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Clinical and psychosocial benefits of 3D printing and virtual planning in complex facial reconstruction after oncological resection: a systematic review

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Abstract

Background. Head and neck cancers and their surgical treatment frequently lead to functional and aesthetic impairments that negatively affect patients' quality of life and psychosocial functioning. The development of virtual surgical planning (VSP) and 3D printing has increased the precision of reconstructive procedures.

Aim. To evaluate the clinical and psychosocial benefits of 3D printing and virtual surgical planning in facial reconstruction after oncological treatment.

Materials and methods. A systematic review of the literature regarding computer-assisted surgery, CAD/CAM technologies, augmented reality, and 3D printing in craniofacial reconstruction following head and neck cancer resection was conducted.

Results. The use of VSP and 3D printing improves the accuracy of resection and reconstruction, shortens operative time, and increases treatment predictability. Patient-specific implants and surgical guides enable better functional and aesthetic outcomes, improving mastication, swallowing, speech, and rehabilitation. These technologies also enhance physician–patient communication, increase treatment satisfaction, and support social reintegration.

Conclusions. Virtual surgical planning and 3D printing significantly improve reconstructive treatment outcomes and quality of life in patients undergoing oncological surgery within the head and neck region.

Keywords: head and neck cancer; 3D printing; virtual surgical planning; mandibular reconstruction; quality of life

1. Clinical background and importance of reconstruction in head and neck cancer

Head and neck cancer is the seventh most common malignancy worldwide [1], accounting for approximately 3–5% of all cancers [2], and its incidence continues to increase. Histologically, squamous cell carcinoma predominates in this group, representing more than 90% of cases [2]. The larynx is the most common primary site [3, 4]. The incidence rises significantly after the age of 45 years, and men are affected more frequently than women [1, 2]. The major risk factors include tobacco smoking, excessive alcohol consumption, and human papillomavirus (HPV) infection [1, 5].

The primary treatment modality is surgical tumour resection, which in some cases requires partial or total mandibulectomy in order to achieve adequate surgical margins and minimize the risk of recurrence [2].

Head and neck cancer, as well as the surgical procedure itself, may result in severe deformities leading to impairment of craniofacial functions such as mastication, swallowing, and speech, thereby significantly reducing quality of life [6, 7]. An additional issue is facial disfigurement, which may lead to the loss of psychophysical aspects, including self-identity, unrestricted communication with facial expression, participation in social life, and stigmatization by society [6].

To restore both function and satisfactory aesthetic outcomes in oncological patients, reconstruction of the bony contour may be performed to re-establish occlusion, provide oral–

nasal separation, and create a basis for rehabilitation [6]. According to studies, more than 50% of patients require reconstructive procedures involving bone and/or soft tissues [7].

The current gold standard is the use of a free fibula flap combined with reconstruction plates [2, 8, 9, 10]. Reconstruction may be performed using one of two main approaches:

1. primary reconstruction – performed during the same procedure as tumour resection;
2. secondary reconstruction – performed after a recurrence-free period.

The first approach requires the presence of two surgical teams; however, it appears technically less demanding due to preserved anatomical landmarks and the absence of scar-related distortions [6, 10]. It is also associated with faster recovery and greater patient satisfaction [6].

Resection and reconstructive surgeries are lengthy and complex procedures requiring careful preparation. To address these challenges, technological solutions have been introduced that not only shorten operative time and reduce costs but also improve surgical precision.

Virtual surgical planning (VSP) software and 3D printing technologies enable highly accurate preoperative planning. These technologies allow reconstruction of bony defects through fibular modelling, determination of the required number of bone segments, and preparation of osteotomy guides, thereby facilitating precise graft harvesting [6, 11].

2. Technological foundations and methodology of virtual surgical planning

The first report concerning 3D printing dates back to 1986, when Charles Hull introduced stereolithography (SLA), a technique based on curing layers of photopolymer resin. Since then, this technology has developed rapidly. Three-dimensional printing gradually began to replace treatment methods based on generalized protocols, leading to the implementation of patient-specific therapeutic planning. This transformation is particularly evident in oral and maxillofacial surgery, where surgeons must rely on precision medicine due to the relatively small operative field [12]. An additional factor is the growing expectation of patients regarding aesthetic treatment outcomes.

During the second decade of the twenty-first century, the fourth industrial revolution introduced additive manufacturing (AM) combined with 3D printing (3DP). AM and 3DP involve the creation of a physical object from a digital 3D model, usually through the sequential addition of material layers [12].

Computer-assisted surgery (CAS) consists of three main phases [13].

The first is the preoperative phase. The treatment process begins with high-resolution imaging (slice thickness ≤1 mm), including computed tomography of the facial skeleton and computed tomographic angiography of the lower extremities [9]. Cone-beam computed tomography (CBCT) and intraoral scanning of dental arches may also be indicated. Ideally, imaging should be performed approximately two weeks before surgery [8]. The acquired DICOM (Digital Imaging and Communications in Medicine) data are subsequently segmented using dedicated software to isolate the region of interest from two-dimensional sections. In the following stage, a virtual 3D model is generated and may either be printed or used for the fabrication of surgical guides made of titanium, hydroxyapatite, or PEEK [14], as well as patient-specific implants (PSIs) [11, 12, 13].

The second, intraoperative phase is based on navigation and/or VR/AR/MR technologies. Augmented reality combined with navigation is particularly useful for determining the actual tumour extent and facilitating the achievement of negative surgical margins [13].

The third phase involves optional postoperative analysis, which provides feedback regarding the effectiveness of preoperative planning. This stage contributes to the accumulation of evidence confirming the benefits of modern technologies in head and neck reconstruction [13].

3. Functional, aesthetic, and psychosocial treatment outcomes

The preoperative stage of virtual surgical planning enables surgeons to simulate individual phases of the surgical procedure, allowing for more accurate prediction of operative outcomes, including occlusal assessment and soft tissue response to changes within the craniofacial skeleton [14].

Additive manufacturing (AM) and 3D printing (3DP) technologies are characterized by the rapid production of complex structures with precise geometry, diverse microarchitecture, and the possibility of designing internal elements or hollow spaces [12].

Mandibular reconstruction using patient-specific mandibular plates (PSMPs) provides a greater sense of control over the treatment process and reduces intraoperative uncertainty by facilitating the transfer of virtual planning into the surgical procedure itself. Consequently, these technologies improve surgical precision and enable more natural aesthetic outcomes [11, 14, 15].

Studies have also demonstrated the benefits of surgical guides in reducing intraoperative complications [14].

Computer-aided design and manufacturing (CAD/CAM) technology not only improves surgical efficiency by reducing operative time by approximately 20%, but also enhances clinical outcomes and increases procedural safety [7, 8, 12, 13, 14, 16].

Achieving negative surgical margins is a crucial aspect of the entire treatment process and represents one of the main prognostic factors for survival in patients with oral cancer. The greatest challenge involves obtaining an adequate soft tissue margin. Incomplete resection may result in residual tumour growth, leading to life-threatening recurrence or postoperative metastases. Conversely, excessive resection may result in tissue discontinuity associated with difficulties in restoring occlusal stability, facial nerve and muscle coordination, temporomandibular joint function, and satisfactory aesthetic appearance. With the use of augmented reality (AR), surgeons are able to visualize critical anatomical structures such as blood vessels and nerves in real time [7, 17].

Studies have demonstrated that R0 resection is achievable using computer-assisted surgery (CAS) in both benign and malignant tumours [17].

Surgeons have also achieved shorter ischemia times, indirectly contributing to reduced hospitalization duration [16].

Due to the increased precision of surgery for locally advanced oral cancer, estimated to be approximately 20% higher compared with conventional methods, satisfactory functional reconstruction outcomes in mastication and swallowing, as well as favourable aesthetic results, have been achieved. Improvements in standardization, predictability, and overall treatment outcomes have also been reported [12, 13, 14, 18, 19].

Importantly, reconstructive outcomes appear comparable among surgeons with varying levels of experience, which may particularly benefit less experienced operators [11].

No significant differences in postoperative complication rates have been observed [16].

Another important advantage is the reduction in overall treatment costs [12]. Although VSP is associated with higher material costs compared with traditional methods, both hospital and operative expenses have been shown to decrease [14].

Ease of use also plays a major role, contributing to the growing availability and widespread implementation of these technologies [12].

Furthermore, VSP enables immediate dental implant placement (IDIP) in selected patients, with precise control of implant trajectory and angulation. This approach provides numerous benefits, including avoidance of an additional implant surgery, increased likelihood of successful dental rehabilitation due to approximately six weeks of osseointegration before radiotherapy initiation, and faster prosthetic rehabilitation. Owing to the polymorphic shape of the fibula, precise placement of IDIP without virtual planning technologies is technically challenging. In addition, delayed implant placement after radiotherapy is associated with a higher risk of treatment failure [9].

4. Limitations and future perspectives of the technology

Like any medical approach, computer-assisted surgery has both advantages and limitations. Existing challenges still require further improvement and optimization.

The main disadvantages include high material costs, the need for additional personnel training, and the requirement for advanced technological infrastructure [12].

The success of virtual surgical planning (VSP) largely depends on the accuracy of preoperative planning [14]. Inadequate preparation may result in procedural errors. Another important issue is that excessive reliance on modern technologies may contribute to the gradual loss of proficiency in conventional surgical techniques. This may become problematic when unexpected intraoperative changes require surgeons to modify the treatment plan and complete the reconstruction using traditional methods, for which they may be insufficiently prepared [9].

Limitations are also associated with the 3D-printed components themselves. Residual metallic particles and surface topography may induce adverse biological reactions, emphasizing the importance of appropriate post-processing procedures. In addition, sterilization of 3D-printed elements remains a challenge. Therefore, significant progress is expected in the development of materials for patient-specific implants (PSIs), particularly those incorporating antibacterial and therapeutic properties [12].

5. Conclusions

The implementation of 3D technologies and virtual surgical planning has significantly improved clinical outcomes in oral and maxillofacial surgery (OMFS) [12]. Virtual surgical planning transfers the decision-making process and shaping of fibula-based mandibular reconstruction to the preoperative stage [11]. The use of modern technologies has increased the predictability and reproducibility of procedures while improving the efficiency and accuracy of both resection and functional reconstruction, thereby facilitating postoperative dental rehabilitation [18].

In addition to the well-documented clinical advantages of computer-assisted surgery (CAS), important psychosocial benefits have also been observed. Surgical visualization not only facilitates the surgeon's work but also improves communication with the patient during the preoperative stage. A better understanding of the treatment process by the patient represents a crucial component of comprehensive care. Precise restoration of facial contours and satisfactory aesthetic outcomes help restore lost psychophysical aspects, including self-identity, unrestricted communication with facial expression, and participation in social life. Faster recovery is additionally associated with greater patient satisfaction.

Together, these factors contribute to an overall improvement in quality of life among oncological patients with head and neck cancer.

Disclosures:

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