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Preoperative Head and Neck Surgical Planning with Computer-Assisted Design and Modeling

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Abstract Virtual surgical planning (VSP) has significantly impacted modern head and neck surgery. Over the past decade, advancements in computer-assisted design (CAD) software have been applied to high-resolution three-dimensional imaging technology to generate powerful tools for planning complex craniofacial resections and reconstructions. These virtual surgical plans incorporate the design of intraoperative surgical guides that are generated through the process of computer-assisted manufacturing (CAM). Virtually planned procedures are then translated to the operating room where they are carried out with unparalleled precision and efficiency. This process allows for accurate operative design that reliably achieves predicted results. Surgical teams are now able to formulate single-staged ablative/reconstructive procedures all the way through to prosthetic dentition and expected soft-tissue outcomes. Recent studies have demonstrated the benefits of preoperative CAD/CAM surgical planning for oncologic resections with immediate reconstructions, severe facial trauma, complex orthognathic and temporomandibular joint procedures, esthetic surgery, and composite tissue allotransplantation. We provide an overview of CAD/CAM applications in head and neck surgery and review the evidence to date regarding the use of preoperative VSP in complex craniofacial reconstruction.

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Introduction

The craniofacial skeleton provides the foundation to support the high functional and esthetic demands of the head and neck. The soft tissues of the head and neck region are dependent on the underlying skeletal framework to maintain appearance, contour, and function, which make precise bone positioning essential for reconstruction. Surgical intervention and functional reconstruction in this complex anatomic region necessitates meticulous planning and precise execution, often by a multidisciplinary surgical team.

Complex head and neck reconstructions historically required a tedious preoperative workup that involved cast models, cephalometric analysis, and intraoperative adjustments based on surgeon experience and anatomic estimation. This process was time consuming and left room for error in an area where even minimal deviations from normal anatomy have significant impact on clinical outcomes. Over the past decade, however, advancements in computer-assisted design (CAD) software have been applied to high-resolution three-dimensional imaging technology to generate powerful tools for planning complex craniofacial resections and reconstructions [1•, 2•, 3, 4•, 5•, 6, 7•, 8].

These virtual surgical plans can then be precisely translated into surgical aids through the process of computer-assisted manufacturing (CAM). Initially these aids were in the form of stereolithographic models to assist with plate bending and orientation preoperatively. This process has evolved even further, however, to generate patient-specific cutting guides, orthognathic guides, and customized plates for intraoperative use.

Virtual surgical planning (VSP) and the CAD/CAM surgical modeling process has significantly impacted modern head and neck surgery. Recent studies have demonstrated the benefits of preoperative CAD/CAM surgical planning for oncologic resections with immediate reconstructions, severe facial trauma, complex orthognathic and temporomandibular joint procedures, esthetic surgery, and composite tissue allotransplantation [1•, 2•, 7•].

Computer-Assisted Design and Computer-Assisted Manufacturing (CAD/CAM)

Indications

At present, there are no set criteria for determining which patients should have preoperative CAD/CAM planning performed. Cases where the use of this technology may have the greatest benefit include delayed reconstructions, anterior mandible defects, significant specimen distortion, bone loss or malposition, and maxillary reconstructions [9•]. Reconstructions that require three-dimensional osteotomy creation, improved osteotomy junction overlap, and precise plate adaptation may also significantly benefit from preoperative VSP [9•]. At our institution, we have reserved the use of this technology for more complex operations on the craniofacial skeleton; however, evidence for reduced operative times and improved functional results have caused us to broaden its use. We have begun using this technology for other complex osseous procedures in other areas of the body as well including the extremities and pelvis.

Operative Planning

Planning starts with a high-resolution computed tomography (CT) scan of the patient's craniofacial skeleton. To improve the accuracy of preoperative modeling, scans can be obtained with the patient wearing fiducial markers on their face for reference. These markers also improve soft-tissue analysis and allow for more accurate estimation of soft-tissue appearance postoperatively. The pitch, yaw, and roll recorded by the fiducial markers in natural head position are used to adjust the 3D CT scan coordinates and digital head position accordingly. If the anticipated bony defect following tumor resection will require free tissue transfer of a vascularized bone flap, a high-resolution CT of the flap donor site is also obtained to have an exact understanding of the vascular and bony anatomy.

For procedures with a dentoalveolar component that will affect occlusion and orthognathic relationships, laser scanned occlusal molds or topographic occlusal imaging is obtained as well. Soft-tissue imaging and simulation software has been shown to be accurate enough for clinical relevance [10•] and may be used as an aid in treatment planning to anticipate the postoperative facial appearance resulting from the planned skeletal changes [11]. These files are then forwarded to a commercial vendor and converted into interactive three-dimensional virtual models of the facial soft tissue, craniomaxillofacial skeleton, and flap donor site. An online meeting is coordinated among the engineers from the modeling company and the relevant surgical teams.

For oncologic/extirpative procedures, resection margins are determined using the virtual model and the engineer marks the desired cutting paths for the osteotomies. If a vascularized bone flap is to be used for reconstruction, following virtual resection of the diseased segment, the virtual image of the flap is superimposed on the ablative defect in the desired vascular and soft-tissue orientation. Virtual osteotomies are then designed to fit the flap precisely into the idealized reconstruction with optimal bony apposition [12•] and adequate vascular pedicle length (Fig. 1). It is important to plan the flap harvest and dissection in standard and safe locations so that these plans can be safely translated in vivo. For instance avoid any destabilization of the joint surfaces and make sure you pick appropriated sidedness and locations for the desired reconstruction. Virtual planning can help you see the bone size and shape prior to being in the operating room, and this allows you to choose the ideal segments of bone for the desired reconstruction.

If you have an approximate or exact knowledge of your vascular perforator locations, VSP can also incorporate the soft-tissue flap component into the reconstructive plan. The free flap construct can be modified to account for the anticipated size of the soft-tissue defect in order to optimize the free flap soft tissue amount and orientation for coverage. In addition, if the soft-tissue defect anticipated is too extensive for coverage with a single flap, preoperative planning is able to identify this and alert the reconstructive surgeon that a second flap will be required for complete soft-tissue coverage. Identification of this problem preoperatively is far more preferable than realizing the need for a second flap to provide soft-tissue coverage intraoperatively.

Orthognathic procedures are planned in similar fashion, but with a focus on osteotomy location and orientation for maxillomandibular correction. The maxillary and/or mandibular movements are then performed virtually until the desired result is achieved. Orthognathic splints are subsequently designed that utilize stable portions of the

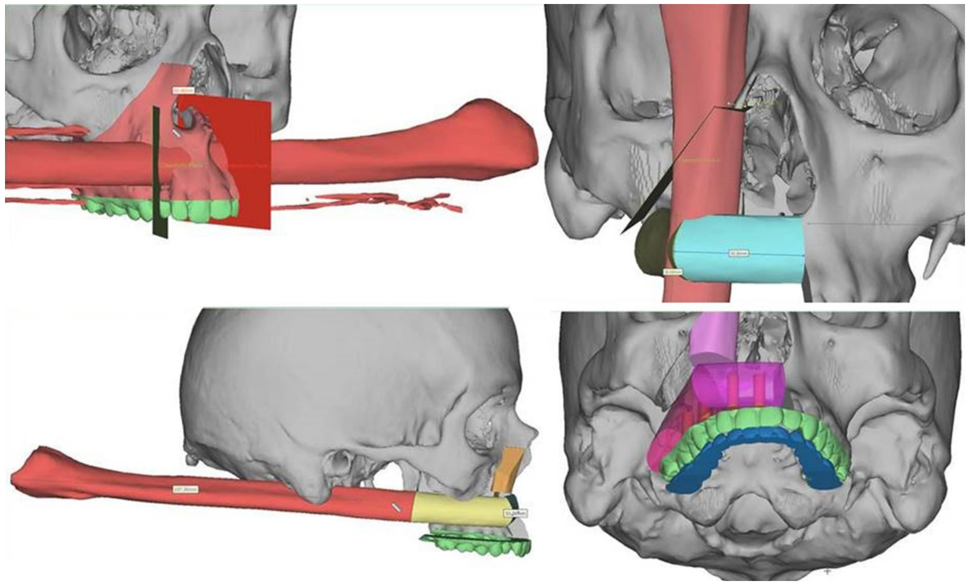

Fig. 1 Virtual osteotomies performed for maxillary resection and free fibula flap to obtain an ideal reconstructive construct

craniofacial skeleton as reference points to guide precise maxillomandibular movements. This process obviates the need for building cast models and mounting them on articulators for preoperative planning.

Virtual planning for complex facial trauma patients allows the reconstructive team to fully evaluate the extent of the defect and all structures involved. Multiple fracture segments can be virtually reassembled into their anatomic positions (Fig. 2). This enables the preoperative identification of soft tissue and bone deficiencies, weakened bony integrity, and functional impairments. Components of reconstruction can then be prioritized and designed accordingly.

CAD/CAM has also been used to facilitate facial composite tissue allotransplantation. Portions of the facial skeleton are transferred with the composite tissue transplant to secure it in place and also suspend the soft tissues. Virtual planning allows for the design of complimentary osteotomies so that the osseous component of the donor tissue fits precisely into the recipient with optimal bony apposition.

For all CAD/CAM applications, the engineers are able to use the geometry of the resected segment or mirror the contralateral disease-free skeleton to recreate the native bony structure and restore occlusal relationships. These techniques are also useful for secondary reconstructions where the resection or injury has already occurred and symmetry has been lost.

The virtual surgery approach allows for a higher number of osteotomies to be planned and multiple different osteotomy combinations trialed until the optimal permutation is identified to restore the craniofacial skeleton. Recent reports suggest reduced operative times using these technologies, despite the increased reconstructive complexity [13•, 14•]. Once the surgical plan is completed, all teams approve the pre-surgical design plan.

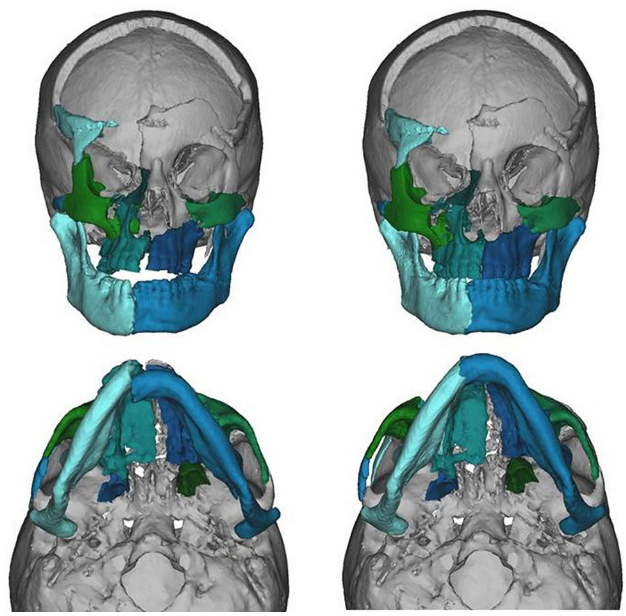

Fig. 2 Panfacial trauma with multiple displaced fracture segments (*left*) and virtual realignment of fracture segments into anatomic position (*right*); significant bone loss was sustained in the superomedial right orbit and frontal bone

Modeling Phase

Based on the virtual plan developed by the multidisciplinary surgical team in conjunction with the engineers from the vendor, stereolithographic manufacturing of the necessary components is performed. A model of the native craniofacial skeleton can be produced for intraoperative reference. Custom splints (Fig. 3) and cutting guides (Fig. 4) are manufactured that fit flush onto the facial skeleton to ensure the osteotomies and any bone repositioning is performed precisely and matches the virtual surgical plan exactly.

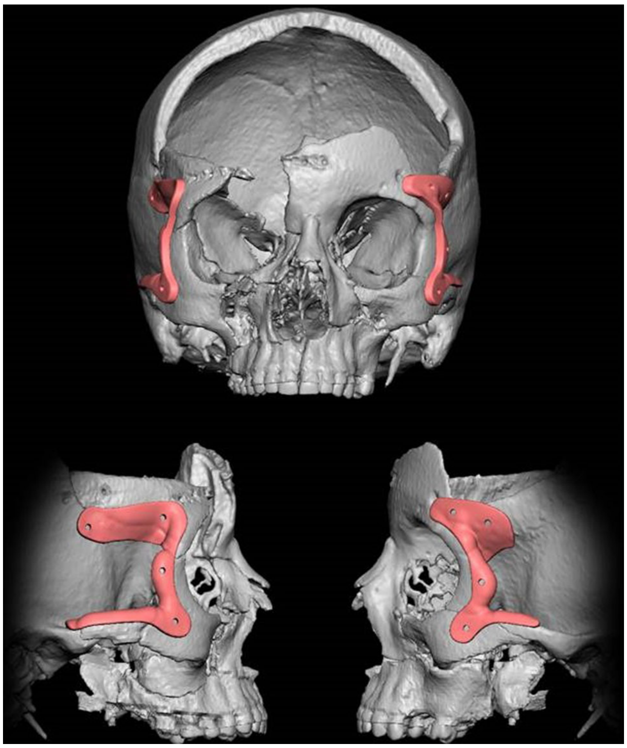

Fig. 3 Custom splints (*orange*) designed to accommodate the multiple displaced fracture segments shown in Fig. 2; these intraoperative splints guide fracture segment assembly into precise anatomic restoration of bilateral orbits

When an osseous free flap or bone graft is used for reconstruction, complimentary cutting guides are manufactured to generate a bony reconstruction that fits exactly into the anticipated defect (Fig. 5). These models and cutting guides facilitate the osteotomy process and allow for seamless integration between the ablative and reconstructive portions of the operation. Virtually planned osteotomies not only streamline the transition from resection to reconstruction, but also allow multiple reconstructive considerations to be taken into account. The cutting jigs are designed to optimize soft-tissue location and orientation, maximize vascular pedicle length, leave sufficient bone at the donor site, and provide ideal alignment for functional dental rehabilitation.

To ensure precise and stable intraoperative occlusal relationships, splints may also be designed and fabricated that enable alignment of the maxillary-mandibular segments to the cranial base in all degrees of freedom [15•, 16•, 17•]. These intraoperative guides establish bony landmarks outside of the resection margins to relate and secure the osteotomized segments of the maxillofacial skeleton into the desired final position. This orthognathic positioning system eliminates the need for intraoperative placement of peripheral reference markers, ensures maintenance of condylar positioning in centric relation, bypasses the traditional time-consuming process of mock surgery on mounted dental models, and obviates the need for fabrication of guiding intermediate splints. This process can allow for complex and multi-part jaw movements that combine orthognathic repositioning, ablative reconstruction, and dental restoration with maximal accuracy.

To facilitate skeletal plating after resection, a reconstruction plate template can be generated to allow for bending of the titanium plate preoperatively. Recent advances in milling processes have also made it possible to custom manufacture reconstruction plates for each

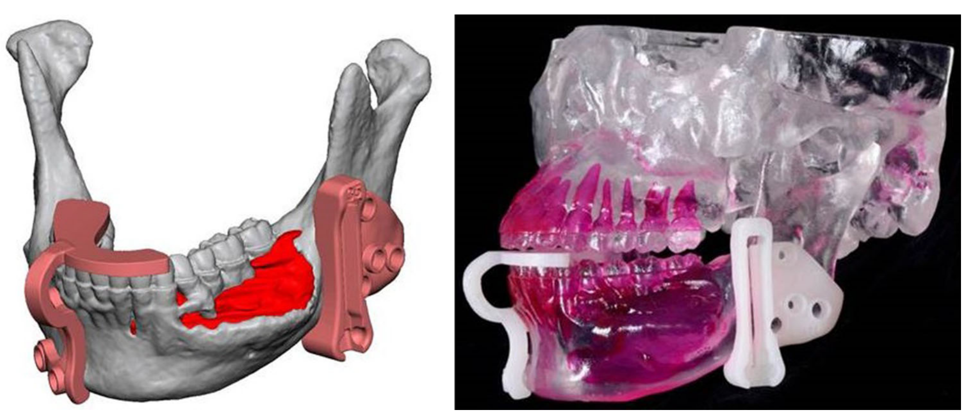

Fig. 4 Virtually designed cutting guides for mandibular ameloblastoma resection (*left*); stereolithographic model with custom cutting guides in place (*right*)

individual reconstruction based on the virtual surgical plan. Titanium plate contour and fixation points are designed to optimize bony apposition, minimize periosteal stripping, avoid damage to nearby vulnerable structures (such as the inferior alveolar nerve), and provide appropriate structure for implant positioning (Fig. 6). Utilization of "predictive holes" allows for repurposing of screw holes initially used for fixation of the ablative cutting guide, for securing the reconstruction plate.

In addition to dental implant planning for delayed prosthodontic denture rehabilitation, certain cases can be designed with both the customized alloplastic implants and denture for immediate placement which allows for the creation of a "Jaw in a Day" [18•] (trademark). It should be noted that if dental implants are being placed, they are drilled prior to performing the osteotomies so that accuracy of placement is not compromised. The dental and alloplastic implants can be designed to obtain optimal soft-tissue changes for very individualized reconstructions [11, 19•].

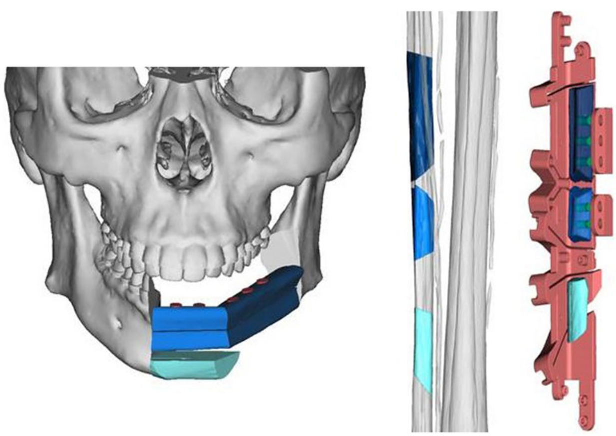

Fig. 5 Virtual model of a three-segment-free fibula flap reconstruction with dental implants shown in *red* (*left*); segment location and osteotomy orientation on the fibula are *color coded* (*middle*); virtually designed cutting guide planned segments in place and dental implant locations shown in *green* (*right*); a custom cutting guide was manufactured based on the virtual design for intraoperative use

Discussion

Complex head and neck reconstructions often require a multidisciplinary surgical team including head and neck surgeons, plastic and reconstructive surgeons, oral and maxillofacial surgeons, and prosthodontists. Computer-assisted operative planning facilitates communication and understanding among the teams involved to produce a comprehensive treatment plan tailored to each individual patient. The operative plan developed on the virtual model is implemented in the operating room through CAM of precise surgical splints and cutting guides, anatomically exact stereolithographic models, and precisely pre-milled plating hardware.

The cohort of patients with head and neck cancer tend to be some of the most debilitated patients with significant comorbidities. Intraoperative accuracy and efficiency is a necessity in order to accomplish complete oncologic ablation and functional reconstruction while minimizing operative time and anesthesia requirements. Computer-assisted surgery improves operative accuracy and efficiency by minimizing the amount of intraoperative guesswork and fine-tuning traditionally required. This technique allows for the assembly of a complex multi-segment osseous component that precisely matches the reconstructive needs without interruption of perfusion or intraoperative measuring. Consequently, both the reconstructive operative time and duration of flap ischemia are reduced significantly [13•, 14•, 20•, 21•]. This is significant, as increased flap ischemia duration has been associated with increased postoperative flap complications [22, 23•].

In addition to improving surgical planning and coordination, this powerful technique has a much shallower learning curve compared to traditional approaches.

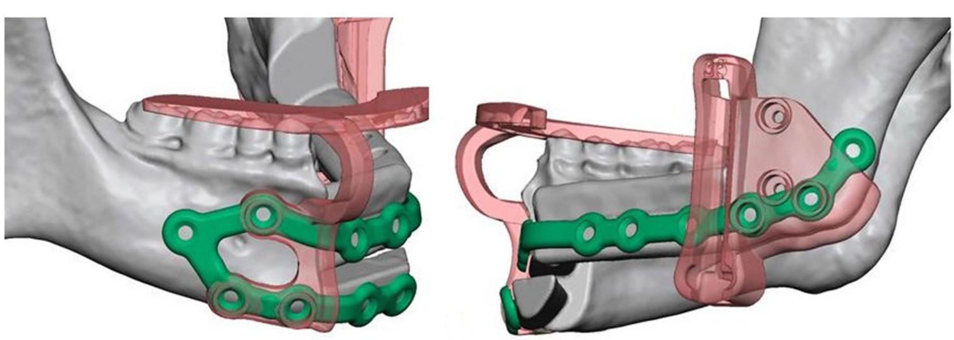

Fig. 6 Virtual plan for a custom milled titanium reconstruction plate that avoids inferior alveolar nerve, allows implant placement, incorporates an osseous genioplasty component, and utilizes prior "predictive" drill guide holes for fixation

Complex head and neck reconstructions are simplified into their component parts to make even the most complicated operations understandable and approachable. This also serves to improve surgical resident education and facilitates better patient comprehension of their planned procedure.

At present, incremental cost associated with computer-assisted techniques is approximately $3000–$5000 per case. For complex operations, however, this is often easily offset by the reduction in operative time [20•], decreased flap complications from shorter ischemia times [13•, 14•, 21•], and improvement in functional outcomes with higher rates of dental rehabilitation [13•]. Patients receiving either intraoperative implant placement alone or implant placement with single-stage denture placement have a significant potential cost savings related to avoiding the surgical staging that would normally be required to obtain a completed dental reconstruction. In addition, using these modeling techniques significantly lowered the time to complete oral and dental reconstruction [13•]. Reduction of anesthesia requirements may also decrease the operative morbidity and risk for postoperative complications, particularly for the head and neck cancer patient cohort. The potential benefit of minimizing the need for later operative revisions also exists due to the relative initial imprecision of reconstructions that were not virtually planned.

Future Directions

The use of CAD/CAM for complex craniofacial reconstructive surgery has gained significant acceptance among the head and neck surgical community, largely due to the advantages detailed above. This technique has been shown to reliably produce successful functional reconstructions of complicated defects despite increased reconstructive complexity. Having established functional reconstructive success, recent technical refinements have been focused on improving the esthetic appearance. As soft-tissue volumetric imaging analysis improves, its incorporation into the surgical plan will allow for further optimization of the reconstruction. Customized plating and alloplastic implant technology continues to improve as well. As utilization of the technique becomes more common, the cost of CAD/CAM planning will likely decrease over time.

Due to its success in head and neck reconstruction, our group has also expanded the use of CAD/CAM technology to other applications. These include limb-sparing sarcoma defect reconstructions in the upper and lower extremities, complex limb-sparing pelvic reconstruction, and traumatic extremity reconstruction.

Conclusions

Computer-assisted surgical planning and modeling allows for accurate operative design with reliably predicted results. Surgical teams are now able to create single-staged ablative/reconstructive procedures all the way through to prosthetic dentition and expected soft-tissue outcomes. These procedures are then translated to the operating room where they are carried out with unparalleled precision and efficiency.

Compliance with Ethics Guidelines

Conflict of Interest Dr. Levine is a consultant for Stryker. Drs. Stranix, Monaco, Brecht, and Hirsch declare no conflicts of interest.

Disclosure The authors report no proprietary or commercial interest in any product mentioned or concept discussed in this article.

Human and Animal Rights and Informed Consent This article does not contain any studies with human or animal subjects performed by any of the authors.

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