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Artificial Intelligence in Oral and Maxillofacial Surgery: Current Transformations and Future Horizons

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Abstract

Oral and maxillofacial surgery (OMFS) is experiencing a paradigm shift driven by the rapid integration of artificial intelligence (AI) into clinical practice. This article provides a comprehensive overview of AI's current and future applications across the entire OMFS care continuum from diagnostics and virtual surgical planning to intraoperative guidance, robotics, and postoperative outcome prediction. Recent advancements demonstrate that AI-powered image analysis, particularly deep learning models like convolutional neural networks (CNNs) and the nnU-Net framework, can achieve high accuracy in segmenting complex craniomaxillofacial anatomy, detecting tumors, and automating landmark identification for orthognathic surgery planning. In virtual surgical planning, AI algorithms now enable sub-millimeter accuracy in predicting soft tissue changes following jaw repositioning and facilitate the design of patient-specific implants (PSIs). Intraoperatively, the convergence of AI with augmented reality (AR) navigation and robotic systems is enhancing surgical precision, with recent studies demonstrating AR-based guidance achieving mean deviations under 2 mm and robotic-assisted contouring reaching sub-2 mm accuracy. Looking toward the future, this article explores emerging frontiers including multimodal AI that fuses CT/MRI/PET data for comprehensive tumor assessment, real-time "videomics" analysis of surgical video, large language models for clinical decision support, and fully autonomous robotic subsystems for specific surgical tasks. However, the integration of AI into OMFS is not without challenges, including data heterogeneity, algorithmic bias, the "black box" problem of explainability, regulatory hurdles, and the need for prospective multicenter validation. This article argues that the future of OMFS lies in synergistic human-AI collaboration, where AI augments rather than replaces the surgeon's expertise, ultimately leading to more precise, personalized, and predictable patient outcomes.

Keywords: Artificial Intelligence, Oral and Maxillofacial Surgery, Deep Learning, Surgical Robotics, Augmented Reality, Virtual Surgical Planning, Precision Medicine, Computer-Aided Diagnosis.

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Introduction

The Evolution of Oral and Maxillofacial Surgery

Oral and maxillofacial surgery (OMFS) stands at the unique intersection of dentistry, medicine, and surgical specialty, encompassing procedures ranging from routine dentoalveolar surgery to complex craniofacial reconstruction, tumor resection, and orthognathic correction. The complexity of the craniomaxillofacial region with its intricate three-dimensional anatomy, vital neurovascular structures, and profound aesthetic and functional implications has historically demanded exceptional surgical skill, experience, and spatial reasoning. For decades, surgical planning relied on two-dimensional radiographs, clinical examination, and the surgeon's mental reconstruction of anatomy [1-5].

The late 20th and early 21st centuries witnessed the first wave of digital transformation in OMFS through the adoption of computed tomography (CT), cone-beam CT (CBCT), and magnetic resonance imaging (MRI), followed by virtual surgical planning (VSP) and computer-aided design/computer-aided

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manufacturing (CAD/CAM) for patient-specific implants. These technologies represented a significant leap forward, enabling surgeons to rehearse complex procedures digitally and fabricate custom cutting guides and implants. However, these tools remained largely passive they required extensive manual input, were time-consuming, and their accuracy depended heavily on operator expertise [6-10].

The Artificial Intelligence Revolution

The current wave of transformation is defined by intelligence, automation, and connectivity. Artificial intelligence (AI), particularly its subset machine learning (ML) and deep learning (DL), is fundamentally changing how oral and maxillofacial surgeons approach diagnosis, planning, execution, and follow-up. Unlike traditional software that follows explicit programmed instructions, AI systems learn from vast amounts of data, identifying patterns and making predictions with increasing accuracy [11-14].

Deep learning, inspired by the structure of the human brain, utilizes artificial neural networks with multiple layers to automatically learn hierarchical representations of data. Convolutional neural networks (CNNs) have proven exceptionally powerful for medical image analysis, while recurrent neural networks (RNNs) and transformer architectures are well-suited for sequential data and natural language processing. In OMFS, these technologies are being applied across the entire surgical care pathway:

- Diagnostics: Automated detection of fractures, tumors, and pathologies from radiographs and advanced imaging
- Planning: Automated segmentation, landmark detection, and proposal of osteotomy lines or implant trajectories
- Intraoperative guidance: AI-powered augmented reality (AR) navigation and robotic assistance
- Outcome prediction: Forecasting postoperative swelling, blood loss, and aesthetic results
- Administrative workflow: Patient triage, scheduling, and documentation

Scope and Objectives

This article aims to provide a comprehensive and forward-looking review of AI in oral and maxillofacial surgery. It synthesizes current evidence from peer-reviewed literature, clinical studies, and expert commentaries published up to 2026, with a particular focus on:

1. Current applications of AI in OMFS diagnostics, planning, and intraoperative guidance
2. The convergence of AI with robotics and augmented reality
3. Emerging future directions including multimodal AI, videomics, and large language models
4. Critical challenges and limitations that must be addressed for responsible clinical integration
5. A vision for the future of human-AI collaboration in OMFS

By examining both the transformative potential and the significant hurdles that remain, this article seeks to provide oral and maxillofacial surgeons, researchers, and trainees with a roadmap for navigating the AI-driven future of their specialty [15-18].

AI in Diagnostic Imaging and Preoperative Assessment

The Foundation: Machine Learning and Deep Learning in Medical Imaging

Medical imaging is the cornerstone of OMFS diagnosis and planning. The craniomaxillofacial region presents unique challenges for image interpretation due to its complex three-dimensional anatomy, overlapping structures, and the presence of both hard and soft tissues with varying densities. AI, particularly deep learning, has emerged as a powerful tool to augment the surgeon's interpretive capabilities.

Machine learning algorithms can be broadly categorized into:

- Supervised learning: Models trained on labeled datasets to predict outcomes (e.g., fracture detection in CT scans)
- Unsupervised learning: Models that identify patterns in unlabeled data (e.g., clustering similar cases, detecting anomalies)

Deep learning, utilizing multilayered neural networks, has proven exceptionally effective in medical imaging analysis. Convolutional neural networks (CNNs) automatically learn hierarchical features from images starting with edges and textures, then progressing to shapes, and finally to entire anatomical structures or pathologies [19-22].

Automated Segmentation of Craniomaxillofacial Structures

One of the most clinically impactful applications of AI in OMFS is automated image segmentation the process of delineating anatomical structures of interest. Manual segmentation of CT or MRI scans is time-consuming, labor-intensive, and subject to inter-operator variability. AI-powered segmentation tools can dramatically reduce this burden while improving consistency.

The nnU-Net framework, a deep learning-based segmentation method that automatically configures itself for new datasets, has demonstrated remarkable accuracy in segmenting craniomaxillofacial CT scans. Dot et al. demonstrated fully automatic segmentation of craniomaxillofacial CT scans for computer-assisted orthognathic surgery planning using the nnU-Net framework, achieving results comparable to manual segmentation. Similarly, deep learning models have been developed to automatically identify cephalometric landmarks with accuracy surpassing human experts in some cases.

Multimodal Image Fusion for Tumor Assessment

Oral and maxillofacial tumors often involve both bone and soft tissues, making accurate preoperative assessment challenging. CT provides excellent visualization of bony structures, while MRI offers superior soft tissue contrast. The integration of these modalities multimodal image fusion provides complementary information essential for determining safe surgical margins.

A recent pilot study by Wu et al. evaluated deep learning-based multimodal CT/MRI image fusion and segmentation strategies for surgical planning of oral and maxillofacial tumors. The study trained nine hybrid deep learning models combining three fusion algorithms (Elastix, ANTs, and NiftyReg) with three segmentation models (nnU-Net, 3D UX-Net, and U-Net). Results demonstrated that the Elastix and nnU-Net combination achieved a Dice coefficient of 0.89 for tumor segmentation, indicating high accuracy. The authors concluded that deep learning-based multimodal image fusion is feasible and could serve as a foundation for virtual surgical planning [23-25].

Detection of Pathologies and Anatomical Variations

Beyond segmentation, AI algorithms have been trained to detect a wide range of pathologies relevant to OMFS. Deep learning models have demonstrated superior accuracy in detecting oral lesions, tumors, and fractures, significantly improving early diagnosis and patient outcomes. In third molar surgery, CNNs have achieved 78.9-90.2% accuracy for predicting extraction difficulty.

AI-powered algorithms can also enhance CBCT image quality by reducing motion artifacts, ensuring clearer imaging and minimizing repeat scans. Furthermore, recent AI-based imaging research has demonstrated high precision in detecting anatomic variations of the mandible and maxilla that are clinically relevant to surgical safety and preoperative planning.

Diagnostic Performance: Evidence from Systematic Reviews

A systematic review by Abdali et al. synthesized AI applications in oral and maxillofacial cosmetic surgery, focusing on diagnostic support. The review found that in orthognathic diagnostics, models using cephalograms and facial photographs reported accuracies above 90%, with specificity up to 99%. For perioperative risk assessment, neural networks predicted postoperative swelling with 98% accuracy and blood loss with mean errors less than 10 mL. These findings underscore the significant potential of AI to enhance diagnostic accuracy and risk prediction in OMFS [26-29].

AI in Virtual Surgical Planning and Custom Implant Design

From Manual Planning to AI-Augmented Workflows

Virtual surgical planning (VSP) has become standard practice in complex OMFS procedures, including orthognathic surgery, tumor resection, and facial reconstruction. Traditional VSP involves manual segmentation, landmark identification, and iterative communication between surgeons and biomedical engineers a process that can take days or weeks. AI is rapidly transforming this workflow by automating time-consuming steps and enhancing planning accuracy [30-32].

Automated Landmark Detection and Osteotomy Planning

Cephalometric analysis, essential for orthognathic surgery planning, traditionally requires manual identification of dozens of anatomical landmarks on lateral cephalograms a tedious and error-prone task. Deep learning models have been developed to automatically identify these landmarks with accuracy comparable to expert orthodontists. Hwang et al. demonstrated that automated landmark identification could potentially outperform human experts in terms of consistency and reproducibility.

Beyond landmark detection, AI algorithms are being developed to propose virtual osteotomy lines and segment repositioning vectors tailored to each patient's anatomy and aesthetic goals. In implantology, Che et al. reported a multicenter study of an AI-based 3D implant planning tool, showing that the AI tool may reduce planning time and assist clinicians in standardizing trajectories, though further refinement is still needed. Similarly, Qiu et al. assessed how AI models perform in evaluating bone quality and quantity in implant planning from radiographic images, highlighting that AI can provide automated assessments that may support decision-making workflows [33-35].

Prediction of Soft Tissue Outcomes

One of the most challenging aspects of orthognathic surgery planning is predicting how facial soft tissues will respond to underlying skeletal movements. Accurate soft tissue prediction is crucial for informed consent and patient satisfaction. AI models have demonstrated remarkable capability in this domain [36-38].

Ter Horst et al. developed a deep learning-based approach for three-dimensional virtual planning in mandibular advancement surgery, achieving sub-millimeter accuracy (~1 mm error) in predicting soft tissue changes. A systematic review by Abdali et al. confirmed that AI models for predicting soft-tissue changes can achieve sub-millimeter error margins, outperforming conventional prediction methods. Rana et al. reported that over one hundred patient-specific orbital floor reconstructions have been successfully completed using AI-enhanced image datasets from CT/MRI to guide implant design, demonstrating the clinical translation of these technologies.

AI-Generated Patient-Specific Implants (PSIs)

Patient-specific implants, fabricated via additive manufacturing (e.g., selective laser melting of titanium), offer significant advantages over stock implants, including reduced intraoperative manipulation, improved fit, and potentially reduced operating time. AI is increasingly being integrated into the PSI design workflow.

Generative AI models can analyze a patient's CT data and compare it to thousands of prior cases to propose an initial implant design or bone graft contour that optimally fits the defect. This AI-assisted design process reduces the manual workload for engineers and can lead to more optimal implant geometries. In mandibular reconstructions, integrating AI into the planning of 3D-printed titanium implants has enhanced the fit and functionality of these prosthetics, reducing the need for intraoperative adjustments [39-41].

Clinical Outcomes with Custom Implants

Reported series in facial plastic and craniofacial surgery suggest "fidelity to plan" in over 90% of cases when using combined cutting guides and custom fixation. In facial reconstructive surgery, several series have attested to implant survival rates greater than 96% at 12 months, with functional improvement in mastication and speech. These outcomes give confidence for the continued translation of AI-enhanced PSIs into routine clinical practice.

Intraoperative AI: Navigation, Augmented Reality, and Robotics

The Challenge of Intraoperative Precision

Translating a virtual surgical plan to the actual operative field with high fidelity remains one of the greatest challenges in OMFS. Small deviations can lead to suboptimal aesthetic outcomes, functional impairment, or injury to vital structures. AI is increasingly being integrated into intraoperative guidance systems to enhance precision and safety [42-45].

Augmented Reality (AR) Navigation

Augmented reality permits the overlay of virtual plans onto the real anatomical field, offering the surgeon live guidance without diverting attention to a separate navigation screen. In orthognathic surgery, this means seeing planned osteotomy lines, segment repositioning vectors, or screw trajectories projected directly onto the patient.

A hallmark study by Żelechowski et al. (2024) compared AR-based navigation techniques with conventional drilling guides in an orthognathic context. They tested two AR methods (one using ArUco marker tracking, another using infrared tracking) and found that AR navigation yielded comparable or even improved accuracy (mean deviations under 2 mm) relative to conventional guides. This work represents a paradigm shift, demonstrating that AR is no longer a future concept but is entering pilot clinical use.

Technical considerations for AR guidance include:

- Registration accuracy: The alignment between patient anatomy and virtual plan must be precise. Errors in registration can propagate to misguidance. Recent strategies involve using fiducial markers or markerless deep learning detection of landmarks to permit continuous image-to-patient alignment.
- Latency: The lag between surgeon motion and AR update must be minimal (< tens of milliseconds) to permit real-time use. Hardware advances and optimized tracking pipelines are critical.
- Tool tracking: A promising approach is STTAR, which uses built-in cameras of AR head-mounted displays to detect retro-reflective markers on instruments without external tracking hardware. This method achieved translational accuracy of 0.09 ± 0.06 mm laterally and rotational accuracy of $0.80 \pm 0.39°$ in test settings [46-48].

AI-Powered Surgical Robotics

Robotic systems are being developed to assist with intricate surgical procedures, offering enhanced precision and potentially reducing the invasiveness of operations. The integration of AI with surgical robotics enables capabilities beyond traditional computer-assisted navigation.

A recent study by Liu et al. (2024) published in BMC Oral Health presented a novel dual-stage robotic-assisted surgical workflow for precision contouring of craniomaxillofacial fibrous dysplasia. The workflow comprised:

1. Robotic localization and depth-controlled drilling: Using a dentition-supported optical registration system for titanium screw placement
2. Automated high-speed robotic contouring: Following the surgical plan

The study included five patients with craniomaxillofacial fibrous dysplasia. All surgeries were completed successfully according to virtual plans, with no intraoperative or postoperative complications. Quantitative evaluation revealed a mean root mean square deviation (RMSD) of 1.77 ± 0.58 mm (range 1.22-2.77 mm), indicating high consistency between planned and actual outcomes. The orbital rim and maxillary surfaces demonstrated the smallest deviations, confirming the accuracy of robotic-guided resection [49-51].

Autonomous Robotic Systems

The Stomatology Hospital of Air Force Medical University in China recently completed the world's first autonomous oral surgery robot-led orthognathic surgery, marking a significant technological breakthrough. While fully autonomous robotic surgery remains in early stages, these developments signal a future where AI-powered robots may perform specific surgical tasks under surgeon supervision.

Commercial development in this space is accelerating. Yangshan Medical, an oral surgery robot company, has developed an unobstructed surgical robot using new navigation technology that features "zero registration, no obstruction, anti-interference, fast surgery, short learning curve, and miniaturization". Such innovations aim to make robotic assistance more accessible and user-friendly for oral and maxillofacial surgeons.

Synergistic Integration: AI + AR + Robotics

When viewed in concert, AI, AR, and robotics form an integrated pipeline from preoperative planning to intraoperative execution:

- Imaging + AI → Preprocessing, segmentation, landmark detection
- Virtual plan generation → Osteotomies, repositioning, aesthetic simulation
- Design of custom implants & guides → Translating plan to physical objects
- AR / navigation assistance → Intraoperative execution with real-time guidance
- Robotic assistance → Precision execution of planned maneuvers
- Quality control → Verification and potential intraoperative adjustment

This integrated approach aims to decrease cumulative spatial error, reduce operating time, enhance symmetry and aesthetic predictability, and improve reproducibility across operators.

AI for Outcome Prediction and Perioperative Management

Beyond the Operating Room: The Full Care Continuum

AI's role in OMFS extends beyond diagnosis and intraoperative guidance to encompass the entire perioperative journey from risk assessment and patient counseling to outcome prediction and long-term follow-up. These applications have significant implications for personalized patient care and shared decision-making [52-54].

Predicting Surgical Difficulty and Complications

Accurate preoperative assessment of surgical difficulty and potential complications allows for appropriate case selection, patient counseling, and resource allocation. AI models have demonstrated promising performance in this domain [55-57].

In third molar surgery, CNNs have achieved 78.9-90.2% accuracy for predicting extraction difficulty based on radiographic features. This information can help surgeons identify cases that may require referral to specialists or additional preoperative imaging.

For perioperative risk assessment, neural networks have been trained to predict:

- Postoperative swelling: Zhang et al. developed artificial neural networks that predicted postoperative facial swelling following impacted mandibular third molar extraction with 98% accuracy
- Blood loss: AI models have predicted intraoperative blood loss with mean errors less than 10 mL
- Length of hospital stay: Machine learning algorithms can integrate patient factors and procedural complexity to predict resource utilization

Aesthetic Outcome Prediction

In orthognathic and cosmetic facial surgery, aesthetic outcomes are paramount. AI models capable of simulating postoperative appearance with high accuracy serve multiple purposes:

- Informed consent: Patients can visualize expected outcomes before committing to surgery
- Treatment planning: Surgeons can compare different surgical approaches and select the one most likely to achieve aesthetic goals
- Managing expectations: Realistic simulations help align patient and surgeon expectations, potentially reducing dissatisfaction

A systematic review by Abdali et al. found that AI models for predicting soft-tissue changes achieved sub-millimeter error margins, outperforming conventional prediction methods. For rhinoplasty, AI applications have quantified age reduction post-surgery and generated simulations with high surgeon agreement.

Large Language Models (LLMs) for Clinical Decision Support

Large language models like ChatGPT are being explored for their potential to support clinical decision-making in OMFS. A review by Haji Bagheri et al. assessed the accuracy of ChatGPT in answering Oro maxillofacial surgery questions. The study found that ChatGPT might be able to assist in responding to Oro maxillofacial questions for supporting clinicians, but its role remains supportive rather than replacing professional expertise. Further development is necessary to enhance the model's ability to handle the complexities of clinical practice, where patient care requires more detailed, context-specific knowledge.

Similarly, Acar investigated whether natural language processing could serve as a consultant in oral surgery, highlighting both the potential and current limitations of these technologies. Puladi et al. provided a narrative review on the impact and opportunities of large language models like ChatGPT in OMFS, emphasizing the need for careful validation before clinical deployment.

Workflow Optimization and Patient Communication

Beyond direct clinical applications, AI is being deployed to optimize OMFS practice operations. Early deployments in OMFS clinics have demonstrated:

- Increased appointment bookings through AI-powered scheduling systems
- Reduced administrative burden through automated documentation
- High patient satisfaction maintained while improving efficiency

AI-powered patient communication tools can provide personalized preoperative instructions, answer common questions, and facilitate remote monitoring of postoperative recovery. These applications free clinical staff to focus on more complex patient interactions while ensuring patients receive timely, accurate information [58-60].

The Future of AI in OMFS: Emerging Frontiers

Multimodal AI: Integrating Diverse Data Streams

Current AI applications in OMFS largely focus on single data modalities primarily imaging. The future lies in multimodal AI systems that simultaneously analyze and integrate diverse data types to provide comprehensive patient assessment and personalized treatment recommendations.

For oral and maxillofacial tumors, multimodal AI could integrate:

- Anatomical imaging: CT for bone, MRI for soft tissue
- Functional imaging: PET for metabolic activity
- Genomic data: Tumor molecular profiles
- Clinical data: Patient demographics, comorbidities, functional status
- Patient-reported outcomes: Quality of life measures, aesthetic concerns

Such integrated models could predict not only optimal surgical margins but also likelihood of recurrence, functional outcomes, and even guide adjuvant therapy decisions. The pilot study by Wu et al. on multimodal CT/MRI fusion for tumor segmentation represents an early step toward this integrated future.

Videomics and Computer Vision in the Operating Room

"Videomics" the extraction of quantitative data from surgical video represents an emerging frontier for AI in surgery. Computer vision algorithms can analyze intraoperative video to:

- Track surgical instruments and provide real-time feedback on technique
- Identify critical anatomical structures and warn of impending danger
- Document surgical steps for quality assurance and education
- Assess surgeon performance and provide objective feedback for training

Paderno et al. discussed computer vision and videomics in otolaryngology-head and neck surgery, highlighting the potential to bridge the gap between clinical needs and the promise of artificial intelligence. In OMFS, where procedures often involve critical neurovascular structures and precise osteotomies, real-time computer vision guidance could significantly enhance safety and precision.

Generative AI and Synthetic Data

Generative AI models, which can create new, realistic data samples, have significant potential applications in OMFS:

- Generative design for implants: AI could generate thousands of implant design variations optimized for different criteria (strength, weight, osseointegration potential) and present optimal options to surgeons
- Synthetic training data: To overcome data scarcity and privacy concerns, generative models could create realistic, anonymized synthetic patient data (CT scans, 3D facial photos) for training new AI models and surgical simulators
- Surgical simulation: Generative models could create realistic surgical scenarios for resident training, including rare pathologies and complications

The RESORBM initiative, which applies machine learning to optimize the design and degradation profile of resorbable molybdenum-alloy implants for pediatric craniofacial patients, exemplifies this generative approach [61].

Federated Learning and Privacy-Preserving AI

One of the major barriers to developing robust AI models for OMFS is the difficulty of aggregating large, diverse datasets from multiple institutions due to privacy concerns and regulatory restrictions. Federated learning offers a solution: AI models are trained across multiple decentralized institutions without exchanging patient data. Each institution trains the model on its local data, and only model updates (not patient data) are shared to improve a global model.

This approach could enable the development of more generalizable AI models that perform well across diverse populations and imaging protocols, addressing one of the major limitations of current single-center studies.

Explainable AI (XAI) for Surgical Decision-Making

The "black box" nature of many deep learning models remains a significant barrier to clinical adoption. Surgeons cannot trust and patients cannot consent to decisions they cannot understand or explain. Explainable AI (XAI) aims to create models that provide transparent rationales for their outputs [62].

In OMFS, XAI could generate heatmaps showing which image regions influenced a diagnosis, highlight specific anatomical features that drove a treatment recommendation, or provide confidence intervals for predictions. Such transparency is essential for regulatory approval, medicolegal defensibility, and clinical acceptance.

The Future of AI in OMFS: The Evolving Role of the Surgeon

From Operator to Orchestrator

As AI systems become more sophisticated, the role of the oral and maxillofacial surgeon will inevitably evolve. Rather than being replaced by AI, surgeons will transition from being primary operators and decision-makers to becoming "orchestrators" of AI-powered surgical ecosystems.

This evolution mirrors historical patterns in surgery: the introduction of surgical navigation didn't replace surgeons but made them more precise; the adoption of endoscopic visualization didn't replace surgeons but expanded their capabilities. AI will similarly augment surgical practice rather than render it obsolete [63].

Core Competencies for the AI-Augmented Surgeon

The surgeon of the future will require an expanded skill set beyond traditional surgical technique:

1. Critical evaluation of AI outputs: Surgeons must understand the strengths and limitations of AI models to appropriately interpret their recommendations. This requires fundamental knowledge of AI concepts, data science, and statistical validation.
2. Integration of multimodal information: As AI systems present increasingly complex, integrated data, surgeons must synthesize this information with their clinical judgment and patient-specific factors to make optimal decisions.
3. Management of AI systems: In institutional settings, surgeons may oversee AI implementation, including selecting appropriate algorithms, monitoring performance, and updating models as new evidence emerges.
4. Ethical oversight: Surgeons bear ultimate responsibility for patient outcomes and must ensure AI systems are used ethically, with appropriate attention to bias, privacy, and informed consent.
5. Preservation of humanistic care: The uniquely human aspects of surgical care empathy, trust-building, understanding patient values and fears will become even more central as technical tasks are increasingly automated [64].

Training the Next Generation

The integration of AI into OMFS training presents both opportunities and challenges. AI-powered surgical simulators could provide residents with unlimited, realistic practice opportunities with objective performance feedback. Virtual patients with AI-generated pathologies could supplement clinical exposure, ensuring trainees encounter rare conditions.

However, training programs must also incorporate new curricula covering:

- Fundamentals of AI and data science
- Interpretation and critical appraisal of AI research
- Ethical and legal aspects of AI in healthcare
- Communication skills for discussing AI-assisted care with patients

Human-AI Collaboration: A Framework

Successful integration of AI into OMFS practice requires a clear framework for human-AI collaboration. Hashimoto et al. outlined promises and perils of AI in surgery, emphasizing that AI should complement rather than replace human expertise. A practical framework might include:

- AI proposes, surgeon disposes: AI generates treatment recommendations or plan options; the surgeon selects and refines based on clinical judgment and patient preferences
- AI monitors, surgeon acts: AI continuously analyzes intraoperative data, alerting the surgeon to potential issues while the surgeon maintains control
- AI automates routine tasks: AI handles time-consuming but straightforward tasks (e.g., initial segmentation, documentation), freeing surgeons to focus on complex decision-making and patient interaction
- AI augments, not replaces: AI provides additional information and decision support, but the surgeon retains ultimate responsibility and authority

The Patient Perspective

As AI becomes more integrated into surgical care, patient perspectives must be considered. Patients may have concerns about AI involvement in their care, including questions about:

- Who is ultimately responsible if something goes wrong?
- How is their data being used and protected?
- Will AI depersonalize their care?

Surgeons must be prepared to address these concerns, explaining how AI is used to enhance not replace human judgment and maintaining transparent communication about the role of technology in their care [65].

Challenges, Limitations, and Ethical Considerations

Data-Related Challenges

The performance of AI models is fundamentally limited by the quality and quantity of data on which they are trained. Several data-related challenges currently constrain AI applications in OMFS:

- Dataset size and diversity: Many published studies are based on small, single-center datasets with homogeneous populations. Models trained on such data may not generalize to different populations, imaging protocols, or clinical settings. The systematic review by Abdali et al. found that most included studies were retrospective, single-center, and limited by small or homogeneous datasets, with an overall high risk of bias.
- Data heterogeneity: Dental and maxillofacial data varies widely due to differences in imaging equipment, acquisition protocols, and patient populations. A model trained primarily on images from one type of scanner may perform poorly when deployed with different equipment.
- Annotation quality and consistency: Supervised learning requires accurately labeled ground truth data. In medical imaging, creating such datasets requires hundreds of hours of expert time, and inter-operator variability in annotations can introduce noise that limits model performance [66].
- Algorithmic bias: If training data underrepresents certain populations (by ethnicity, age, gender, or socioeconomic status), AI models may perform poorly for those groups, potentially exacerbating healthcare disparities.

Validation and Generalizability

The gap between research prototypes and clinically validated tools remains substantial. Most AI studies in OMFS are proof-of-concept or retrospective validations. Prospective multicenter studies with diverse patient populations are urgently needed to establish real-world performance and generalizability [67].

Standardization of metrics and protocols is another challenge. Reviews like Macrì et al. emphasize the lack of consistent protocols for training, ground truth labeling, and evaluation across studies in AI-assisted implant planning. Without standardized reporting, comparing model performance and determining clinical readiness is difficult.

The "Black Box" Problem and Explainability

Many high-performing deep learning models, particularly complex CNNs, are essentially "black boxes" it can be extremely difficult to understand why they made a particular prediction or recommendation. This lack of interpretability is a major barrier to clinical acceptance. Surgeons cannot trust and patients cannot consent to decisions they cannot understand or explain to others.

The field of explainable AI (XAI) is actively developing methods to provide rationales for model decisions (e.g., heatmaps showing influential image regions), but these techniques are still evolving and not yet standard in clinical AI tools.

Regulatory and Legal Challenges

AI-powered medical devices face significant regulatory hurdles. In the United States, the FDA has developed frameworks for AI/ML-based software as a medical device (SaMD), but the regulatory landscape remains complex and evolving. In Europe, the Medical Device Regulation (MDR) and emerging AI Act impose additional requirements.

Legal questions regarding liability remain unresolved: if an AI system misses a diagnosis or recommends incorrect treatment, who is responsible? The surgeon? The hospital? The AI developer? Clear legal frameworks are urgently needed [68-69].

Ethical Oversight and Data Governance

The use of large datasets for training AI systems raises concerns about data security and patient confidentiality, which must be rigorously protected. Ethical oversight is vital to ensure that AI integration respects patient rights and maintains trust. Key considerations include:

- Informed consent: Patients should be informed about how AI is used in their care and how their data may be used for research and development
- Data security: Robust cybersecurity measures must protect sensitive health information from breach or misuse
- Transparency: The role of AI in clinical decisions should be transparent to patients and clinicians
- Fairness: AI systems should be monitored for bias and equitable performance across populations

Clinical Integration and Workflow Challenges

Even accurate, validated AI tools will fail if they cannot be seamlessly integrated into clinical workflows. Key considerations include:

- Interoperability: AI systems must integrate with existing electronic health records, practice management software, and imaging systems

- User experience: AI tools should enhance, not impede, clinical efficiency
- Cost-effectiveness: The benefits of AI implementation must justify the costs of hardware, software, and training

Conclusion

Artificial intelligence is fundamentally transforming oral and maxillofacial surgery across the entire care continuum from initial diagnosis through preoperative planning, intraoperative guidance, and postoperative outcome prediction. The evidence synthesized in this review demonstrates that AI, particularly deep learning, has achieved remarkable performance in:

- Automated segmentation of craniomaxillofacial anatomy and pathology, with models like nnU-Net achieving accuracy comparable to human experts
- Prediction of surgical outcomes, including soft tissue changes with sub-millimeter accuracy and postoperative complications with up to 98% accuracy
- Intraoperative guidance through AI-powered augmented reality navigation and robotic assistance, with studies demonstrating mean deviations under 2 mm
- Design of patient-specific implants, reducing intraoperative adjustments and improving outcomes

The convergence of AI with complementary technologies—augmented reality, surgical robotics, multimodal imaging, and large language models—promises to further enhance surgical precision, personalization, and predictability. Emerging frontiers including videomics, federated learning, and explainable AI will address current limitations and expand the scope of AI applications in OMFS.

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