A Virtual Surgical Planning Algorithm for Delayed Maxillomandibular Reconstruction

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Background: The absence of a tumor specimen from which to obtain measurements at the time of delayed maxillomandibular reconstruction introduces degrees of uncertainty, creating the need for substantial intraoperative guesswork by the surgeon. Using the virtual surgical planning environment, the size and shape of missing bony elements is determined, effectively "recreating the defect" in advance of the surgery. Three virtual surgical planning techniques assist the reconstructive surgeon: patient-specific modeling, mirroring the normal contralateral side, and scaled normative data. To facilitate delayed reconstruction a hierarchical algorithm using virtual surgical planning techniques was developed.

Methods: Delayed maxillomandibular virtual surgical planning reconstructions were identified from 2009 to 2016. Demographics, modeling techniques, and surgical characteristics were analyzed.

Results: Sixteen reconstructions were performed for osteoradionecrosis with displacement (50.0 percent) or oncologic defects (37.5 percent). Most patients had prior surgery (81.3 percent) and preoperative radiation therapy (81.3 percent); four had failed prior reconstructions. The following delayed virtual surgical planning techniques were used: patient-specific modeling based on previous imaging (43.8 percent), mirroring normal contralateral anatomy (37.5 percent), and scaled normative data (18.8 percent). Normative and mirrored reconstructions were designed to restore normal anatomy; however, most patient-specific virtual surgical planning designs (71.4 percent) required nonanatomical reconstructions to accommodate soft-tissue limitations and to avoid the need for a second flap. One partial flap loss required a second free flap, and one total flap failure occurred. Hardware exposure was the most common minor complication, followed by infection, dehiscence, and sinus tract formation.

Conclusions: Virtual surgical planning has inherent advantages in delayed reconstruction when compared to traditional flap shaping techniques. An algorithmic approach based on available imaging and remaining native anatomy enables accurate reconstructive planning followed by flap transfer without the need for intraoperative guesswork. (*Plast. Reconstr. Surg.* 143: 1197, 2019.)

CLINICAL QUESTION/LEVEL OF EVIDENCE: Therapeutic, IV.

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Over the past decade, there has been widespread expansion in use of virtual surgical planning for reconstruction of a variety of osseous defects. The advantages of the virtual surgical planning process over traditional techniques become pronounced when patients require delayed reconstruction of existing defects. Traditional techniques for shaping osseous flaps in head and neck reconstruction require assessment of

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the defect along with precise measurement of the tumor specimen.[1–3] In considering delayed reconstructions, normal anatomical landmarks are distorted from soft-tissue scarring and/or radiation therapy and the tumor specimen is no longer available. The need for precision remains, however. The delayed scenario requires substantially more guesswork for the surgeon compared with immediate reconstructions; therefore, these defects are amenable to the potential advantages provided by the virtual surgical planning environment.[4–8]

A case series is presented of delayed reconstructions performed using a hierarchical algorithm of three computer-assisted modeling techniques. The study aim is to highlight to plastic surgeons how virtual surgical planning technology can be used to eliminate the intraoperative guesswork associated with the traditional free-hand approach in this challenging subset of craniofacial defects.

PATIENTS AND METHODS

The study design is a retrospective review of delayed maxillary or mandibular osseous reconstructions performed with virtual surgical planning between 2009 and 2016. Procedures were performed at two major academic medical centers. Demographic and surgical characteristics of the cohort were analyzed. Virtual surgical planning was performed as part of the standard of care at both institutions. 3D Systems (Littleton, Colo.) (formerly Medical Modeling, Inc., Golden, Colo.) assisted with the virtual surgical planning process and cutting guide fabrication. Conceptual considerations and refinements in the virtual surgical planning process were evaluated and determined by the senior authors (E.M. and E.S.G.). Internal review board approval was obtained from both institutions.

Virtual surgical planning reconstructive techniques were chosen at the discretion of the operating surgeon on a case-by-case basis according to the hierarchical algorithm shown in Figure 1. Defect location, size, anatomical distortion or constraints, and available imaging were taken into consideration. Cases of osteoradionecrosis were included in the series only if there was fracture of the mandible with significant displacement. Cases were further subclassified as anatomical versus nonanatomical reconstructions depending on whether the remaining anatomy would permit restoration to original proportions or whether accommodations were needed for soft-tissue scarring or radiation-induced fibrosis. Once the dimensions of the defect were accurately reestablished along with the optimal reconstructive plan, the operation was performed similar to any other immediate virtual surgical planning reconstruction.

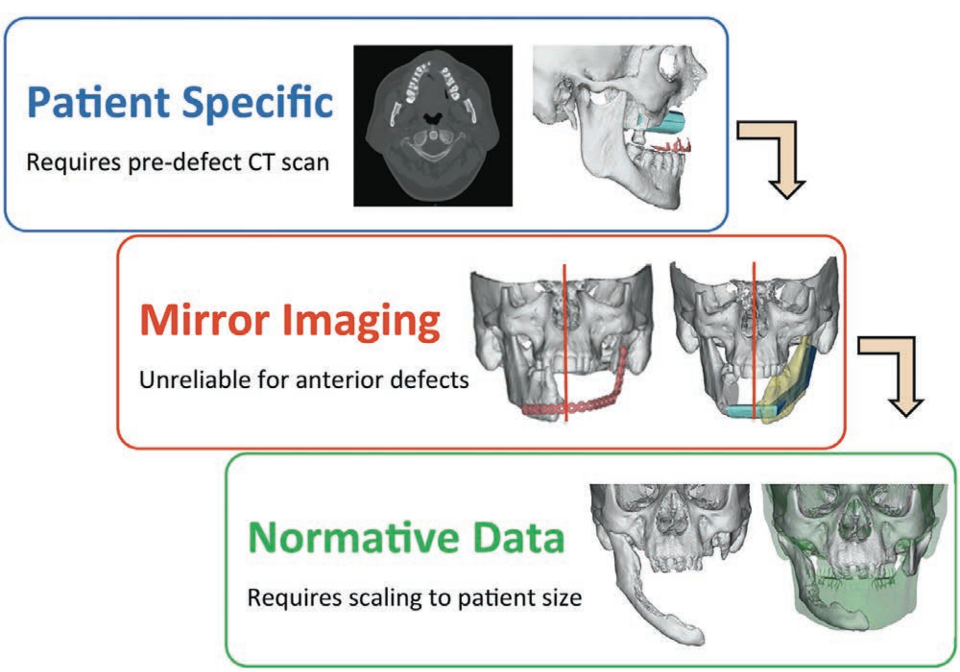

Fig. 1. Stepwise virtual surgical planning technique algorithm for delayed reconstruction. The algorithm starts at the top and proceeds to lower tiers depending on the data available and location of the defect. *CT*, computed tomographic.

Defining the preoperative resection specifically for osteoradionecrosis involved a number of considerations distinct from other delayed reconstructive scenarios. Most important were the radiographically determined extent of disease and the level of disease/fistula formation on

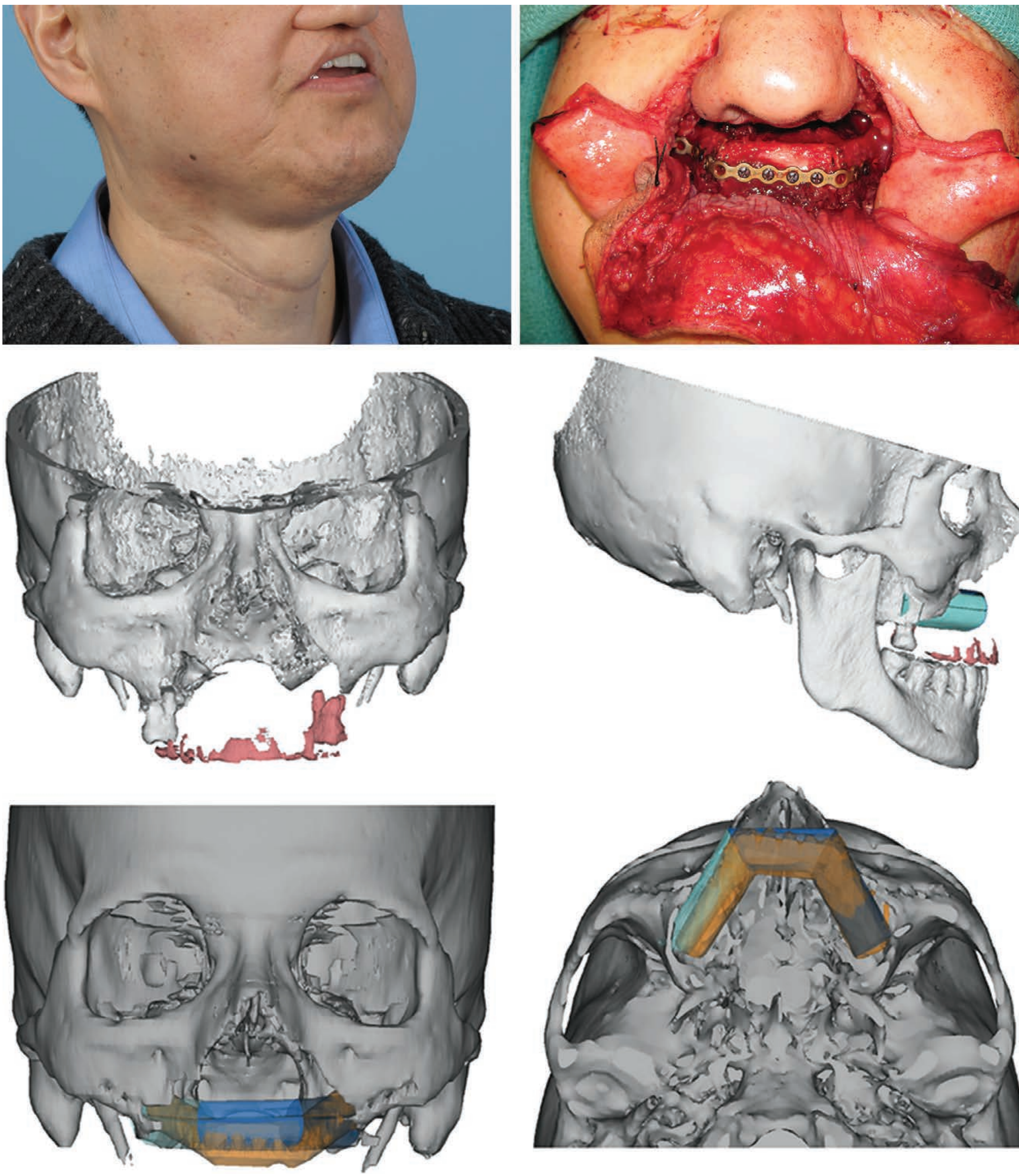

Fig. 2. Patient-specific computed tomographic data were used to plan the delayed maxillary reconstruction. The patient had a limited soft-tissue envelope with a contracted upper lip following radiation therapy (*above, left*). Barium (*red*) was painted onto the obturator before the computed tomographic scan to design the fibula reconstruction to fit the existing upper lip soft-tissue envelope precisely. This would be considered a nonanatomical reconstruction (*center*). Fibula inset before upper lip closure (*above, right*). Postoperative result with the fibula (*orange*) overlaid with the surgical plan (*blue*) demonstrating precise execution (*below*).

examination. First, we design the reconstruction to remove bone mesially and distally until the next anatomical mandible osteotomy is reached (parasymphysis, midbody, and angle). Next, two separate resections are planned, termed the narrow and wide margins, with two sets of mandible and fibula guides planned for manufacturing.[6] Thereafter, the virtual surgical planning techniques described below are used to guide the virtual reconstructive process. Finally, during surgery, the resection is performed until bleeding bone is visualized in accordance with the narrow and wide osteotomies. In none of the cases was there deviation from the preoperative virtual surgical plans.

Patient-Specific

High-quality imaging of the patient's craniofacial skeleton before the trauma or resection serves as the anatomical reference for the virtual surgical plan. These cases have the greatest fidelity because the patient's own morphometric data are used to guide the reconstructive process. In the absence of soft-tissue constraints that preclude restoration of normal anatomy, this technique enables an accurate reconstructive design (Fig. 2).

Mirroring

For unilateral defects, a mirror image of the patient's uninvolved contralateral side is inverted on the screen in the virtual environment. It is then positioned over the defect, aligning it with remaining portions of the jaw or the temporomandibular joint. The osseous reconstruction is then virtually designed based on the mirrored normal anatomy. This technique is less reliable as defects become more anterior, especially if they extend across the midline because no remaining uninvolved structure exists to mirror (Fig. 3).

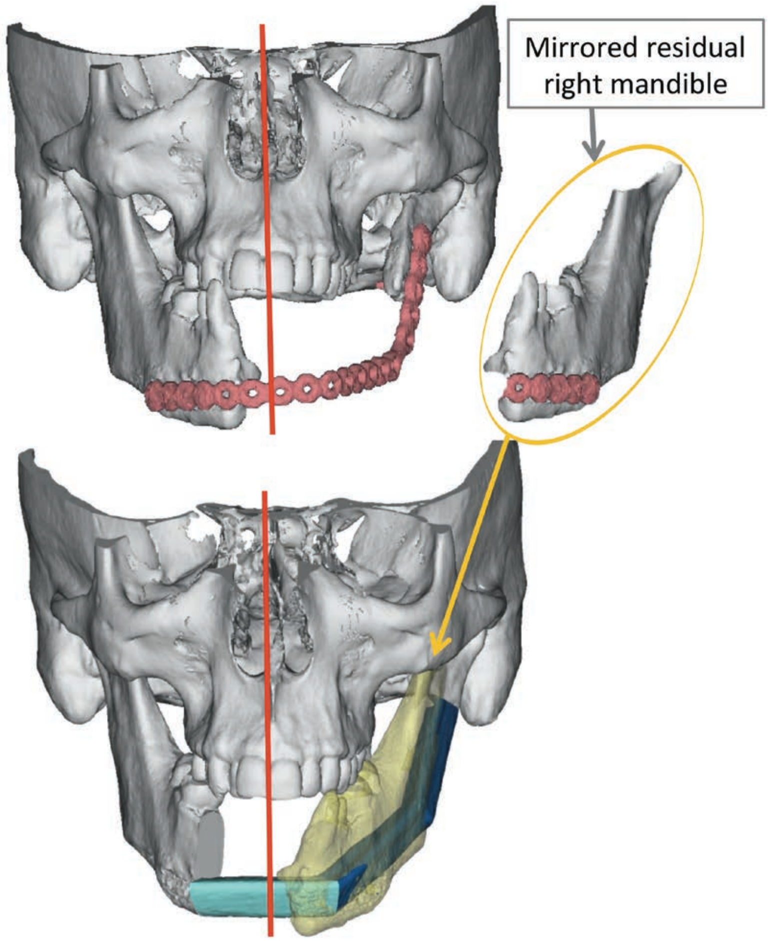

Fig. 3. The mirroring technique generates a mirror image reflection (*yellow*) on the midline of the remaining normal anatomy. It is repositioned at the defect, serving as a reference for the free fibula reconstruction (*blue*). Note the limitation of this technique in the setting of a large defect that extends anteriorly across the midline.

Normative

Although heterogeneity in mandibular size exists among individuals, the angles of the mandibular parabola at the parasymphysis, midbody, and angle, are relatively constant or preserved.[7] Therefore, a standard anatomical template can be used for reference after it has been adjusted by scaling up or down in size in the virtual environment to match the patient's mandible (Fig. 4). An example of delayed lateral mandible reconstruction using normative data and a scapula flap is demonstrated in Figures 5 and 6. The normative method can also be particularly useful for anterior defects (Fig. 7). Importantly, because use of normative data uses none of the patient's own anatomy, it represents the lowest tier on the delayed virtual surgical planning hierarchical algorithm. As such, cases planned with this technique in particular must be critically evaluated to ensure that the design adequately restores facial shape and normal occlusion.

RESULTS

Over the 7-year study period, 16 complex maxillary and/or mandibular osseous reconstructions with vascularized bone were performed in a delayed fashion in 15 patients using virtual surgical planning. Patient demographics are listed in Table 1.

There was a male predominance (60 percent), with a mean age of 51.7 years (range, 28 to 76 years). Most reconstructions were performed for either osteoradionecrosis with displacement/distortion (50.0 percent) or oncologic defects (37.5 percent); two patients sustained gunshot wounds to the face (12.5 percent). The majority of patients had undergone prior surgery (81.3 percent) and preoperative radiation therapy (81.3 percent). Four patients (25 percent) had failed prior reconstructions. Mandibular defects were most common (81.2 percent), followed by the maxilla (12.5 percent), and one combined maxillary and mandibular defect (6.3 percent).

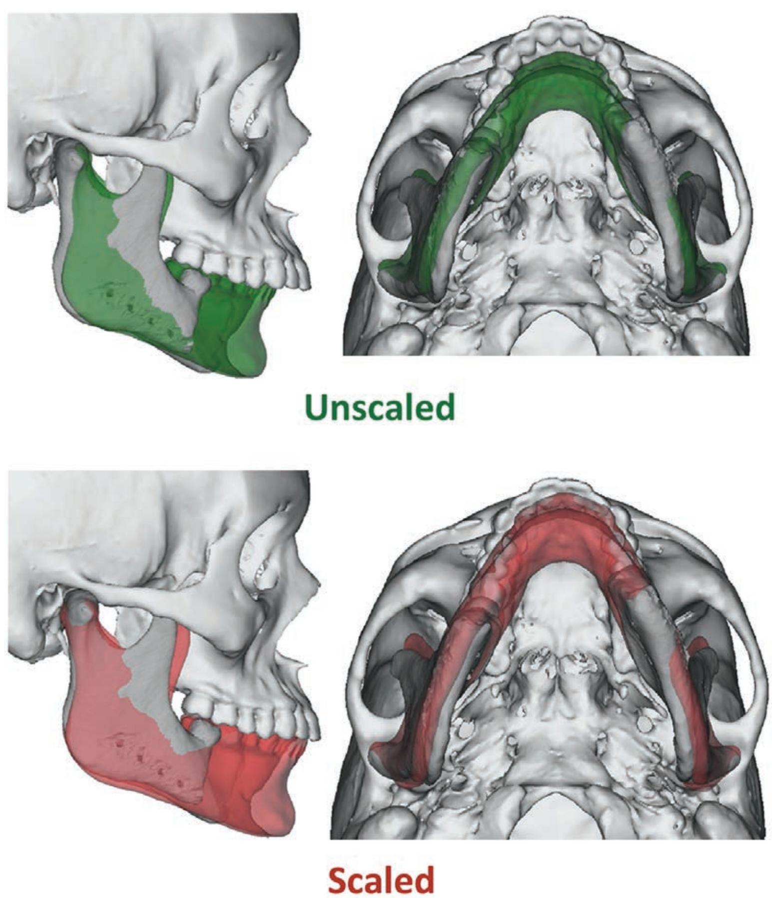

Fig. 4. Normative data take advantage of preserved angles between mandibular anatomical segments to generate a virtual reference for reconstruction (*green*); however, it must be adjusted to the appropriate scale based on patient size (*red*).

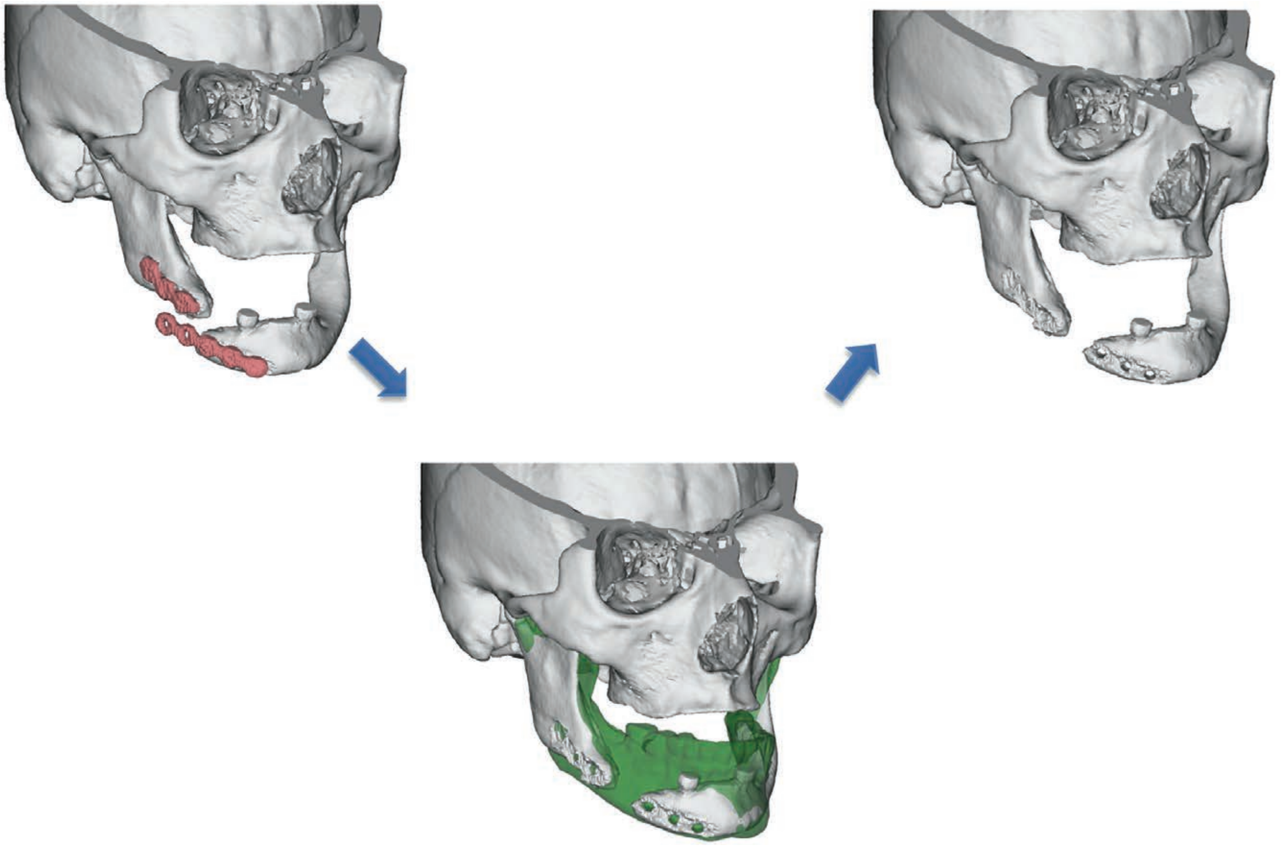

Fig. 5. Collapse of the right lateral mandible following fracture of a reconstruction plate (*above*, *left*). The size of the original segmental defect can be appreciated through overlay of a normative green mandible (*below*). Virtual surgical planning proceeds like any other immediate reconstruction based on the corrected defect size (*above*, *right*).

Free fibula flaps were used in all but one case for vascularized bone, with an average of 2.38 ± 0.72 segments per flap. Flaps for anterior mandible defects had a greater number of segments (2.83 ± 0.41) compared with lateral mandible defects (1.71 ± 0.49) ($p < 0.01$). All three maxilla reconstructions required three bone segments.

Patient-specific modeling was used most commonly [n = 7 (43.8 percent)], followed by mirroring normal contralateral anatomy [n = 5 (31.3 percent)], and finally scaled normative data [n = 4 (25.0 percent)]. The virtual surgical planning techniques used according to each defect are listed in Table 2. Normative and mirrored reconstructions were designed to restore normal anatomy. However, all but two of the patient-specific reconstructions (71.4 percent) necessitated nonanatomical reconstructions related to limitations imposed by adjacent native bone and/or soft tissue. No virtual surgical plans were aborted intraoperatively. The mean follow-up length was 20.9 months (range, 10 to 38 months).

Reconstructive outcomes are listed in Table 3. Four flaps (25 percent) suffered from perioperative vascular compromise requiring return to the operating room for exploration, with one partial flap loss requiring a second free flap (6.3 percent), and one total flap failure (6.3 percent). Hardware exposure was the most common minor complication (n = 3), followed by infection (n = 2), dehiscence (n = 2), and sinus tract formation (n = 2). Five flaps underwent revision procedures and two patients achieved dental restoration with osseointegrated implants.

DISCUSSION

To effectively restore normal and functional anatomy, a top priority should be a precise and accurate reconstruction. Although traditional methods of vascularized bone flap design are capable of reliably addressing the majority of craniofacial defects, when anatomical reference points are missing or distorted such as in delayed reconstruction, the shortcomings of the freehand technique become more obvious. The key to success in delayed reconstruction is recreation of the original defect; however, using the freehand

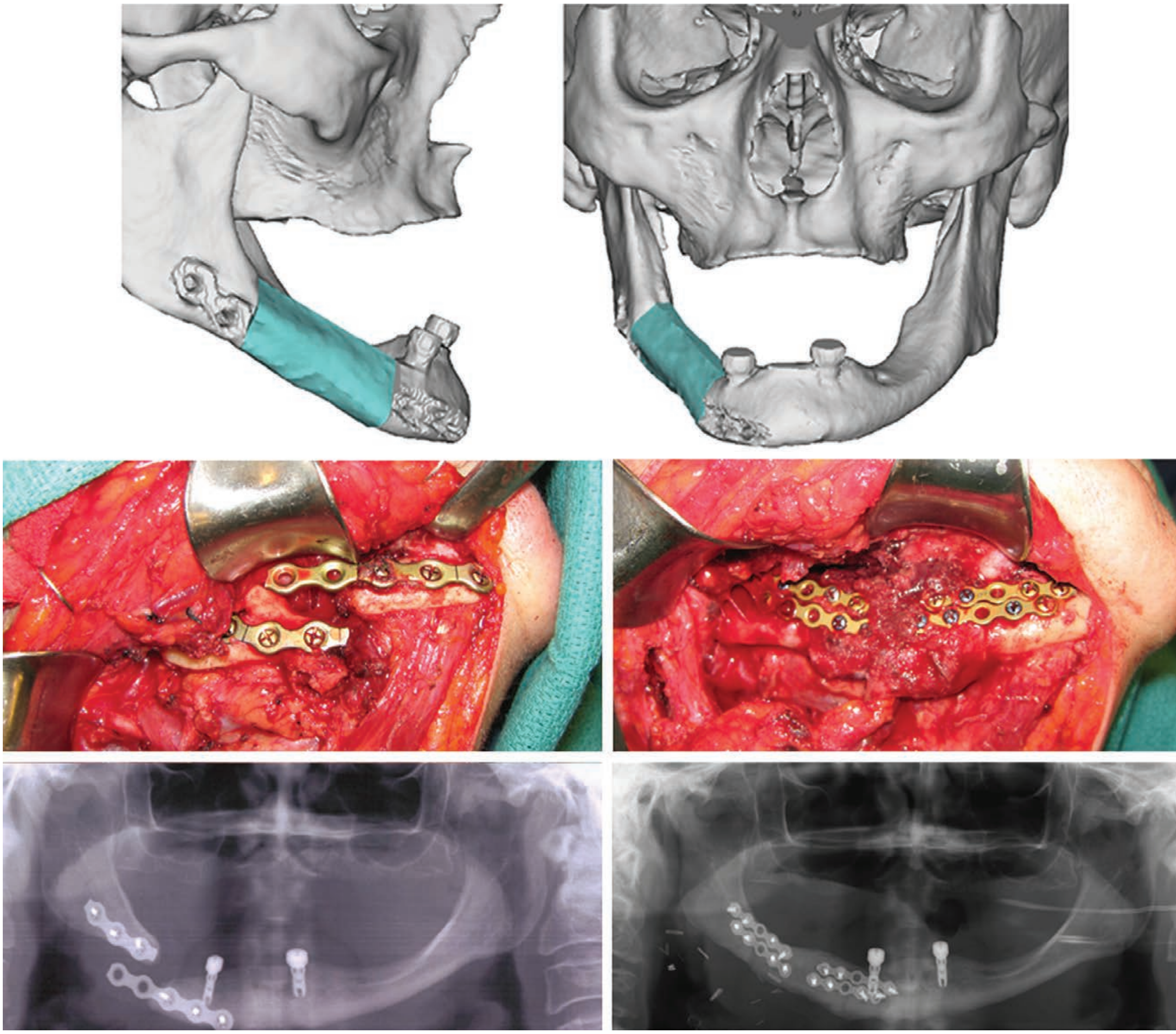

Fig. 6. Remaining portions of the right mandible body are planned to be excised to healthy thicker bone stock using virtual surgical planning and intraoperative cutting guides (*above*). Preoperative and intraoperative photographs (*center*) demonstrate the fractured plate and bony defect with displacement of the distal and mesial mandible segments. Collapse of the segments on each other makes determination of the original defect unreliable. Note that the segments' orientation to each other is reversed because of the mobility of the ramus. Intraoperative and long-term postoperative images of the reconstructed mandible (*below*).

technique, there is a significant degree of trial-and-error because the surgeon cannot reliably estimate the initial defect in the absence of a specimen and in the presence of soft-tissue contracture. In contrast, the virtual surgical planning environment facilitates precise determination of the size and shape of missing bony elements, more effectively "recreating the defect," and doing so in advance of the surgery. Intraoperatively, the surgery proceeds akin to an immediate rather than a delayed reconstruction because of the assistance of customized cutting guides that obviate the need for traditional landmarks and enable execution of the virtual plan.[9–12] Importantly, the actual osseous construct becomes an added "known" reference point because of its reliability in size and shape when created using virtual surgical planning. Although gross visual inspection of the final reconstruction may appear no different when compared to the traditional method of bone shaping, the virtual surgical planning reconstruction is performed on an anatomically precise defect more closely resembling the premorbid state.

There is an assumption that application of virtual surgical planning in reconstruction of osseous

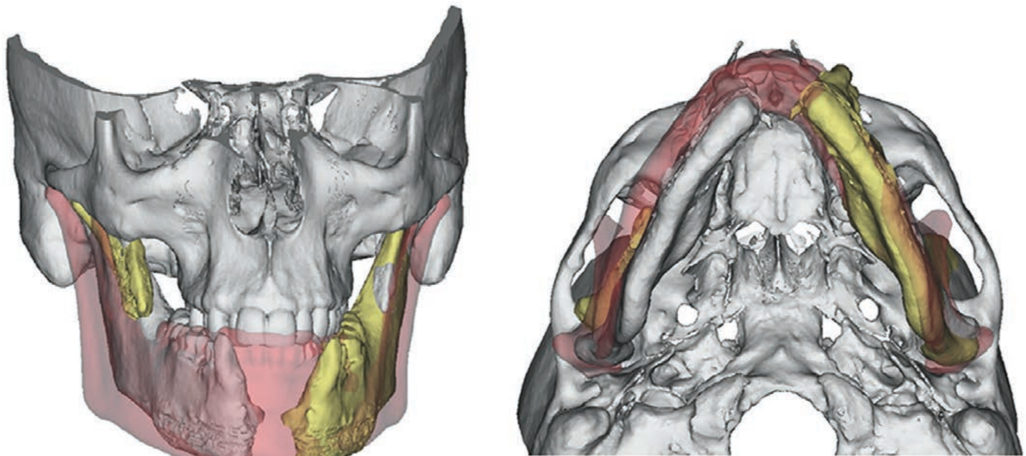

Fig. 7. Comparison of mirroring (*yellow*) and normative (*red*) virtual surgical planning techniques for defects that extend anteriorly across the midline.

Table 1. Patient Demographics

Characteristic	Value (%)
No. of patients	16
Mean age ± SD, yr	51.7 ± 14.7
Sex	
Male	9
Female	7
Prior surgery	13 (81.3)
Prior reconstruction	4 (25.0)
Preoperative radiation therapy	13 (81.3)
Mean follow-up ± SD, mo	20.9 ± 17.7
Diagnosis	
ORN	8 (50.0)
Oncologic	6 (37.5)
GSW	2 (12.5)

ORN, osteoradionecrosis; GSW, gunshot wound.

defects is straightforward. However, implementation and adoption of new technology is associated with a learning curve that can be more rapidly overcome through knowledge conveyed by colleagues. Thus, one premise of the current report is to disseminate information about the application of virtual surgical planning for delayed repair of maxillomandibular defects using an algorithm developed at two academic medical centers with significant experience. The algorithm described is distinguished from classification schemes because it enables an unambiguous conceptual approach to address any delayed defect. As one proceeds from top to bottom, less of the patient's own anatomy is used to model the reconstruction, and therefore it is deemed less accurate. Although some of the individual techniques described may already be in use by some, no literature exists describing a systematic approach using computer-assisted design technology to reliably reconstruct the current set of defects. Moreover, surgeons who are new to the virtual surgical planning process can use the described algorithm to allow for a systematic approach to some of the most complicated reconstructions.

The patient-specific technique is primarily used in oncologic or osteoradionecrosis cases, because it is unusual for trauma patients to have preinjury imaging studies available. This approach allows for design of the optimal reconstruction taking into account the anatomical limitations of each individual defect. These cases are further subdivided into anatomical versus nonanatomical reconstructions, depending on whether or not the patient's anatomy was completely restored. As illustrated in Table 2, the majority of cases using this approach actually required nonanatomical adjustments.

Looking specifically at the five nonanatomical reconstructions using the patient-specific technique, four of them were designed to result in an underprojected anterior mandible or maxilla because of restrictions of the soft-tissue envelope from scarring or radiation therapy. Although the original anatomy is adjusted, it still uses the patient's own anatomical proportions, especially when compared to the normative approach. This method also avoids the need for a second free flap for external soft-tissue coverage[13] along with the identification of an additional set of recipient vessels, and optimizes aesthetic outcomes by eliminating an external patch–like appearance. The fifth patient had severe osteoradionecrosis of the mandibular body bilaterally with a unilateral pathologic fracture. This reconstruction was designed with reduced mandible proportions, as it was felt that attempting to restore an anatomically correct position would potentially result in fracture of the contralateral diseased mandible.

Table 2. Virtual Surgical Planning Technique According to Reconstruction

VSP Method	Diagnosis	Location	Defect Subtype*	Anatomical	Flap	Recipient Artery	Recipient Laterality	Bone Segments
Normative	Osteosarcoma	Mandible	Anterior, lateral	Y	Fibula	Facial	Ipsilateral	3
Normative	SCC	Mandible	Anterior, subtotal	Y	Fibula	External carotid	Right (n/a)	3
Normative	ORN	Mandible	Lateral	Y	Fibula	Facial	Contralateral	2
Normative	SCC	Mandible	Lateral	Y	Scapula	Facial	Ipsilateral	1
Mirroring	ORN	Mandible	Lateral	Y	Fibula	Superior thyroid	Ipsilateral	2
Mirroring	SCC	Maxilla	Type III	Y	Fibula	Superficial temporal	Ipsilateral	3
Mirroring	GSW	Mandible/maxilla	Lateral, type II	Y	Fibula	Facial	Ipsilateral	3
Mirroring	GSW	Mandible	Lateral	Y	Fibula	Superior thyroid	Ipsilateral	2
Mirroring	ORN	Mandible	Lateral	Y	Fibula	Transverse cervical	Ipsilateral	1
Patient-specific	SCC	Maxilla	Bilateral, type III	N	Fibula	Lingual	Left (n/a)	3
Patient-specific	ORN	Mandible	Lateral	N	Fibula	Facial	Ipsilateral	2
Patient-specific	Ameloblastic carcinoma	Mandible	Anterior, lateral	N	Fibula	Facial	Contralateral	3
Patient-specific	ORN	Mandible	Anterior, subtotal	N	Fibula	Facial	Right (n/a)	3
Patient-specific	ORN	Mandible	Anterior, subtotal	N	Fibula	Lingual	Left (n/a)	3
Patient-specific	ORN	Mandible	Lateral	Y	Fibula	Facial	Contralateral	2
Patient-specific	ORN	Mandible	Anterior, subtotal	Y	Fibula	Lingual	Left (n/a)	2

VSP, virtual surgical planning; Y, yes; N, no; SCC, squamous cell carcinoma; ORN, osteoradionecrosis; GSW, gunshot wound; n/a, not applicable.
*Maxillectomy: type II, hemimaxillectomy with orbital floor preserved; type III, hemimaxillectomy with preservation of orbital contents.

Table 3. Reconstructive Outcomes

Complication	No.
Major	
Take-back	4
Partial flap failure	1
Total flap failure	1
Minor	
Hardware exposure	3
Infection	2
Wound dehiscence	2
Chronic sinus tract	2
Oncologic recurrence	2
Flap revision	5
Dental restoration	2

The second tier of the algorithm also uses the patient's own anatomy. Mirroring is a simple and reliable method to reestablish normal anatomy for unilateral defects. On-screen manipulation of the uninvolved side in the virtual environment can, for example, allow correct repositioning of a lateral ramus segment that has been pulled toward the midline because of unopposed action by the pterygoids. However, for anterior defects, especially those extending across the midline, no mirrored structure exists, so this technique becomes less precise, with an element of approximation required.

The lowest tier of the delayed virtual surgical planning reconstruction algorithm uses normative data stored by the surgical planning vendor. Prior studies have demonstrated that the shape, but not the size, of the mandible is highly conserved among individuals.[7] The traditional osteotomy angles, performed for mandible reconstruction, vary by less than 5 degrees among individuals at the parasymphysis, midbody, and angle. Normative data, adjusted to scale, take advantage of this phenomenon.

Another area where virtual surgical planning appears to have substantial advantages over traditional shaping techniques is in maxillary reconstruction. The compact and highly three-dimensional architecture of the maxilla results in a significant reconstructive challenge. Multiple acute osteotomies of small bone segments are required, as the shape of the maxilla changes significantly within a limited amount of space, especially when compared to the relatively gradual changes seen in the mandible.

The current study has some limitations, including its retrospective nature. The small cohort size reflects the low incidence of defects with the degree of reconstructive difficulty required for inclusion in this series. Furthermore, the unique and complex nature of each case did not enable a meaningful comparison with a matched control group undergoing reconstruction using traditional shaping techniques. Therefore, demonstration of superiority of traditional versus virtual surgical planning techniques was not intended, nor was it possible. Lastly, the inherently complex nature of delayed reconstructions, including factors such as previous surgery, vessel-depleted necks, and prior radiation therapy, may partially explain the high rate of vascular compromise observed. Although there were four reoperations for vascular compromise, three were salvaged, with only one complete flap loss.

CONCLUSIONS

Experience with this complicated subset of delayed maxillary and mandibular abnormality highlights technical advantages of virtual surgical planning. The ability to accurately design an optimal reconstruction and precisely execute it in the absence of normal anatomical landmarks constitutes a powerful modern surgical tool not previously available to the reconstructive surgeon.

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