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Patient-Specific Implants and Digital Planning in Oral and Maxillofacial Surgery: A Literature Review

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Abstract: ***The integration of virtual surgical planning (VSP) and patient-specific implants (PSIs) marks a significant advancement in contemporary oral and maxillofacial surgery (OMFS) practice. Improvements in three-dimensional (3D) imaging, segmentation algorithms, and computer-aided design/computer-aided manufacture (CAD/CAM), have assisted surgeons in preoperative simulation of complex operations and executing these plans in the operating theatre with improved precision. Patient-specific implants (PSIs) are designed and produced according to the virtual planning to match the patient's anatomy and the intended surgical outcomes; They are used in several oral and maxillofacial surgery procedures, including orthognathic surgery, reconstruction of the mandible, management of orbital and midface trauma, craniofacial reconstruction, and rehabilitation of the temporomandibular joint (TMJ). This paper examines and reviews the recent literature of virtual surgical planning (VSP) and patient-specific implants (PSIs) in maxillofacial surgery practice, focusing on clinical applications, Digital Planning and PSIs workflow principles, and long-term outcomes.***

Keywords: virtual surgical planning, patient specific implants, maxillofacial surgery, digital workflow

1. Introduction

Oral and maxillofacial surgery lies at the interface of dentistry and medicine and deals with one of the most anatomically complex regions of the human body, where even minor inaccuracies may result in notable functional or aesthetic consequences[1].

Historically, reconstructive and corrective surgical procedures in oral and maxillofacial surgery (OMFS) relied mainly on the surgeon's experience, intraoperative judgment, and manual adaptation of conventional reconstruction plates and fixation systems[2]. Surgical planning was often performed mentally or using two-dimensional imaging, with numerous decisions being made entirely during the surgery.

These traditional methods continue to be used, but they involve inherent uncertainties during surgery. Resection margins, occlusal alignment and Plate bending often rely on repeated adjustments during surgery, which may increase operative time and increase technical complexity. [3]

The use of computer-assisted surgery in the cranio-maxillofacial domain began several decades ago, with the initial emphasis on navigation-aided orbital reconstruction and correcting craniofacial deformities. [3, 4] Clinical outcomes of navigation-aided surgery have indicated that digital technology can improve spatial orientation and anatomical reconstruction, thereby establishing a foundation for contemporary VSP practices. [4,5]

In the past twenty years, advancements and innovations in imaging technologies, segmentation software, and CAD/CAM production have led to the development of digital workflows that are integrated in diagnosis, treatment, and postoperative evaluation.[3, 5] VSP is the conceptual framework for digital surgery in OMFS. That allows surgeons to simulate osteotomies, skeletal movement, and reconstructions. PSIs, on the other hand, are the physical results and clinical tools of these plans, providing customised implants and fixation systems.[5, 6]

2. Digital Planning and patient Specific Implant Protocols

2.1 Imaging and Data Acquisition

Virtual surgical planning depends largely on the accuracy of the imaging data utilised for segmentation and three-dimensional modelling. Computed tomography (CT) scan is widely acknowledged as the standard for complex virtual planning because of its consistent voxel geometry and accurate representation of both cortical and cancellous bone. [7]

Cone-beam computed tomography (CBCT) is widely used in dental and maxillofacial surgery because it uses less radiation and provides clear resolution of bone structures. CBCT, however, offers limited soft-tissue contrast, which may reduce segmentation accuracy in complex reconstructive surgeries. [7, 8]

It is essential to recognise imaging-related inaccuracies, whether they appear in CT or CBCT such as motion artefacts, metallic restorations, and inadequate acquisition parameters, as any of which can impair the accuracy of segmentation, causing differences between the virtual plan and intraoperative execution. [3, 5,7]

2.2 Segmentation and Three-Dimensional Modelling

The segmentation process converts DICOM imaging data into three-dimensional surfaces models that can display different anatomical parts of the body, like teeth, bone, and nerves.[7, 9]

Semi-automated algorithms have improved segmentation efficiency, yet manual refining is still very important in areas with thin cortical bone, comminuted fractures, or post-operative distortion.[7]

Segmentation errors during planning can lead to major inaccuracies, resulting in patient-specific implants (PSIs) that appear satisfactory virtually but do not fit accurately during surgery

2.3 Virtual Surgical Planning

Virtual surgical planning enables complex procedures to be evaluated and planned before surgery by preoperative simulation of osteotomies, skeletal movements, defect reconstruction, and fixation strategies. [11]

A key step in virtual surgical planning is the use of mirroring techniques that help reconstruct unilateral defects, where the contralateral side serves as a guide for reconstruction[12]. However, this method requires the presence of initial facial symmetry within normal parameters, which may be absent in patients with congenital deformities or those who have had severe prior trauma.[2-3,7, 12]

2.4 Implant Design and Manufacturing

After approval of the final virtual design, the patient-specific implant and any surgical guides are transferred to the manufacturing phase using CAD/CAM or 3D printing.[10]

3. Clinical Applications

3.1 Orthognathic surgery

Orthognathic surgery is the most studied application of virtual surgical planning in oral and maxillofacial surgery.[9, 13-15] Numerous systematic reviews have demonstrated that virtual planning displays increased accuracy and reproducibility, particularly in double-jaw surgery and asymmetric cases. [9, 13-15]

Alkhayer et al. stated that differences between planned and actual outcomes typically fall within acceptable clinical ranges; such variations are affected by the measurement technique and surgical technique. [14]

Clinical data from prior research generally indicate that 3D-printed splints yield more reliable outcomes than traditional splints; yet challenges involving splint placement, condylar alignment, and intraoperative handling persist in clinical practice. [13]

Customised plates, particularly when used in the maxilla, have been proposed to improve precision and reduce dependence on splints.[13, 15]

3.2 Mandibular Reconstruction

Many studies have shown that Virtual surgical planning and patient-specific implants (PSI) enable accurate reconstruction of the mandible after tumour resection or major trauma reduction and fixation.[14, 16]

Wilde et al. demonstrated the reliability and precision of CAD/CAM-guided mandibular reconstruction using cutting guides and prebent plates, resulting in improved alignment and reduced intraoperative time for plate adaptation as well as reliable occlusal relationships. [17]

The use of patient-specific reconstruction plates and implants in microvascular reconstruction has been shown to shorten ischaemia time by eliminating extensive intraoperative plate adaptation; however, complication rates are influenced by patient-related factors such as previous radiation, infection, and soft-tissue condition.[3, 18]

3.3 Reconstruction of the Orbital and Midfacial Regions

Navigation-assisted orbital reconstruction represents one of the initial applications of computer-assisted maxillofacial surgery.[4]

Recent studies indicate that patient-specific orbital implants enhance anatomic accuracy, minimising the risk of postoperative enophthalmos, diplopia, and asymmetries, especially in cases involving large or complex defects and secondary reconstructions. [12,21]

In the midface region, A series of recent studies has indicated that VSP enables preoperative planning and assessment of complex fractures, congenital anomalies, and secondary reconstructions by combining skeletal, dental, and soft-tissue factors into a single workflow. PSIs have been increasingly utilised in the zygomaticomaxillary complex or infraorbital rim regions which has enhanced anatomical compatibility, resulting in a more reliable restoration of midfacial projection and symmetry. [21,22]

3.4 Craniofacial Reconstruction and Cranioplasty

Craniofacial reconstruction and cranioplasty are among the initial applications of PSIs. Prior research suggests that using PSIs facilitates the accurate restoration of the skull's contour and symmetry. [19,23] titanium or polyetheretherketone (PEEK) are the most common materials used in craniofacial reconstruction. PEEK implants are radiolucent and have an elastic modulus that is close to that of cortical bone. Titanium, on the other hand, is stronger and integrates better with bone [19,23].

3.5 Reconstruction of the Temporomandibular Joint

VSP allows detailed three-dimensional assessment of the cranial base, mandible, occlusion, and joint anatomy, giving

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the surgeon the chance to accurately plan condylar position, ramus height, and mandibular alignment before surgery

Previous studies have emphasised that Personalised temporomandibular joint prostheses provide a precise treatment option for patients with severe or degenerative TMJ disease, especially when traditional reconstructive choices are limited which result in satisfactory clinical outcomes, including pain reduction, increased mouth opening, and stable occlusion. [20]

4. Clinical Outcomes

4.1 Accuracy and predictability

There have been numerous studies to investigate the Accuracy and predictability of using VSP and PSIs across a wide range of oral and maxillofacial surgery applications, which showed enhanced geometric accuracy and more precise placement of bone segments and implants, leading to better restoration of anatomical contours compared with conventional freehand techniques.[3,6,10,13,14]

According to these authors, the ability to view the defect in three dimensions during virtual planning and to preoperatively determine the shape and position of the implant diminishes intraoperative uncertainty and enhances the predictability of surgical outcomes. [3,6,10,13,14]

4.2 Efficiency

A series of recent studies has indicated that the use of PSIs decreases the operative time and is also associated with fewer intraoperative implant adjustments and modifications. These advantages are more pronounced during lengthy procedures, where shortened operative time reduces general anaesthesia duration, blood loss and surgeon fatigue. [9,16,17]

4.3 Complications and Long-Term Outcomes

Regarding complications, Previous studies have shown that complications associated with the appropriate use of VSP and PSI are similar to those of traditional methods.Common complications reported by those authors include postoperative infection, implant exposure, and mechanical failure. These complications are usually related to patient factors such as uncontrolled systemic disease, soft tissue conditions, and a history of previous surgery .[5,18,19]

5. Practical Considerations

An accurate CT or CBCT scan is essential for ensuring accurate design of patient-specific implants (PSIs) to provide smooth contours and accurate adaptation of PSIs to the surrounding tissues to avoid complications like stress concentration and implant exposure. [7,19]

Delivery time is a critical factor, particularly in oncologic reconstruction where treatment delays affect prognosis. Unlike elective deformity or secondary reconstruction cases, cancer surgery often requires prompt intervention and treatment delay affects the patient's prognosis. [24]

The safe practice of patient-specific implants depends on strict following of established manufacturer's instructions, validated sterilisation protocols, appropriate verification procedures, and local regulations. [19]

6. Future Directions

Ongoing advances in automation, artificial intelligence, and data integration are gradually changing how VSP is carried out in everyday practice. Tasks that once required extensive manual input, such as image segmentation and plan refinement, are increasingly supported by machine-learning tools. These advancements allow surgeons to work more efficiently and with greater confidence. These tools also reduce planning time and improve consistency, especially in complex craniofacial reconstructions.[6,7]

Research regarding PSI is increasingly focused on designing implants that combine fixation with regenerative potential, which will improve osseointegration and lower the risk of complications. [5,7,10]

7. Conclusion

Virtual surgical planning and patient specific implants continue to shape modern oral and maxillofacial surgery by offering greater precision, reduced operative complexity, and more predictable functional and aesthetic outcomes. Current evidence supports their value across a broad spectrum of clinical applications, from orthognathic procedures to craniofacial and temporomandibular joint reconstruction. As digital workflows become more refined through advancements in imaging, segmentation, and automated design tools, surgeons are increasingly able to deliver tailored interventions with higher accuracy and efficiency. Future developments in materials science and bio integrated implant design hold additional promise for improving long term clinical success. These ongoing innovations underscore the expanding role of digital planning and personalised implant technologies within contemporary maxillofacial practice.

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