

Virtual Surgical Planning for Oncologic Mandibular and Maxillary Reconstruction

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Summary: Virtual surgical planning (VSP) with computer-aided design and computer-aided modeling (CAD/CAM) enables the opportunity to provide personalized medicine in complex head and neck reconstruction. This innovative technology allows ablative and reconstructive surgeons to virtually create and manipulate three-dimensional anatomic models to plan both the resection and reconstruction of complicated maxillofacial defects. Studies demonstrate improvements in preoperative planning, operative efficiency and accuracy, and postoperative outcomes. VSP facilitates immediate dental implantation in selected patients, which can improve the likelihood of achieving dental restoration. This article outlines strategies for technique optimization as well as the applications, advantages and disadvantages of VSP in complex oncologic head and neck reconstruction. (*Plast Reconstr Surg Glob Open* 2021;9:e3672; doi: [10.1097/GOX.0000000000003672](https://doi.org/10.1097/GOX.0000000000003672); Published online 17 September 2021.)

INTRODUCTION

The modern era of head and neck reconstruction has witnessed several paradigm shifts. The first major leap was the transition from local and regional pedicle flaps to free tissue transfer, including osteocutaneous flaps. More recently, the development of virtual surgical planning (VSP) through computer-aided design and computer-aided modeling (CAD/CAM) has further advanced oncologic head and neck reconstruction. VSP offers numerous applications, assisting in the reconstruction of the entire maxillofacial skeleton (and beyond) for both oncologic and nononcologic surgeries. This technology generates three-dimensional (3D) images that are manipulated with advanced computer software, improving the accuracy and precision of both the ablative and reconstructive surgery.¹⁻⁶

The fibula free flap^{7,8} is the workhorse donor site for osseous facial reconstruction, though other osteocutaneous options have been described.^{8,9} Before VSP, various techniques were utilized to shape the bony construct.^{7,10,11} One such method uses two-dimensional acrylic templates in conjunction with the surgical specimen. The mandibular parabola is traced using a wax pencil on a printed 1:1

axial computed tomography (CT) image of the mandible, serving as a reference for anterior and body defects. A tracing on a lateral cephalogram is used to replicate the mandibular angle for posterior defects. These x-ray tracings are converted to acrylic templates and sterilized for use in the operating room to guide the angulation of closing wedge osteotomies. To determine bony segment length, the specimen is measured directly (Fig. 1). In comparison, by using patient-specific CAD/CAM cutting jigs, VSP permits customized fibular osteotomies considering the individual differences in the fibula shape. VSP also provides cutting guides for the oncologic resection, improving the accuracy of bony cuts, which is valuable when tumor extent cannot be visualized from the external surface of the bone.

VSP begins with a multidisciplinary web-based teleconference with a biomedical engineer from a modeling company, a reconstructive surgeon, an extirpative surgeon and a dental surgeon (if endosseous implants are required) 1–2 weeks preoperatively.^{6,12,13} Patients obtain a high-resolution CT scan (≤ 1 mm cuts) of the lower extremities (CT angiogram) and facial skeleton for production of 3D renderings. These images should be completed near the time of surgery, especially if the tumor is rapidly growing to avoid significant derangements between the preoperative plan and intraoperative findings. Ideally, the head and neck scan is performed on a different day than the CT angiography of the lower extremity, as the timing of contrast is different (although this can be logistically challenging).⁶ Lower extremity images are useful to locate the septocutaneous peroneal perforators when including a skin paddle (Fig. 2). Advanced knowledge of which portion of the fibula will be

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Received for publication August 6, 2020; accepted May 14, 2021.

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DOI: [10.1097/GOX.0000000000003672](https://doi.org/10.1097/GOX.0000000000003672)

Disclosure: This research was funded in part through the NIH/NCI Cancer Center Support Grant, P30 CA008748. The authors have no financial interest to declare in relation to the content of this article.

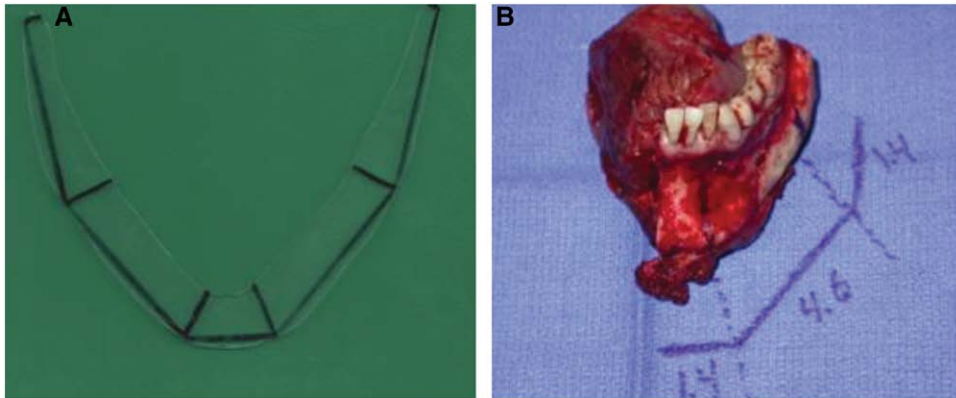


Fig. 1. Pre-VSP, acrylic templates and the surgical specimen were used to plan the construct. A, Two-dimensional acrylic template used to determine osteotomy angles (B) measurements of specimen to determine reconstruction segment lengths. Reprinted with permission from *J Reconstr Microsurg* 2014;30:289–296.

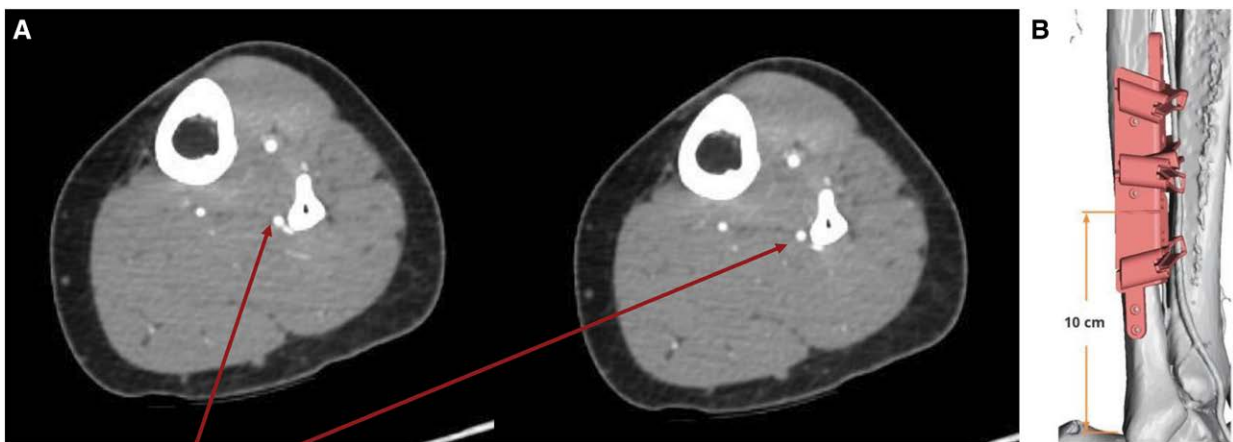


Fig. 2. CTA is utilized to determine the skin paddle perforator which can be marked on the cutting guide. A, Preoperative CTA of LE outlining perforator. Osteotomies are planned to include the perforator. B, Hash mark on fibular cutting guide denotes septocutaneous perforator location and appropriate guide position.

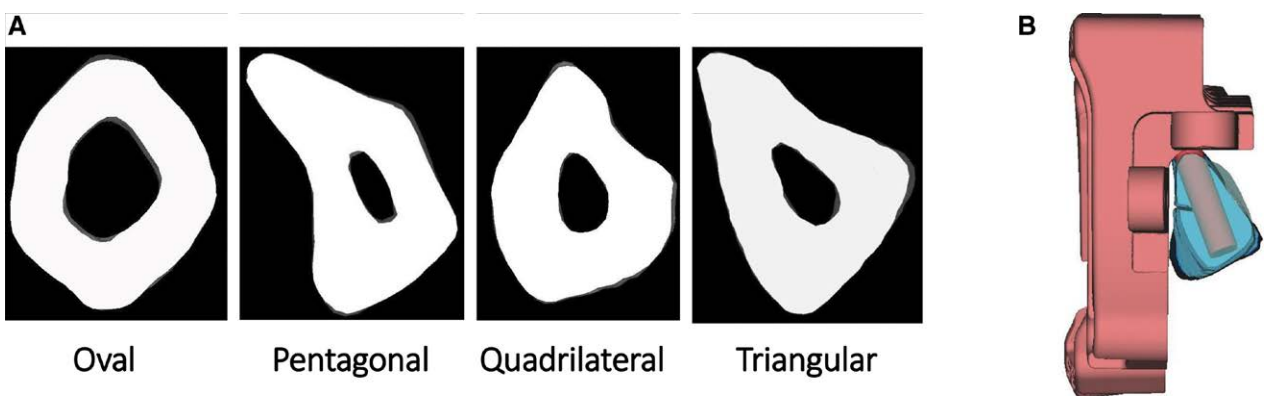


Fig. 3. The fibula can vary in shape, which impacts adaptation of the cutting guide. A, Varying shapes of the fibula along its course. B, Cross-section of cutting guide with a dental implant positioned precisely within a specific fibula shape. If the correct portion of the fibula is not used, as identified in the modeling session, the guide will not adapt properly leading to malposition of the implant.

used in the final reconstruction is critical as the shape of the bone varies significantly from proximal to distal (Fig. 3A). If ignored, this can be associated with maladaptation of the cutting jig to the fibula, leading to either incorrect angulation of the osteotomies or the dental implants (Fig. 3B).

CAD/CAM technology is intuitive and creates reliable and reproducible results. The current article outlines strategies for technique optimization as well as the applications, advantages and disadvantages of VSP for complex oncologic head and neck reconstruction.

TECHNIQUE OPTIMIZATION

Preoperative Planning

With increasing experience of VSP and CAD/CAM, technological nuances continue to impact process and improve outcomes. Process optimization begins with the initial planning call. It is recommended to design two separate extirpative and reconstructive plans when possible. Despite thorough preoperative planning, the extirpative surgeon may require wider margins than initially anticipated in immediate reconstruction. As such, a second, “wide” plan is imperative (Fig. 4). Additional cutting guides with wider resection margins are designed based on discussion between surgeons. Alternatively, surgeons can primarily commit to a single wider plan than the oncologic surgeon initially depicted. A secondary benefit of preoperative tumor visualization is the ability to predict the reconstruction segment size. For example, a tumor resection that cuts through the midline between the central incisors will require an anterior reconstructive segment of only approximately 1 cm—a length at high risk for devascularization. With this information available, removal of a wider margin of tissue around the tumor is planned and a longer reconstructive segment is designed. Although there is no consensus, generally the bone segments should be approximately 2 cm to ensure adequate vascularity.

Cutting Guide Placement

A determinant of intraoperative success is strict adherence to the preoperative plan, beginning with accurate cutting guide placement.⁶ For mandibular body and ramus osteotomies, the angle is a helpful landmark to align the cutting guides (Fig. 5A). All soft tissue must be cleared from the periosteum to allow for close apposition

of the guide to the bone. Additionally, dentition can assist in guide placement as the cutting slot is aligned with the root of a specific, predetermined tooth to be extracted (Fig. 5B). In the scenario of the edentulous patient, the distal cutting slot is secured around mandibular angle, whereas the mesial slot is maintained in a fixed position with a cutting bridge (Fig. 5C).

More recently, intraoral scanners are used as a novel imaging technique to design cutting guides. Rather than basing guides on the inferior mandible border, they are created relative to the occlusal plane using dental impressions obtained from the intraoral scanner. This method is highly accurate for guide position because of the lock and key fit between the guide and the occlusal surface of the teeth¹⁴ (Fig. 6).

Osteotomy Optimization

Osteotomy creation, of both the maxillofacial skeleton and the fibula, can be optimized for accuracy. When considering the fibula osteotomies, it is important to use minimal screws to secure guides, especially in small segments, to prevent devascularization. Ideally, cuts are made at perpendicular angles to the bone surface to avoid saw blade slippage. As such, different locations along the fibula necessitate different approaches. For mandibular angle reconstruction, osteotomies are perpendicular to the fibula when approaching from the lateral aspect. Body or parasymphseal osteotomies are perpendicular when approaching fibula from anterior surface. “Wrap around jigs” have been constructed to accomplish both approaches (Fig. 7). Most osteotomies for maxillary reconstruction are completed on the lateral surface, though if multiple segments are required, the cuts may be in various planes.^{3,15}

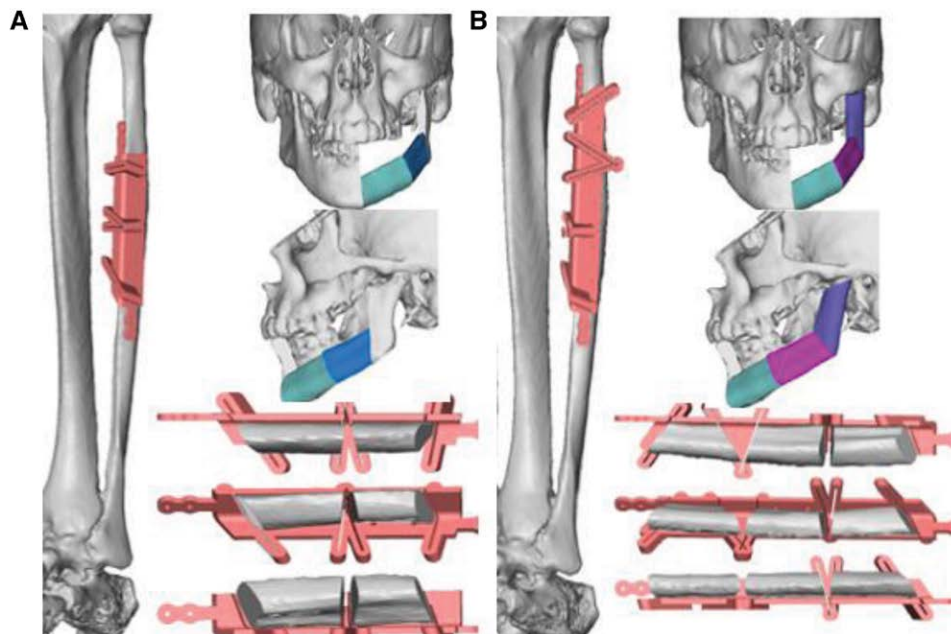


Fig. 4. Examples of two plans with differing margins and guides. A, Narrow and (B) wide margin plans of mandible reconstruction.

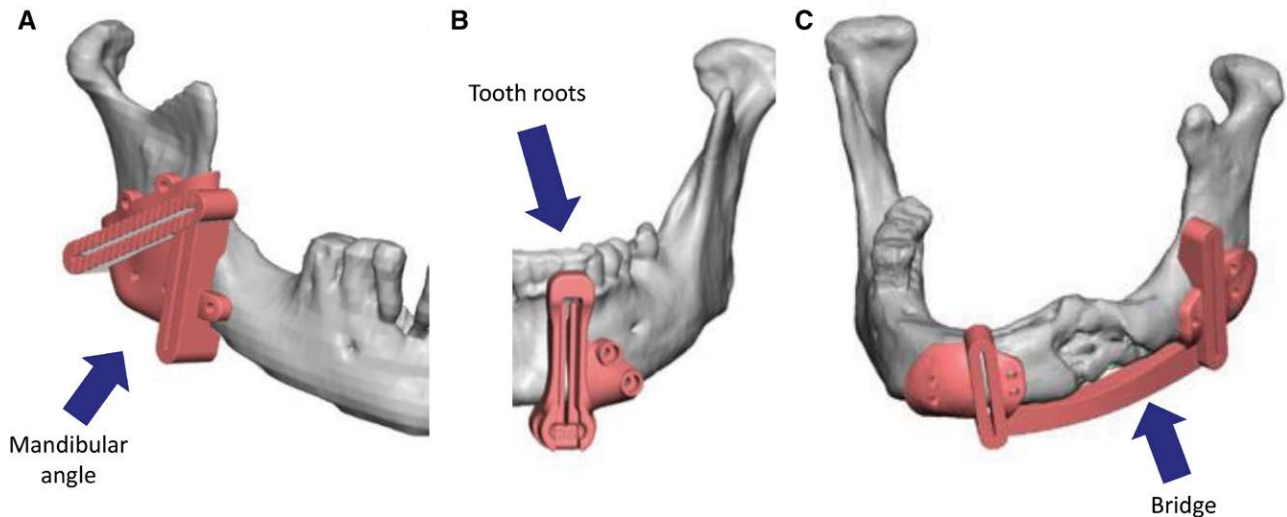


Fig. 5. Mandibular resection cutting guides can be based on anatomic landmarks. a) mandibular angle adaptation. b) anterior tooth root alignment. c) Bridged cutting guide for the edentulous patient to secure appropriate spacing. A, Mandibular landmarks for accurate guide placement at the angle and (B) along tooth roots. C, Bridged cutting guide for the edentulous patient to secure appropriate spacing.

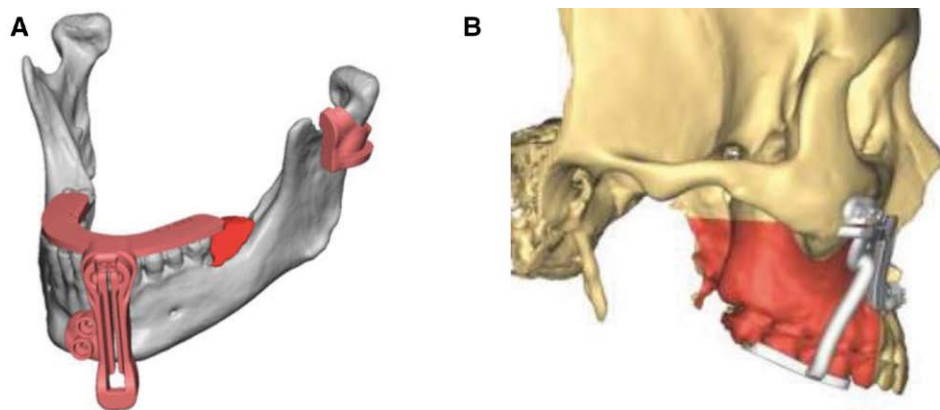


Fig. 6. Cutting guides can be based on occlusion for the mandible (A) and maxilla (B).

Creating osteotomies in three distinct planes also improves segmental collocation. Using the cutting guides, the saw position controls the axial, sagittal, and coronal axes for precise intraoperative execution.^{3,6} For example, from distal to mesial, the mandible trajectory takes a cranial to caudal course. This is challenging to reliably accommodate with free-hand osteotomies; however, the angulation of the cutting slot can adjust for this anatomy (Fig. 8). The osteotomy angles can also be altered to maximize bony apposition, increasing the area of overlap of adjacent bone segments. This creates an optimal healing environment at the osteotomy junction, which is particularly useful for osteoradionecrosis (decreased vascularity) or at the ramus (thin bone).¹⁶

Specimen Distortion

Before CAD/CAM, it was critical to measure the specimen to plan osseous flap segment lengths (Fig. 1).⁸ The angulation template was then referenced for osteotomy angles and an overall reconstruction plan was designed. Frequently, these measurements were imprecise, altered in

the operating room by a number of factors including tumor distortion, adjacent soft tissue, and pathologic fractures.^{3,6} CT images and VSP allow for precise measurements that do not require the physical specimen, avoiding any inaccuracies.

Precision Oncology

The extirpative surgeon faces challenging tumor locations without clear surface bony landmarks, such as intracranial, maxillary antral, or palatal. This difficulty is compounded by limited exposure through minimal access incisions potentially resulting in inadequate tumor margin or piecemeal tumor removal.⁶ To ensure appropriate tumor excision, CAD/CAM technology designs cutting jigs fabricated to the exact desired intraoperative position based on the unique structure of the patient's anatomy (Fig. 9). They may utilize foramina or bony landmarks to afford further precision.

Customized Fixation Hardware

With traditional methods, plates were hand bent preoperatively using a printed stereolithographic model or

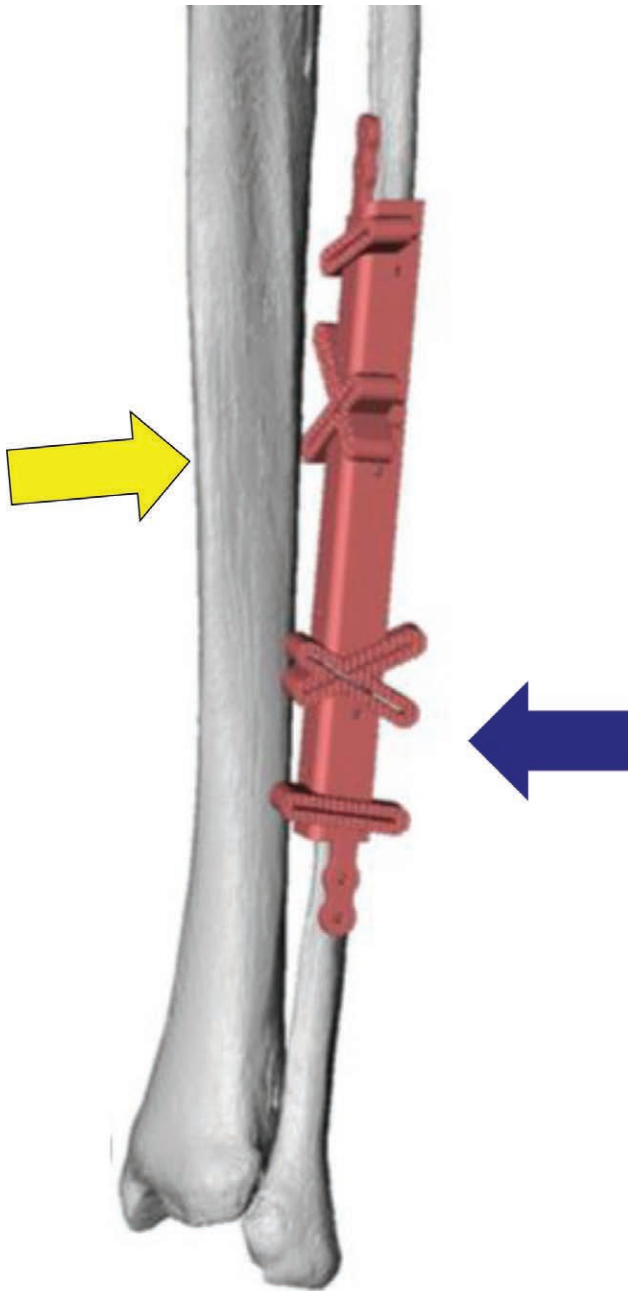


Fig. 7. “Wrap around” cutting guide for lateral (blue arrow) and anterior (yellow arrow) osteotomies.

in situ before tumor removal. In these instances, plates were bent to the mandible—not to the fibula (to which they will ultimately be fixed)—resulting in poor apposition of the fibula to the miniplates or reconstruction bar. Moreover, bending plates by hand can strain or weaken the titanium as well as distort the shape of fixation holes rendering them unusable. In contrast, VSP customized plates are fabricated preoperatively to the reconstructed fibula based on the final plan and remaining anatomy. This results in better adaptation of the plate to the reconstruction.¹⁷ The maxillofacial and fibula cutting guides can also be planned with predictive drilling holes which align

with the screw locations of the final hardware, removing yet another level of estimation. The combination of the customized hardware and predrilled cylinders ensures the proper downward cant or trajectory of the anterior mandible (Fig. 10).

For maxillary reconstruction, novel shaped hardware can be planned with extension arms to allow adaptation to any anatomic scenario. The hardware can also be designed to capture the thickest areas of bone such as the buttresses of the midface (Fig. 11). Although customized hardware is not necessary for the majority of VSP cases, it is essential for delayed reconstruction, maxillary defects, and dental restoration.¹⁸

APPLICATIONS

Anterior Mandibular Reconstruction

Reconstruction of anterior mandibular defects is challenging as most of the remaining lower dentition is removed. Additionally, with loss of central osseous support, the posterior segments are free-floating. Using traditional shaping methods, inaccurate anterior segment specimen measurements and plate apposition (secondary to tumor distortion) often resulted in incorrect positioning of the remaining native posterolateral mandible. Cumbersome external fixation was often necessary to secure the relative position of the free-floating segments. Using VSP, the neomandible and customized hardware serve as a reference allowing for precise positioning of the lateral segments (Figs. 10 and 12).

Delayed Mandibular Reconstruction

Delayed reconstruction is particularly difficult given the absent surgical specimen on which to base measurements as well as chronic soft tissue distortion³; this includes both delayed reconstructions and traumatic scenarios. Stranix et al¹⁹ presented an algorithm for delayed reconstruction to help guide this challenging problem. Ideally, VSP can be accomplished based on patient-specific imaging obtained before the defect resection (Fig. 13A). This is more likely available in the oncologic population than in trauma patients. If patient-specific imaging is available, it is preferable, though adjuvant radiation therapy may alter the soft tissue envelope. Additionally, most patients present from an outside institution, with low-quality imaging or no imaging at all, rendering this technique impossible. For delayed unilateral defect reconstruction, a mirror image is created based on the remaining contralateral segment and then aligned with the remaining mandible or temporomandibular joint (Fig. 13B). Unfortunately, this method cannot be employed for anterior defects, as there is nothing to mirror. The least preferable option is vendor production of mock mandibles with similar morphology based on normative values (Fig. 13C). Scaling up or down mock mandibular size is possible as the angles at parasymphysis, midbody and angle are relatively preserved between individuals.^{11,20}

Maxillary Reconstruction

VSP is particularly useful in midface osseous reconstruction.^{3,4,6,15,21} Maxillary access is difficult due to

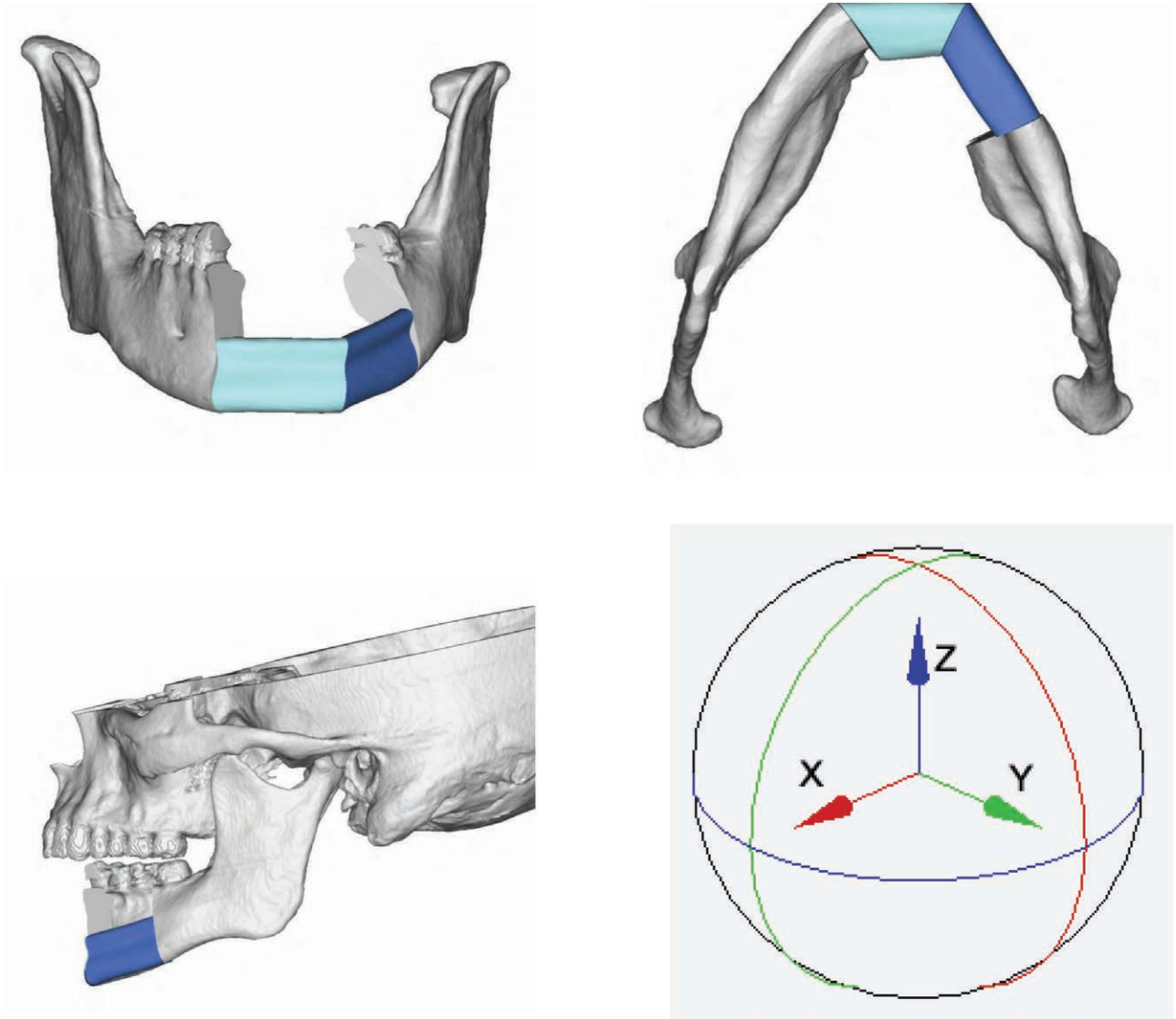


Fig. 8. Mandibular trajectory is inferior and medial, which cannot be replicated with traditional 2D techniques. Cutting guides designed through VSP allow for adjustment in all axes.

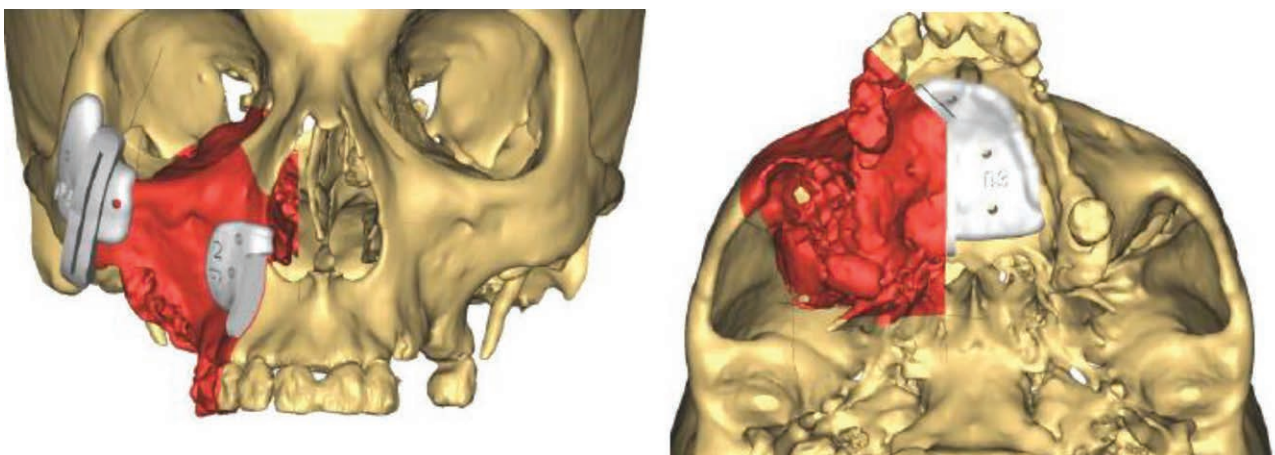


Fig. 9. Precision oncology using VSP. Cutting guides designed to snugly fit the unique structure of challenging maxillofacial topography to improve the ablative surgery.

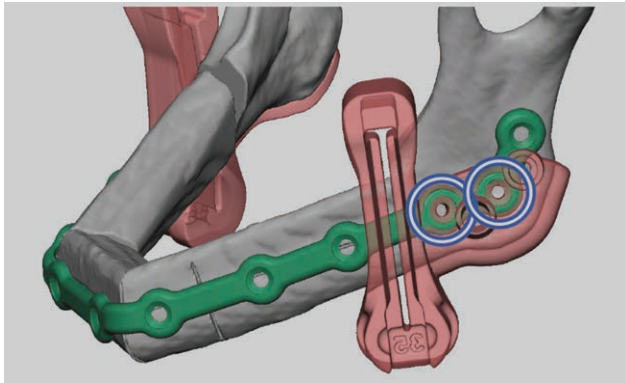


Fig. 10. Predictive cylinders (blue and white circles) drilled for precise flap fixation.

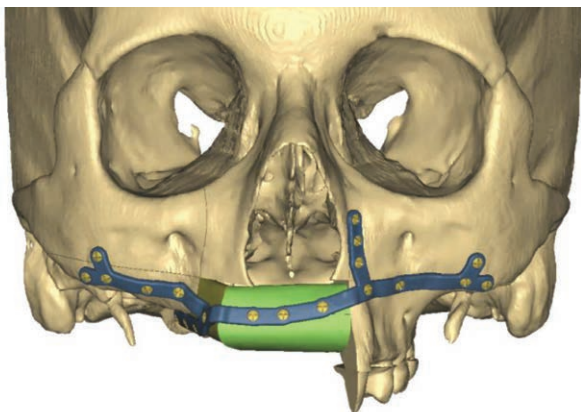


Fig. 11. Customized hardware that is designed to capture the thick bone stock of the nasomaxillary, zygomaticomaxillary buttresses.

limited exposure constraining the reliable and accurate positioning of the final reconstruction. Furthermore, the maxilla's compact, boxy geometry exhibits more changes in shape over the same distance compared to the mandible, necessitating more osteotomies with smaller segments. A single inaccurate cut can affect multiple subsequent osteotomies, negatively impacting the ultimate structure of the nose, upper lip, or orbit. VSP

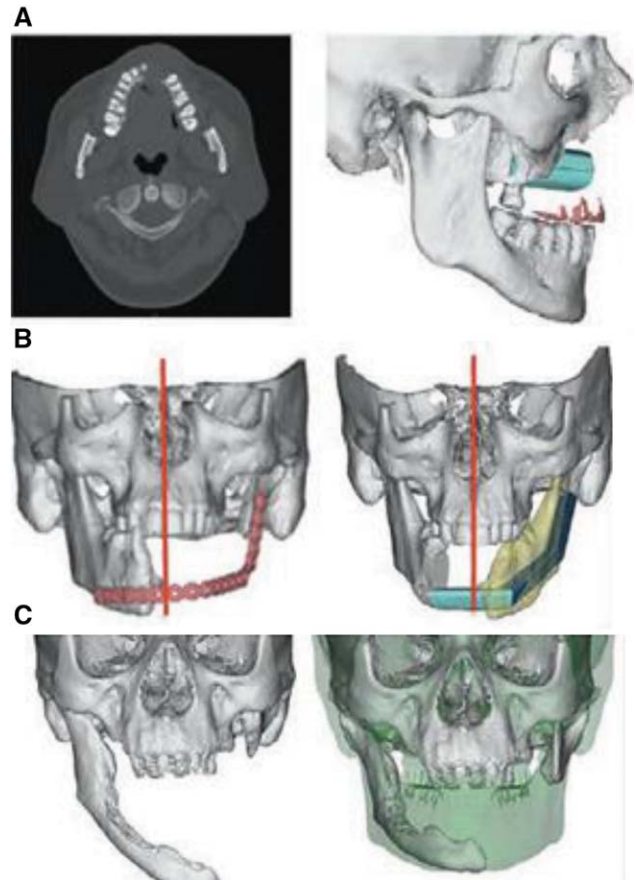


Fig. 13. Delayed mandibular reconstruction. VSP plan based on (A) patient-specific predefect imaging, (B) mirror image of contralateral native mandible, and (C) normative values. Reprinted with permission from *Plast Reconstr Surg* 2019;143:1197–1206.

addresses this directly by providing a better precision of the osteotomies. Intraoperative stereotactic navigation can be used for improved spatial positioning, orienting small segments accurately in 3D.²² Prefabricated fixation plates are essential in maxillary reconstruction with VSP to remove inaccuracies that are inherent to free-hand positioning and hand-bent fixation plates (Fig. 11).

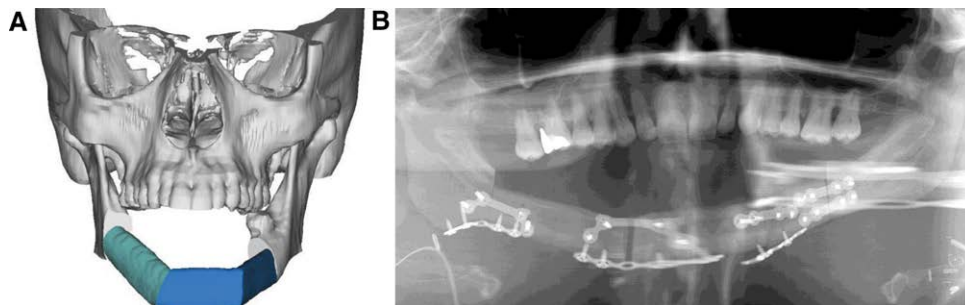


Fig. 12. Anterior mandible reconstruction with VSP. A, Projected VSP reconstruction of an anterior mandible defect and free-floating posterolateral segments with a (B) postoperative radiograph showing anatomic positioning of these segments using VSP reconstruction.

Immediate Dental Implantation

The benefit of immediate dental implant placement (IDIP) is increased rates of dental rehabilitation with minimal additional operating room time.^{23–25} Without VSP, immediate dental implants are difficult to place precisely, given the polymorphous shape of the fibula. Proximally, the bone is triangular, but distally, it is pentagonal with an alpha helix trajectory in the axial plane and variable height and width throughout¹⁴ (Fig. 3A). During the planning session, the height, location, and size of implants are designed considering these structural characteristics. Dental implants are placed, whereas the fibula is still perfused in the donor site.²⁴ The fibula jig ensures appropriate implant trajectory and inclination (Fig. 3B). Fibula fixation with occlusive guides, splints, or navigational technology prevents rotation of the implant bearing segments securing the desired position.¹⁴ IDIP with VSP affords head and neck oncology patients a greater likelihood of achieving successful dental restoration, allowing for a 6-week period of osseointegration before initiation of radiotherapy. In contrast, delayed implant placement following radiotherapy has a higher rate of implant failure.²⁴

OUTCOMES

The literature supports favorable outcomes with CAD/CAM technology.^{13,26} Roser et al¹² found a mean distance of 2.00 ± 1.12 mm between the actual mandibular osteotomy compared to the virtual mandibular osteotomy. In studying the fibular segments, the mean distance of the actual osteotomy compared to the virtual osteotomy was 1.30 ± 0.59 mm. The mean percentage overlap of actual plate to virtual plate was $58.73\% \pm 8.96\%$. Hanasono and Skoracki²⁷ discovered a difference of 2.4 ± 2.06 mm and 3.51 ± 2.69 degrees between actual and projected fibular segment lengths and angles, respectively. A systematic review by Pucci et al²⁶ demonstrated similar findings from 12 studies. Wang et al²⁸ compared preoperative and postoperative CT scans of native and reconstructed mandibles and found a difference of 1.16 ± 0.45 mm in height and 3.09 ± 1.44 degrees in angle. Zhang et al²¹ compared the fibula flap position of patients undergoing maxillary reconstruction with VSP ($n = 8$) and conventional surgery ($n = 19$). In this study, the CAD/CAM group exhibited more ideal fibula positions in vertical distance ($P = 0.01$), horizontal position ($P = 0.019$), and extension of the posterior end ($P = 0.041$). The average difference between the actual postoperative position and VSP was less than 5 mm. Many of the studies are underpowered due to small sample size.

Advantages/Disadvantages

As with any technologic advancement, there are advantages and disadvantages of the technique, as well as a curve to adoption. Using technology to preoperatively plan the resection and reconstruction affords the ability to correct or compensate for unappreciated anatomical aspects. This results in improved reconstructive accuracy (shape and occlusion) and efficiency while minimizing “eyeballing” intraoperatively. Less time is spent in the operating room as the planning is already completed, eliminating intraoperative plate bending as well when prefabricated plates are used. Additionally, fibular osteotomy, contouring, and inset are

accelerated with this process.²⁹ Chang et al³⁰ compared 92 patients who underwent free flap mandible reconstruction with VSP ($n = 43$) and without ($n = 49$) showing significant decrease in operative time (666 versus 545 min; $P < 0.005$).

The oncologic and dental surgeons benefit as well. Using VSP, the oncologic surgeon can better understand the spatial relationship of the tumor to surrounding structures and precisely plan the operative approach. The cutting jigs permit correct intraoperative positioning on the mandible or maxilla ensuring the desired angles for tumor removal (especially helpful in palatal resection). Immediate, accurate dental implant placement can improve chances that a patient will obtain dental restoration. This is important in the oncologic patient, as placing dental implants into radiated bone was historically feared. IDIP also eliminates a future dental procedure for the patient.^{24,25} Another useful application of VSP is designing custom implants for nononcologic cases to restore craniofacial volume and contour (ie, trauma and cranial vault reconstruction) where radiation is not indicated.^{31–33}

It should be emphasized that VSP facilitates improved preoperative communication between the surgical services. With surgeons, dentists, and vendors together formulating the operative plan before surgery, anticipated challenges are rectified as a team to augment patient care.³ Additionally, VSP offers great benefit to challenging scenarios of reconstruction, including the anterior mandible, delayed reconstruction, and maxilla. Using CAD/CAM technology, surgeons perform more personalized or customized reconstructions with increased number and complexity of osteotomies showing reproducibility across institutions.⁶

Although the disadvantages of VSP are few, several warrant a discussion. Reliance on this technology can contribute to a loss of familiarity with traditional techniques, which may become problematic if a circumstance dictates that a surgeon must perform reconstruction by hand. Similarly, if unforeseen intraoperative changes to the plan arise, the surgeon may not be equipped to make the necessary adjustments to complete the reconstruction.

Possibly the biggest disadvantage is in the cost of VSP. The planning, model, and cutting guides incur an added cost to the surgical procedure; however, less time may decrease operating room utilization charges. Beyond the operating room, it is difficult to put a monetary value on the potential for dental restoration or improved occlusion. Previous studies demonstrate the cost efficiency in terms of OR time saved,^{34,35} though a recent investigation by Fatima et al³⁶ highlights the uncertainty of this conclusion. This is indeed an area of ongoing debate, and one that necessitates continued critical focus and examination with further cost utility analyses.

SUMMARY

VSP and CAD/CAM are an important tool for oncologic osseous reconstruction of the mandible and midface. Compared to traditional methods of bony flap shaping (eg, free-hand shaping), this technological advancement provides improved precision and accuracy. As experience with this technology grows, continued refinements will lead to greater accuracy, efficiency, and potentially improved patient outcomes.

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