional (3D) printing and computer-aided design/computer-aided manufacturing (CAD/CAM), (3) virtual surgical planning (VSP), (4) robotic-assisted surgery, (5) augmented and mixed reality (AR/MR), and (6) bioprinting and tissue engineering for craniofacial reconstruction. AI-powered implant navigation systems now achieve angular deviations as low as 1.2° and tip errors of 0.4 mm, while robotic-assisted maxillofacial reconstruction has demonstrated mean positional deviations of 0.8 ± 0.3 mm versus 2.1 ± 0.7 mm for conventional surgery.

Keywords: artificial-intelligence, 3D-printing, CAD/CAM, virtual-surgical-planning, robotics, augmented-reality, bioprinting

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Introduction

The digital transformation of dentistry

The practice of dentistry and oral–maxillofacial surgery has undergone a profound transformation over the past decade. Traditional workflows that relied on plaster models, two-dimensional radiographs and manual surgical guides are progressively giving way to fully digital pipelines encompassing cone-beam computed tomography (CBCT), intraoral scanning, computer-aided design and manufacturing, and additive manufacturing. This shift has been propelled by advances in computing power, miniaturized sensors, cloud-based data management and, most recently, machine learning algorithms that can analyze imaging data with speed and consistency surpassing human performance in many tasks.[7][1][8][9][10]

The integration of these technologies is not simply an incremental improvement but represents a paradigm change in how clinicians diagnose, plan, execute and evaluate dental and surgical treatments. Patient-specific implants can now be designed on a computer screen and printed within hours; surgical movements can be simulated virtually before a scalpel is lifted; and robotic arms can guide osteotomies with sub-millimetre precision. Simultaneously, augmented and mixed reality systems are beginning to overlay digital plans onto the real surgical field, and bioprinting is moving from laboratory curiosity toward clinical translation for craniofacial tissue regeneration.[8][3][11][12][13][14][15][7]

Scope and rationale of this review

Despite the rapid pace of innovation, the evidence base is fragmented across subspecialties—implantology, orthognathic surgery, reconstructive surgery, prosthodontics, conservative dentistry—and across technology types. Clinicians seeking to adopt digital workflows face an overwhelming, sometimes contradictory literature. This review therefore aims to provide a unified, critical synthesis of the most recent evidence (2023–2026) across six major digital technology domains, evaluate their clinical impact, identify shared challenges and limitations, and outline a roadmap for future research and implementation.

Materials and Methods

Search strategy

A structured narrative review was conducted using PubMed, Scopus, Web of Science, Cochrane Library and Google Scholar. Search terms included combinations of: "digital dentistry," "3D printing oral surgery," "CAD/CAM dentistry," "virtual surgical planning orthognathic," "AI dental implant navigation," "robotic oral maxillofacial surgery," "augmented reality dentistry," "bioprinting craniofacial," "deep learning caries detection," and "digital workflow implant accuracy." Searches were limited to articles published from January 2023 to January 2026, with seminal earlier works included where necessary for context.

Selection criteria

Priority was given to systematic reviews, meta-analyses, randomized controlled trials, prospective cohort studies and scoping reviews published in peer-reviewed journals. Narrative reviews and expert opinions were included when primary data were sparse, particularly for emerging technologies such as robotic surgery and bioprinting. Conference abstracts and non-English publications were excluded unless they reported unique quantitative data not available elsewhere.

Data synthesis

Findings were organized thematically under six technology domains. For each domain, the review addresses: (a) technological principles and recent advances, (b) clinical applications and reported outcomes, (c) comparative data versus conventional approaches, and (d) limitations and knowledge gaps. Where quantitative pooled data from meta-analyses were available, these are presented; otherwise, individual study outcomes are discussed narratively.

Results

1. Artificial intelligence in diagnostics and surgical navigation

AI for caries detection

Artificial intelligence, particularly convolutional neural networks (CNNs), has emerged as a powerful tool for detecting dental caries on radiographic images. A 2025 systematic review and meta-analysis examining AI accuracy in caries detection found that deep learning models achieved sensitivity and specificity levels that frequently matched or exceeded those of experienced clinicians, substantially reducing inter-observer variability inherent in traditional visual and radiographic assessment. Additional studies in 2025 and 2026 confirmed that CNN-based systems accurately identify interproximal and occlusal caries on bitewing and panoramic radiographs, with particular promise for early-stage lesions that are often missed by the human eye. Multimodal AI approaches that integrate radiographic data with intraoral photographs and patient histories are now being explored to further improve diagnostic accuracy and reduce false positives.[16][17][18][10][19]

AI in implant planning and navigation

AI is transforming dental implant surgery through automated planning and real-time intraoperative guidance. A comprehensive scoping review covering 2019–2025 reported that AI algorithms can map bone structures with 96.4% accuracy, reducing planning time and errors compared with manual methods. During surgery, AI-enhanced dynamic navigation systems achieve angular errors as low as 1.2° compared with 3.8° in traditional dynamic navigation, and tip positioning errors of 0.4 mm even in challenging scenarios involving metallic restorations that distort imaging. A clinical audit of 245 patients demonstrated that AI-assisted navigation ensured 98% adherence to preoperative plans, including cases performed by novice surgeons, suggesting that AI can democratize expert-level surgical precision. Furthermore, AI-powered systems can reduce overall surgery time by up to 30%.[1][20]

A 2025 systematic review and meta-analysis comparing computer-assisted implant surgery (CAIS) approaches—static guided, dynamic navigated and robotic—against conventional freehand and guided techniques found that robotic CAIS (r-CAIS) achieved the highest placement accuracy overall, though the authors noted that high costs and operational complexity may limit suitability for straightforward cases. Fully digital static CAIS workflows reduced coronal global deviation to 0.85 mm (95% CI: 0.70–0.99) compared with 1.18 mm for partially digital workflows ($p < 0.05$).[21][22]

2. Three-dimensional printing and CAD/CAM

Principles and clinical devices

3D printing (additive manufacturing) has become an indispensable tool in oral and maxillofacial surgery, enabling the fabrication of patient-specific implants, surgical guides, splints, anatomical models and regenerative scaffolds directly from digital designs derived from CT or intraoral scan data. By conducting digital design on patient-derived anatomical data, surgeons develop devices precisely aligned with individual anatomy, improving surgical accuracy, reducing complication rates and shortening operative times. CAD/CAM technology streamlines complex workflows in prosthetic design, while 3D-printed bone models serve as cost-effective simulation tools for surgical training, replacing expensive and scarce cadaveric specimens.[7][8][23]

Clinical impact across subspecialties

In maxillofacial reconstruction, 3D printing enables the creation of custom titanium plates, patient-specific cutting guides and pre-bent reconstruction plates that facilitate more predictable free flap positioning and reduce intraoperative guesswork. In orthognathic surgery, 3D-printed surgical guides and splints translate virtual surgical plans into the operating room with translational deviations within 1.6–2.3 mm and rotational deviations between 1.2° and 2.75°. In implantology, 3D-printed surgical guides based on CBCT and intraoral scan data allow flapless, minimally invasive procedures with improved accuracy over freehand placement.[8][24][23][21][9][25]

Material advances

Recent reviews highlight expanding material options including biocompatible resins, polyether ether ketone (PEEK), titanium alloys and ceramic composites, with ongoing development of bioactive materials that promote osseointegration and tissue healing. The cost-effectiveness of 3D printing has improved substantially, with point-of-care manufacturing now feasible in many hospital settings, although standardization of material testing and quality control remains an area requiring further development.[23][26][7][8]

3. Virtual surgical planning

VSP in orthognathic surgery

Virtual surgical planning has revolutionized orthognathic surgery by replacing two-dimensional cephalometric analysis and hand-articulated model surgery with three-dimensional computer simulations. A 2025 systematic review and meta-analysis evaluating 474 patients across 10 studies found that VSP demonstrated superior accuracy in skeletal repositioning compared with traditional surgical planning (TSP), with postoperative positioning typically within ±2 mm of intended movements. A particularly striking finding is that up to 83% of two-dimensional treatment plans required significant corrections when converted to three-dimensional VSP, especially regarding yaw rotation and midline alignment, with skeletal interferences identified in nearly half of cases.[27][2]

Clinical benefits consistently reported include improved facial symmetry, shorter operative times, fewer intraoperative adjustments, higher aesthetic satisfaction scores and reduced relapse. The combination of VSP with CAD/CAM-fabricated patient-specific surgical guides and fixation plates further enhances the transfer accuracy of virtual plans into the operative field. However, limitations remain, particularly in soft tissue simulation and the need for manual adjustments when integrating CBCT data.[24][2][28][27]

VSP beyond orthognathics

VSP principles are also applied in trauma reconstruction, temporomandibular joint replacement and oncologic resection with microvascular free flap reconstruction, where precise osteotomy planning and pre-bent plates significantly reduce ischemia time and improve three-dimensional accuracy of the reconstructed mandible or maxilla.[8][23][29]

4. Robotic-assisted surgery

Current evidence

Robotic-assisted surgery in the oral and maxillofacial region represents an emerging but rapidly advancing frontier. A 2025 prospective randomized controlled trial of 120 patients requiring maxillofacial reconstruction compared robotic-assisted surgery ($n = 60$) with conventional techniques ($n = 60$) and found significantly higher precision in the robotic group (mean deviation 0.8 ± 0.3 mm vs. 2.1 ± 0.7 mm, $p < 0.001$). Although operative time was longer in the robotic group (245 ± 35 min vs. 195 ± 28 min, $p < 0.001$), it resulted in fewer complications (8.3% vs. 21.7%, $p = 0.032$) and better patient-reported satisfaction at six months (mean score 8.7 ± 1.2 vs. 7.2 ± 1.5, $p < 0.001$).[3]

In implantology, robotic CAIS has been identified as the most accurate computer-assisted approach in a 2025 systematic review and meta-analysis, outperforming both static and dynamic guided approaches in angular and positional accuracy. Robot-guided laser osteotomy for bone cutting in OMFS is also under active investigation, with early accuracy data suggesting advantages over conventional oscillating saws in complex geometries.[22][30]

Future trajectory

Expert projections anticipate substantial transformation of OMFS by 2030, with robotic systems expected to expand into complex reconstruction, TMJ surgery, orthognathic procedures and minimally invasive approaches. The integration of AI with robotic platforms, real-time haptic feedback, and tele-surgical capabilities are identified as key development priorities. However, current barriers include high capital and maintenance costs, operating room space requirements, the need for specialized training, and limited evidence from multicenter, long-term outcome studies.[11][31]

5. Augmented reality and mixed reality

Clinical applications

Augmented reality (AR) and mixed reality (MR) systems overlay digital information—such as implant trajectories, anatomical landmarks and nerve paths—directly onto the surgical field or the surgeon's visual display, enabling real-time navigation without the need to look away at a separate screen. A 2025 study introduced a consumer smartphone-based AR system for real-time navigation in dental implant placement, demonstrating feasibility and acceptable accuracy in a clinical setting. A portable MR navigation system for OMFS was reported in 2025, expanding the potential for AR/MR adoption beyond specialized centers equipped with expensive head-mounted displays.[14][15][32][33]

In dental education, AR and VR environments are enhancing training by providing immersive, repeatable simulations of complex procedures, with evidence that VR-based training improves psychomotor skill acquisition and reduces the learning curve for invasive procedures such as implant placement and orthognathic surgery. AR has also been applied to patient communication, allowing three-dimensional visualization of treatment plans to improve informed consent and satisfaction.[5][33][14]

Limitations

Adoption challenges include high implementation costs, limited haptic feedback, latency in real-time rendering, calibration requirements and the complexity of integrating AR/MR into existing clinical workflows. Robust evidence from randomized trials comparing AR/MR-guided surgery with conventional or standard navigated approaches remains scarce, and long-term outcome data are lacking.[34][33][14]

6. Bioprinting and tissue engineering

Principles and progress

Three-dimensional bioprinting represents a paradigm shift in craniofacial tissue engineering by enabling the fabrication of cellularized constructs that combine biomaterial scaffolds with living cells and growth factors, closely mimicking native tissue architecture. Recent reviews (2025–2026) describe advances in bioprinted constructs for bone defect repair, cranial reconstruction, cartilage regeneration and localized therapeutic delivery in the craniofacial region.[35][12][13][36][37]

Key innovations include immunomodulatory scaffolds that direct the local immune response toward regeneration, multiphasic vascularized constructs that address the critical challenge of nutrient supply in large grafts, and the use of multiple bioink materials within a single print to recreate the heterogeneous tissue composition of craniofacial structures. Clinical translation has advanced to the point where customized bioprinted bone implants have been successfully implanted in human patients with maxillofacial defects in Phase 4 clinical settings, with high aesthetic and functional success rates reported, though isolated infection events underscore the need for continued safety monitoring.[12][13]

Challenges to clinical adoption

Despite exciting progress, bioprinting for craniofacial applications faces substantial translational barriers, including difficulties in achieving adequate vascularization of large constructs, long-term mechanical stability, regulatory approval pathways for patient-specific living implants, scalability of manufacturing and cost. Future directions emphasize the integration of bioprinted, vascularized, multiphasic tissues alongside personalized therapies and advanced fabrication techniques to accelerate clinical adoption.[13][37][35][12]

Discussion

Convergence and synergy across technologies

A central theme emerging from this review is the convergence of multiple digital technologies into integrated workflows that are more powerful than any single innovation in isolation. For example, a contemporary implant case may involve CBCT acquisition, AI-automated bone segmentation, virtual implant planning, CAD/CAM surgical guide fabrication via 3D printing, AI-enhanced dynamic navigation during surgery and AR overlay for real-time verification—all within a single clinical pathway. Similarly, complex orthognathic or reconstructive cases increasingly combine VSP, 3D-printed patient-specific guides and plates, intraoperative navigation and, in emerging protocols, robotic assistance.[1][8][24][2][3][21][9][25][15]

This convergence is reflected in the market: the global digital dentistry devices market, valued at USD 4.14 billion in 2024, is projected to grow at a compound annual rate of 9.7% to reach USD 7.77 billion by 2032, driven by CAD/CAM, 3D printing, AI integration and rising demand for minimally invasive, personalized treatments.[6]

Evidence quality and gaps

While the volume of published research is impressive, the quality of evidence varies substantially across domains. AI in caries detection benefits from multiple systematic reviews and meta-analyses with large pooled datasets, and VSP in orthognathic surgery is supported by a growing body of comparative studies and meta-analyses. In contrast, robotic surgery in OMFS relies primarily on a single large RCT and several smaller series, and AR/MR evidence is dominated by feasibility studies and small observational reports. Bioprinting, despite rapid preclinical progress, has only isolated Phase 4 case reports in the craniofacial literature.[27][24][2][28][3][13][14][15][10][33]

A consistent limitation across domains is the scarcity of long-term outcome data. Most studies report short-term accuracy, operative efficiency or immediate complication rates, but few track implant survival, functional outcomes or patient-reported quality of life over years or decades. This is particularly relevant for AI-selected implant placements, 3D-printed custom implants and bioprinted tissues, where long-term biological behavior and mechanical durability are critical but largely unknown.

Barriers to adoption

Several cross-cutting barriers emerge:

- Cost: High initial investment in hardware (intraoral scanners, 3D printers, robotic systems, AR headsets), software licensing and maintenance remains prohibitive for many practices, especially smaller clinics and those in low-resource settings.[4][5][38][39]
- Learning curve: Each technology requires dedicated training, and the pace of technological change often outstrips educational curricula. Many dental technicians and clinicians need intensive retraining, and faculty development lags behind clinical innovation.[5][38][39][4]
- Standardization: Lack of universal file formats, interoperability standards and validated clinical protocols makes it difficult to compare outcomes across centers and creates vendor lock-in.[9][40][25][5]
- Regulatory frameworks: Novel technologies such as AI diagnostic tools, patient-specific 3D-printed implants and bioprinted living tissues exist in regulatory grey zones in many jurisdictions, slowing adoption and creating liability uncertainty.[1][13][5]

- Equity: The concentration of advanced digital infrastructure in high-income settings risks widening disparities in access to state-of-the-art dental and surgical care.[11][1][5]

Ethical and regulatory considerations

AI-driven clinical decision support raises questions about algorithmic transparency, bias, accountability and the appropriate balance between automated recommendations and clinician judgment. Clinicians should view AI as a partner rather than a replacement, leveraging its capabilities while preserving professional judgment to deliver patient-centered care. For bioprinting and patient-specific living implants, ethical frameworks for informed consent, long-term safety surveillance and equitable access are urgently needed.[1][35][12][13][17][18]

Future directions

The next wave of innovation is likely to include:

- AI-AR integration: Real-time projection of AI-optimized surgical plans directly onto the operative field via AR/MR headsets, eliminating the cognitive load of translating screen-based plans into physical space.[1][14][15]
- Autonomous and semi-autonomous robotics: Robotic systems capable of performing defined surgical subtasks (osteotomies, implant drilling) with minimal human intervention, supported by AI-driven real-time error correction and haptic feedback.[11][31][30]
- Personalized bioprinted grafts: Vascularized, multiphasic tissue constructs printed from autologous cells and tailored to patient-specific defect geometries, moving craniofacial reconstruction beyond the current paradigm of donor site morbidity.[12][13][36][37]
- Cloud-based, federated AI training: Large-scale, multi-institutional datasets enabling more generalizable AI models that perform consistently across diverse populations and imaging protocols.[10][1]
- Cost reduction and accessibility: Miniaturization, open-source platforms and point-of-care manufacturing are expected to progressively lower barriers, potentially making advanced digital workflows accessible to a broader range of clinical settings globally.[7][23][6]

Conclusion

Dentistry and oral–maxillofacial surgery stand at the threshold of a genuinely intelligent era. The six technology domains reviewed here—AI, 3D printing/CAD/CAM, virtual surgical planning, robotics, augmented/mixed reality and bioprinting—are no longer isolated innovations but increasingly interlocking components of integrated, patient-specific clinical workflows. The evidence accumulated between 2023 and 2026 demonstrates measurable improvements in diagnostic accuracy, surgical precision, operative efficiency and, in early reports, patient satisfaction and complication rates. AI-enhanced navigation achieves implant placement accuracy measured in fractions of a millimetre; virtual surgical planning has made traditional two-dimensional cephalometric prediction nearly obsolete for complex orthognathic cases; and robotic surgery is beginning to show that superior precision need not come at the cost of higher complications—indeed, the opposite may be true.

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