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Virtual Surgical Planning in Craniomaxillofacial Reconstruction

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1. Introduction

Craniomaxillofacial reconstruction poses inherent and unique challenges due to the three-dimensional configuration of the proposed construct and the critical importance to restore speech, swallowing, mastication and symmetrical facial contour. Additionally, reconstruction results are often inconsistent and learning curve dependent.[1-43] Until recently, the overall success in bony reconstruction of the craniomaxillofacial skeleton has relied mainly on the use of surgical trial-and-error and 2D imaging modalities. Virtual surgical planning (VSP) and computer aided design (CAD) / computer aided modeling (CAM) is an exciting new technology that presents advantages in complex craniomaxillofacial reconstruction, with potential to transform the approach and execution of challenging head and neck reconstructions.[30] Among the reported benefits of VSP- CAD/CAM are increased reconstructive accuracy, reduced OR and graft ischemia time, improved patient satisfaction and ease of use.[1, 9, 19] VSP- CAD/CAM is gaining traction in craniomaxillofacial reconstruction applications and offers opportunity for increased accuracy, improved efficiency, enhanced outcomes and ease of use.[34, 43] To illustrate this point, the usage of this technology in different applications is presented in subsequent sections with an emphasis and case study example for an oncologic indication.

2. Applications

VSP- CAD/CAM is a novel technology which has been described for a range of surgical applications ranging from trauma to oncologic reconstruction. Widening utilization in craniomaxillofacial reconstruction is largely due to its unique capability that allows the
surgical team to visualize and manipulate patient-derived virtual and stereolithographic models in three dimensions during the virtual pre-operative planning phase. Due to refinements in pre-operative planning, many studies, though limited, have reported improved outcomes through CT evaluation of actual versus planned height and width dimensions, volumes, osseous graft overlap, and aesthetic outcomes.[24] For these reasons, VSP-CAD/CAM has been of benefit for the following applications:

**Craniofacial / Orthognathic procedures**—VSP-CAD/CAM is a useful technology to address craniofacial anomalies or maxillofacial deficiencies. Until recently, traditional imaging methods only allowed for 2D images in a single plane to visualize the irregular and uniquely shaped donor-graft and recipient sites.[3] While multiple imaging studies may aid in forming a pre-surgical plan, the outcomes of movements outside the plane of imaging cannot be reliably predicted. Therefore, complex reconstructions requiring correction for craniofacial and maxillofacial applications can induce asymmetry since the traditional radiological studies cannot plan movements in three dimensions; a capability that VSP-CAD/CAM offers.[23] In addition, pre-made guides for harvesting and transplanting autografts as well as customized allograft materials (e.g. pre-bent plates) facilitate achieving a result consistent with the craniofacial reconstructive plan.[23, 43] In maxillofacial procedures, VSP-CAD/CAM eliminates several other sources of error when planning midline correction by allowing the surgeon to account for the natural yaw, pitch, roll of a head position, and assessing heights and widths; virtual manipulations of the patient model to millimeter precision can be performed to achieve accurate maxillofacial balance and appropriate orthognathic relationships. Pre-bent fixation plates further promote accurate translational movements intraoperatively that are pre-planned in the virtual environment. When compared to the ‘classic’ method of building acrylic intermaxillary occlusal splints using plaster models, VSP-CAD/CAM was shown to be superior when evaluating post-operative maxillary position and centrality of the condyles in the temporomandibular joint.[43]

**Trauma**—VSP-CAD/CAM has been utilized for reconstruction of traumatic facial injuries, including comminuted mandible and panfacial fracture reduction and repair. Three-dimensional modeling of craniomaxillofacial injuries facilitates precise intraoperative reduction of displaced bone fragments, while CAD/CAM produces occlusal splints that allow superior restoration of facial symmetry, appearance, and function to those fitted intraoperatively.[35] Avulsed or necrotic areas can be replaced with grafts or covered with custom implants. Additionally, implementation of VSP-CAD/CAM offers use of pre-manufactured cutting guides for improved accuracy and reduced trial-and-error when harvesting and shaping autologous implants, thus helping to ensure optimal bone-to-bone contact and aesthetic outcome. Pre-bent fixation plates decrease intraoperative time and limit the extent of subperiosteal dissection, thus minimizing avascularization of bony fragments.[35] Utilization of VSP-CAD/CAM starting at initial presentation of traumatic facial injury does not result in increased time to reconstruction and has been shown to better preserve facial height and width.[6, 35]

**TMJ reconstruction**—Traditional temporomandibular joint (TMJ) reconstruction is a two-stage approach beginning with gap arthroplasty followed by postoperative CT to plan implant design and fabrication. A subsequent procedure is then required to inset the pre-designed TMJ implant. VSP-CAD/CAM however, enables single-stage reconstruction of the TMJ as gap arthroplasty simulation and TMJ implant pre-fabrication can be performed on a virtual 3D
model. Planning and simulation of TMJ movements and jaw occlusion can also be assessed on stereolithographic models prior to implant in-setting resulting in improved functional outcomes and reduced postoperative complications.

Mandibular Atrophy – In a case series of seven patients, VSP-CAD/CAM was utilized to repair atrophic mandibular alveolar crest defects in patients after all other treatment modalities had failed. A free iliac crest transplant was harvested and anastomosed to the thoracodorsal artery and vein in the axilla. Grafts were harvested three months later, after having developed a whitish tissue layer on the bone, which was used as a mucous membrane following fixation to the mandible. All grafts fit the mandible as predicted in the initial pre-reconstructive planning phase and no implants were lost after 7 years of follow up.

Oncologic resection and reconstruction – Craniomaxillofacial reconstruction using free fibula flaps, as first described by Hidalgo, has traditionally relied on surgical skill, judgment, and intra-operative trial and error to create the neomandible. Reconstruction of the mandible and maxilla has therefore been considered to be learning curve dependent, often with inconsistent results during the skill acquisition phase. Furthermore, preoperative planning and communication between the oncologic and reconstructive teams has been limited by the lack of data regarding the anatomy of the lesion, precise margins of resection, and anatomy of the graft recipient site, which prior to use of VSP-CAD/CAM, are only revealed in the operating room. Thus, for a procedure requiring a high degree of precision for optimal orthognathic and aesthetic outcomes, craniomaxillofacial reconstructive success has historically been hindered by prolonged intraoperative time and suboptimal reconstructions. VSP-CAD/CAM offers significant benefits for use in complex oncologic osseous head and neck reconstruction by providing enhanced cooperation between surgical teams, pre-operative planning, and the ability to customize models to patient’s individual characteristics, which offers potential for considerable intraoperative time saving.

VSP-CAD/CAM allows for a cooperative team approach to plan the resection and reconstruction by synergistically facilitating pre-operative collaboration between the extirpative and reconstructive teams, maximizing chances for tumor-free resection margins. Additionally, as the extirpative surgeon is provided with pre-operative 3D CT visualization of the lesion borders and a comprehensive plan from the reconstructive team, he may be more inclined to plan liberal resection margins initially; thus potentiating decreased local recurrence rates and intraoperative time. Similarly and in reciprocal fashion, reconstructive planning may be better realized for the reconstructive surgeon with advance knowledge of the resection plan. As refinements in the VSP-CAD/CAM interface have become progressively more user-friendly for both the extirpative and reconstructive surgeon, adoption of this technology and coordinated pre-operative planning has continued to increase.

3. Process

Computer-assisted craniomaxillofacial surgery is based on four specific, well-described phases, which are all necessary in order to achieve predictable outcomes: planning, modeling, surgery, and evaluation. These steps are detailed as follows:
The first phase, planning, begins with a high-resolution computed tomographic (CT) scan of the craniofacial skeleton and the possible donor sites, (e.g. lower extremities) if considered necessary. A 3D reconstruction of the CT images is performed and then forwarded to the desired modeling company. A web-based teleconference is then held between the surgical teams and a biomedical engineer to allow participation from remote locations. During this phase, the resection and reconstruction is virtually planned, with key parameters including resection margins, osteotomies, placement of the vascularized bone graft in oncologic reconstruction, accurate reduction of the fractured bony segments for traumatic injuries, and the staged virtual movement of the jaws in orthognathic procedures.

![Overlay of the planned reconstruction with the native diseased mandible after virtual planning of the osteotomies.](image)

The modeling phase begins based on the virtual surgical plan. Stereolithographic models are manufactured of the area of the craniomaxillofacial skeleton of interest, along with specific cutting guides for both the resection and the vascularized bone graft that will be used for oncologic bony reconstruction (e.g. fibula), if indicated. In orthognathic procedures, pre-bending of plates allows for accurate translation of the osteotomized segments for advancement/setback and precise execution of the pre-operative plan (e.g. LeFort I, Bilateral Sagittal Split Osteotomy). In oncologic reconstruction, this also allows for manufacturing of a reconstruction plate or plate-bending template; the specific guides and templates can be tailored to
the surgeon’s preference and the stereolithographic models can help to create pre-bent plates prior to reconstruction[17, 19]

Figure 2. Positioning of the designed neomandible adjusted to optimize bony contact and restore the anticipated mandibular defect. Note the osseous segments to be produced via guided cuts of the free fibula graft.

During the surgery phase plate-bending templates and pre-bending of plates also expedites the fixation step. Osteotomies are made in the mandible or maxilla based on the cutting guides, typically after maxillomandibular fixation is achieved. In the case of oncologic reconstruction,
the harvested osseous flap is also cut and osteotomized in-situ based on the cutting guides and typically fixed to the reconstruction plate before the composite unit is secured into the maxillofacial/mandibular defect. With the bony foundation restored, the soft tissue reconstruction can be carried out synergistically.

Figure 4. Intraoperative placement of osteotomy guide to fibula facilitating guided cuts for the neomandible.

The evaluation phase begins in the post-operative period, with a repeat high-resolution CT scan performed, based on the same preoperative protocol.[17] While the method of evaluation varies between institutions, a postoperative CT scan allows for a quantitative evaluation of the surgical outcomes and can complement subjective assessments by the surgeon and patient of restored oral and maxillofacial function. 3D models of the post-operative results are overlaid with the pre-operative plan to determine accuracy and success of reconstruction including actual mandibular angle and margins of bony contact in addition to accuracy of the VSP-CAD/CAM plan including; bony segment overlap (repeatability) and mean service deviation, overall positioning, osteotomy site differences, and reconstructive plate overlap.[3, 9, 25, 20] Clinical parameters can then be correlated in the evaluation phase with functional parameters including occlusion, mastication, and speech, in addition to overall aesthetic outcome, and patient satisfaction.
Oncologic Case – A 61-year-old male patient presented to an oral surgeon for evaluation of the right posterior mandible for potential chronic osteomyelitis. He stated that he had felt a “dull pain” since nine months prior. Teeth #31 and #32 were extracted 16 and 9 months ago, respectively. Since extraction, the patient had completed multiple courses of antibiotics, most recently Augmentin 500mg.

On exam the patient displayed normal facial symmetry with a non-tender movable lymph node <1cm right Level 1b without erythema, discharge or skin changes. The right mandible was slightly tender to palpation with only minimal expansion, with slight “crepitus” appreci-
ated upon opening, concerning for osteolysis. Radiographic appearance on panorex was notable for significant bone distraction appreciated on the right mandible involving the body to the inferior border. Initial workup of the patient included an incisional biopsy and curettage of the area under local anesthesia in order to rule out osteomyelitis. The pathology report described a well-differentiated squamous cell carcinoma of right posterior mandible. The patient was referred to oral-maxillofacial surgery for extirpation of the affected region of the mandible with adequate margins and concomitant right free fibular osteocutaneous flap reconstruction of the mandible by plastic and reconstructive surgery. High-resolution CT scans were performed and sent to an outside company for modeling via CAD/CAM software.

After rendering the virtual models, the extirpative and reconstructive teams formulated a surgical approach and consulted the modeling company for manufacturing of the desired guides.

The virtual three-dimensional model of the craniofacial skeleton was first used to plan the resection of the lesion and then the subsequent reconstruction of the defect by the extirpative and reconstructive teams respectively in a joint teleconference facilitated by the biomedical engineer from the modeling company. During the surgical phase, the oral-maxillofacial team first excised the diseased mandible as planned using the prefabricated cutting guides. The fibular osteocutaneous flap was then harvested by the reconstructive team; prefabricated templates and guides were used by both the extirpative and reconstructive teams to ensure the precise location and angle of osteotomies. The harvested, osteomized flap was fixed to the pre-bent plate in-situ and subsequently inset to the mandibular defect. The free condylar end of the graft was contoured to fit the articular disk of the temporomandibular joint and the
graft placed into position. After successful fixation of the plate and graft to native bone, the donor cutaneous flap was tailored for use in reconstruction of the oral mucosa. The flap vasculature was then anastomosed, adequate circulation ensured, and both sites were closed in a layered fashion.

After surgical completion, a high-resolution CT scan was obtained and sent to the original modeling company for evaluation of reconstructive success. Comparisons were made between the anatomical dimensions of the pre-operative and post-operative skull and mandible. Reconstructive plate overlap was considered to be acceptable and the patient achieved excellent functional and aesthetic results. The evaluation phase allowed for review of surgical outcomes in a multidisciplinary fashion to further refine the technique.
Figure 9. Virtual placement of the pre-manufactured extirpative osteotomy guide on the patient’s native mandible and resection /osteotomy guide on the patient’s fibula for creation of the neomandible.

Figure 10. Intraoperative comparison of the virtual surgical planned reconstruction model with the fibular osteomyo-cutaneous flap segments secured to the pre-bent reconstruction plate (left). Placement of the plate secured fibula graft to the native mandible (right).
4. Advantages

Heightened aesthetic outcomes and reconstructive accuracy are realized with the multi-stage implementation of virtual surgical planning throughout the four phases of computer-assisted craniomaxillofacial surgery and the use of cutting guides, stereolithographic models and prefabricated plates. In particular, the surgical course with VSP-CAD/CAM implementation, specifically in the oncologic reconstruction of the mandible and maxilla, has been favorably altered when compared to intraoperative planning and in-situ plate bending.[2, 23] More pervasive use of the technology throughout the reconstructive process reduces translational
error due to human error. The virtual model data allows manufacturing of cutting guides, plate bending templates, prefabricated reconstruction plates, and also stereolithographic models to facilitate an accurate execution of the virtual plan in the operating room. Pre-operative simulation of the maxillo-mandibular relationship facilitates proper alignment of the graft for proper dental occlusion and proper orthognathic relationships. As the majority of the planning of this process has occurred pre-operatively, total operating time is also reduced concordantly.

While achieving reconstructive success was previously reliant on the surgeon’s experience and intra-operative trial-and-error using 2-D imaging, VSP-CAD/CAM offers cited benefits over traditional methods which include increased bone-to-bone contact, better dental alignment, improved aesthetic contour, reduced complication rates and decreased intraoperative time. In our review of surgeon-reported benefits, increased reconstruction accuracy in 92% of cases proved to be a major perceived advantage demonstrated by this technology. Furthermore, a future direction of the VSP-CAD/CAM technology includes planning of osseointegrated implants for mandibular reconstruction at the initial virtual planning session to greater improve functional outcomes.

Quantifiable patient satisfaction surveys, subjective outcome evaluations, and clinical assessment can help to measure functional and aesthetic outcomes. Likely results from more true-to-plan reconstructions attained by use of this technology, VSP-CAD/CAM has been purported to translate to increased patient satisfaction. In a 2012 study comparing VSP-CAD/CAM with conventional surgery, patients were asked to report satisfaction on a scale of 0-100. Patients who underwent virtually planned surgery reported an average score of 88 compared to an average score of 68 by those patients undergoing traditional reconstruction.

The technical accuracy achieved as a consequence of VSP-CAD/CAM utilization can be enumerated with evaluation of the final reconstruction with the virtual plan via comparison of pre-operative and post-operative three-dimensional CT scans. Performing osteotomy with use of cutting guides has been shown to assist in more accurately designed free flaps, while use of pre-manufactured reconstruction plates versus hand-bent reconstruction plates has been shown to promote true-to-plan reconstructive results. Additionally, a noted decreased difference in the overall positioning between the native and reconstructed mandibles was found in VSP-CAD/CAM aided reconstructions when comparing standard technique reconstructions. Thus, improved reconstructive accuracy via the reduction of human error can be achieved with pre-manufacturing of the reconstructive plates and implementation of VSP-CAD/CAM more pervasively throughout the reconstructive process. It follows that application of VSP-CAD/CAM to refine preoperative planning, intraoperative contouring, and postoperative orthodontic relationships in each surgical step can improve functional and aesthetic outcomes. With completion of the VSP process to the final evaluation phase, 3D comparison imaging not only permits assessment of the reliability of the technology, it allows the collaborative discussion between surgical teams to assess technique and identify areas for improved performance.
Pre-operative planning of the resection and reconstructive segmental osteotomies results in enhanced operative time efficiency so that the extent of surgical time required is optimized to precisely execute the previously developed plan. Intraoperative surgical planning is thereby converted to a preoperative event so that substantial savings in intraoperative time and reductions in the surgical learning curve may be realized. Such savings may be further realized in reduced surgeon fatigue and concomitant reduced surgical error. Decreased operative time and increased accuracy have been noted in multiple reconstructive series, further illustrating the utility of VSP-CAD/CAM in dealing with complex head and neck reconstruction for various surgical indications. [6, 28, 35] in mandibular reconstructions using fibula free flaps, Hanasono reported a significant decreased mean intraoperative time when utilizing VSP-CAM/CAD. [8] While Seruya et. al did not find a significant decrease in operative time; they described a decrease in mean ischemic time in CAD assisted mandibular reconstructions. [29] Reduced ischemia time has been shown to result in decreased flap loss and overall post-operative complications. [27, 29] Enhancing overall intra-operative efficiency is facilitated by the use of pre-manufactured cutting guides and models which enables faster and
more accurate osteotomies and graft placement. [7, 31] Use of manufactured pre-bent reconstructive plates can also significantly decrease the total operative time; total reconstructive operative time was reported in one case to be less than 90 minutes.[3, 19, 31]

5. Disadvantages

With regard to the current economic climate in healthcare, potential limitation of widespread incorporation of VSP-CAD/CAM technology is its added cost and the resultant financial burdens that may be placed on the patient and medical system.[8, 17, 28, 34] Given the economic healthcare constraints, the improved patient outcomes seen with VSP-CAD/CAM have to be balanced against the cost of the technology.[24, 39] Potential costs are further increased with the use of the manufactured pre-bent reconstruction plates. Given the qualitative nature of many benefits of VSP-CAD/CAM and the paucity of data currently available, the total value added and cost efficiency of VSP-CAD/CAM utilization has not been formally evaluated and still remains the subject of future studies.[24] As previously discussed, reductions in ischemia and/or overall operative time is a potential source of cost reduction. Additionally, the decreased complications and patient morbidity, and generalized improved outcomes seen signify cost savings that may offset the technological costs.[24] However, the clinical implications and economic benefits have yet to be formally analyzed with the added cost of VSP-CAD/CAM in the context of various expanding clinical applications including trauma, temporomandibular joint reconstruction, cancer, and skull base surgery.[6, 28, 35, 38] In head and neck cancer reconstruction, patient lifespan, risk for tumor recurrence and disease progression, and quality of life are additional factors that add complexity to the cost-benefit evaluation of the technology in an oncologic setting.

6. Summary

VSP-CAD/CAM is a novel technology that holds potential to consistently and predictably advance reconstructive outcomes, both aesthetically and functionally. This technology is suited for use in spatially complex reconstructive cases due to its ability to visualize and virtually manipulate 3D configurations of the craniomaxillofacial skeleton in a collaborative, synergistic fashion. Its applications are expanding for cases of varying levels of complexity that require precise millimeter precision particularly in trauma, orthognathic procedures and oncology to obtain optimized function and aesthetic outcomes. Implementation of VSP-CAD/CAM into each stage of the reconstruction affords the opportunity to reduce human translational error and facilitates intra-operative decision-making with expedition of the surgical phase.[1, 10, 11, 13, 21, 24] VSP-CAD/CAM technology is attaining acceptance across the multiple surgical disciplines as efforts towards validating its use are increasing, thereby holding promise as an mainstay, innovative solution in the management of challenging head and neck reconstruction cases.
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