Computer Planning and Intraoperative Navigation in Cranio-Maxillofacial Surgery

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Complex congenital, developmental, and acquired deformities of the cranio-maxillofacial skeleton are currently managed by reestablishing facial symmetry and projection through restoration of known horizontal, vertical, and sagittal buttresses using craniofacial techniques that have been developed and refined during the past 30 years.1,2 Advances in diagnostic imaging, rigid internal fixation, and microvascular free tissue transfer have profoundly affected the predictability in which today's surgeons are able to restore patients to form and function. Despite notable successes, however, problems remain with regard to reestablishing facial symmetry, consistently restoring orbital volume, and accurately repositioning skeletal or composite tissue constructs into optimal anteroposterior, vertical, and sagittal relationships. These relationships should ideally result in favorable facial proportions and allow for successful implant-supported prosthetic rehabilitation.

Some patients with complex problems undergo surgical treatment with suboptimal results that are apparent to both patient and clinician, despite well-planned operations by experienced surgeons. There are several factors that contribute to poor outcomes, including the surgeon's reliance on 2-dimensional (2-D) imaging for treatment planning on a 3-dimensional (3-D) problem; difficulty in assessing the intraoperative position, projection, and symmetry of repositioned or deformed skeletal anatomy; poor visualization of deep skeletal contours involving the orbit, mandibular condyle, and skull base; variability in the anteroposterior, vertical, and sagittal jaw and tooth position relative to each other and the skull base; and variations in head position and craniofacial development, as well as disproportionate growth.

Recently, surgeons have begun to adopt computer-aided design and computer aided modeling (CAD/CAM) software—initially engineered for applications in neurosurgery and radiation therapy—to assist in the planning and implementation of complex cranio-maxillofacial (CMF) procedures.3 CAD/CAM software enables the clinician to import 2-D computed tomography (CT) data in DICOM format (Digital Imaging and Communications in Medicine) to a computer work station and generate an accurate 3-D representation of the skeletal and soft tissue anatomy. The data set can then be used to additively manufacture a stereolithographic model or it can be manipulated by segmentation, reflection, or insertion of specific anatomic regions for purposes of treatment planning.

Computer-aided CMF surgery can be divided into three main categories: (1) computer-aided presurgical planning; (2) intraoperative navigation; and (3) intraoperative CT/MRI imaging (Fig. 1). Presurgical planning software allows the surgeon to import CT data to provide a 3-D rendering of the skull for purposes of visualization, orientation, and diagnosis; analysis with 2-D and 3-D linear and volumetric measurements; manipulations or surgical simulation by mirroring, segmentation, or...
insertion of anatomic structures; and creation of a planning model or custom implant. The virtual data can then be imported into a navigation system (frameless stereotaxy) that is used to provide guidance for the accurate and safe placement of hardware or bone grafts, movement of bone segments, resection of tumor, and/or osteotomy design. Finally, newly designed, mobile intraoperative CT scanners can be used to confirm the accuracy of the reconstruction before the patient leaves the operating room.

STEREOLITHOGRAPHIC MODELS

Using CT data sets to construct a stereolithographic model is a useful technique for evaluating and treatment planning complex facial deformities that was developed and popularized in the later part of the twentieth century.4–9 As CT imaging has become more resolute, the quality of the additively manufactured model has likewise improved, resulting in a high-quality, precise representation of the patient’s underlying skeletal anatomy. Two decades of experience has refined the indications for obtaining these models. In the author’s opinion, they are most useful as an adjunct to maxillo-mandibular reconstruction, orbital reconstruction, and complex craniofacial/orthognathic surgery, primarily facial asymmetry.

Stereolithographic models are useful in maxillo-mandibular reconstruction as a guide to plate adaptation, jaw contouring, anteroposterior jaw positioning, and as an aid to constructing patient-specific custom implants.10,11 They are equally as efficacious in orbital reconstruction by facilitating the planning of ideal osteotomy designs, allowing preoperative plate adaptation, and enabling intraoperative bone graft contouring for precise inset into the patient at the time of surgery.12 Craniofacial/orthognathic surgical planning is enhanced through stereolithographic modeling by giving the surgeon a tactile, 3-D representation of pitch, roll, and yaw; through vector planning in distraction osteogenesis; and as an aid to osteotomy design.13,14 Unfortunately, modeling alone is limited by the fact that there is inadequate precision of the occlusal surfaces so as to eliminate the need for plaster casts or to provide a method for implementing the surgical plan in the patient; performing osteotomies is laborious; and there is no predictable method, when used alone, that the surgical plan as performed on the model can be transferred to the patient.

COMPUTER-ASSISTED SURGICAL SIMULATION

Computer planning systems have been developed for use in the craniofacial skeleton that provide individualized, 3-D manipulation of CT data-sets,15–18 which can then be combined with intraoperative navigation to facilitate accurate implementation of the virtual plan.19,20 Virtual bone-based reconstruction can be performed through mirror imaging the opposite (presumably unaffected) side; by segmentation and virtual manipulation of deformed anatomic regions; or by inserting new anatomic structures into acquired, developmental, or congenital defects. Specifically, in maxillo-mandibular reconstruction, for example, mandibular contours can be virtually manipulated to accommodate for vertical, sagittal, and horizontal discrepancies, and the stereolithographic model can then be additively manufactured based on the virtual reconstruction.

Numerous CAD/CAM programs are currently commercially available for applications in craniofacial surgery, orthognathic surgery, head and neck reconstructive surgery, and dental implantology (Box 1). In the author’s opinion, the ability to “back convert” data from their proprietary language to the standard DICOM format, so that digital reconstruction may then be imported into a surgical navigation system, is a distinct advantage of some systems over others. This also allows clinicians to transfer data back and forth for purposes of treatment planning or teaching. For example, iPlan and Voxim are both excellent software programs, but they do not offer the ability to be “back converted” into DICOM format, which can be understood by navigation systems other than their proprietary counterparts (BrianLab and Voxim, respectively). Analyze is an excellent
research tool, but not very useful for routine clinical use. For this reason, the author prefers to use Surgi Case CMF (Materialise, Leuven, Belgium) for maxillo-mandibular reconstruction; and Sim-plant OMS (Materialise Dental, Leuven, Belgium) for orthognathic surgery, both of which can then be “back converted” into the Intellect Cranial Navigation System (Stryker, Freiburg, Germany) for intra-operative guidance. The virtual reconstructions can be milled into a stereolithographic model, and a custom implant or surgical splint can be constructed and the final result is confirmed with intraoperative imaging.

INTRAOPERATIVE NAVIGATION

Intraoperative navigation is comparable to GPS systems commonly used in automobiles and is composed of three primary components: a localizer, which is analogous to a satellite in space; an instrument or surgical probe, which represents the track waves emitted by the GPS unit in the vehicle; and a CT scan data set that is analogous to a road map (Fig. 2). Intraoperative navigation systems were initially developed for use in neurosurgery and are now commonly used in endoscopic sinus surgery. Recently, several computer-aided surgical navigation systems became commercially available for use in cranio-maxillofacial surgery as well. All of these “frameless stereotaxy” systems allow precise location of an anatomic landmark or implant with a margin of error that is typically less than 1 to 2 mm.

Early navigation systems, such as Instatrak, relied on electromagnetic fields, superimposed over the operative site, to achieve “satellite tracking” of the surgical instrument. The position of the tracking probe was determined by analyzing the effect of its ferromagnetic parts on the magnetic field. The problem with these systems lies in the variable stability of the magnetic field, such as that which can occur from metallic instruments. More contemporary navigation systems use optical instrument-based designs that rely on detection of light-emitting diodes (LEDs) by infrared cameras.

There are two types of commercially available optical instrument-based systems: active and passive. Active systems have battery-powered LEDs attached to the instrument probes that can be used anywhere in the body with a high degree of accuracy. Passive systems, on the other hand, replace the active light sources with reflectors, which are then illuminated by infrared flashes. The principal advantage of passive systems is that there is no need for electrical wires or batteries; thus, the handheld instrument is potentially lighter and more user friendly. The

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**Box 1**

Commercially available CAD/CAM programs

- Amira (Berlin, Germany)
- Analyze (AnalyzeDirect, Lenexa, Ann Arbor, MI)
- Intellect Cranial Navigation System (Stryker, Freiburg, Germany)
- iPlan (BrainLab, Westchester, IL)
- Maxilim (Medicim, Bruges, Belgium)
- MIMICS (Materialise, Leuven, Belgium)
- Surgi Case CMF (Materialise, Leuven, Belgium)
- Sim Plant OMS (Materialise Dental, Leuven, Belgium)
- Voxim (IVS Solutions, Chemnitz, Germany)
- 3dMD (Atlanta, GA)

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**Fig. 2.** Components of a surgical navigation system. Intraoperative navigation is comparable to GPS systems commonly used in automobiles and is composed of three primary components: A localizer, which is analogous to a satellite in space; an instrument or surgical probe, which represents the track waves emitted by the GPS unit in the vehicle; and a CT scan data set that is analogous to a road map.
The primary disadvantage of passive systems is that artificial light sources may interfere with tracking, and they cannot be used within an enclosed cavity.

The position of the instrument relative to the patient is determined by the computer using the “local rigid body” concept, which states that “an object must have at least three fixed reference elements that span the coordinate system of the object in question.” The process of correlating the anatomic references to the digitalized data set constitutes the registration process. There are two types of registration: invasive and noninvasive. Invasive registration involves the placement of fixed markers that are secured to the patient’s head with screws via small incisions in the scalp (or alternatively to the occlusion using a custom splint). The primary disadvantage of these fixed markers is the need for operative insertion and the need to immobilize the patient’s head by attaching it to a Mayfield headset. Noninvasive registration methods, however, do not require head immobilization and can be performed by applying adhesive skin markers, either individually at various points on the face, or by using a commercially available LED mask. This technique is quick, simple, and accurate. Alternatively, a markerless technique called “surface matching” can be used in which a series of points on the face are scanned and correlated with the CT data set. The primary disadvantage of this approach is that it is time consuming. The author prefers noninvasive, mask registration whenever possible to avoid the use of a Mayfield head frame. Unfortunately, if a coronal flap is required, the LED mask cannot be used and either surface matching is required or the patient must be placed into a Mayfield and the registration completed using fixed skull markers.

Numerous clinical applications for these computer-based technologies are possible and will continue to be explored. More than a decade of experience has led most surgeons to conclude that computer-aided CMF surgery is indicated in the circumstances listed in Box 3.

**Orbital Reconstruction**

High-velocity injuries often result in a “shattered orbit” with large volumetric increases internally, massive herniation of periocular contents into the surrounding anatomic spaces, and cranial neuropathies. Although advances in craniomaxillofacial surgical approaches and biologic materials have improved our ability to more predictably restore these patients to form and function, a significant number of patients will still require revisional surgery despite the best efforts of an experienced surgeon. When the entire orbit is disrupted and there are no posterior bony landmarks to guide in the reconstruction, accurate positioning of bone grafts or mesh plates becomes problematic. There is difficulty in establishing proper orbital contour, volume, and ethmoidal or antral bulge projection, as well as risk of encroachment upon the orbital apex and optic nerve (Fig. 3). Recently, preformed orbital mesh plates based on a composite of normal orbital CT data sets were developed and made commercially available for use in complex orbital trauma (Synthes, Paoli, PA) (Fig. 4). Presurgical planning using stereolithographic models to establish proper plate contour, as well as intraoperative navigation to ensure accurate and safe positioning of the plate in a poorly visualized anatomic region affords even the experienced surgeon greater confidence and predictability in the deep orbit (Figs. 5 and 6).

In addition to navigating the orbital apex, computerized planning and pre-bent orbital mesh has the potential to predictably restore the difficult-to-access posterior medial bulge (ethmoidal bulge) region, also known as the key area, as well as the posterior orbital slope (antral bulge). Recently, Metzger and colleagues described...
a semiautomatic procedure for individual preforming of titanium meshes for orbital fractures. By using CT scan data, the topography of the orbital floor and wall structures can be recalculated. After mirroring the unaffected side onto the affected side, the defect can be reconstructed virtually. Data of the individual virtual model of the orbital cavity are then sent to a template machine that reproduces the surface of the orbital floor and medial walls. A titanium mesh can then be adjusted preoperatively, or custom implant constructed, for exact 3-D reconstruction. It is then placed using intraoperative navigation to ensure accurate position within the orbit.

At the time of surgery, patients are typically approached via a transconjunctival incision alone or combined with an upper blepharoplasty or coronal approach depending on the clinical scenario. The internal orbit is reconstructed with the previously contoured titanium orbital plate or bone grafts. The external orbital frame is reduced or repositioned and stabilized using 1.3-mm and/or 1.5-mm titanium plates and screws (Stryker, Kalamazoo, MI; Synthes). Intraoperative navigation is then used to assess the accuracy of the restored internal and external orbital anatomy (Surgical Tool Navigation System, Stryker Navigation, Kalamazoo, MI).

Intraoperative navigation is performed by means of frameless stereotaxy with three infrared cameras controlling the pointer via integrated LEDs. The patient’s position is identified with a digital reference frame that is fixed to an adhesive mask. The mask has a total of 31 LEDs that it uses for registration. A minimum of 21 of the LEDs are required to achieve optimal registration accuracy. Various points on the virtual image at the workstation and the patient are matched and compared with anatomic landmarks. An acceptable margin of error is defined as less than 1 mm. If a 1-mm margin of error is not obtained, then the registration is made using a fixed skeletal reference tool. Proper position of the bony

Fig. 3. Factors leading to difficulty identifying and accurately reconstructing orbital bony landmarks. (A) Sagittal CT scan demonstrating the normal ascending slope of the posterior orbit (left) and the common surgical error (right) of inadequate restoration of the height of the posterior orbit. (B) Axial CT scan demonstrating the normal postero-medial orbital bulge (left, red), and the common surgical error (right, red) of inadequate restoration of the postero-medial bulge. The green line represents optimal orbital contour.

Fig. 4. Preformed orbital mesh plates based on a composite of normal orbital CT data sets are now commercially available for use in complex orbital trauma.
Fig. 5. A 35-year-old male involved in motor vehicle collision sustaining displaced right orbito-zygomaticomaxillary complex fracture and left orbital blowout fracture. (A) Preoperative appearance with LED mask applied. (B) Preoperative axial, coronal, sagittal, CT scans with 3-D reconstructions demonstrating medially displaced orbito-zygomaticomaxillary complex fracture with orbital displacement and increased orbital volume. (C) Intraoperative view following open reduction and internal fixation of the ZMC component with reconstruction of the orbital floor. (D) Intraoperative view of fixation at the maxillary buttress. (E) Virtual reconstruction by mirror imaging of the unaffected side with intraoperative navigation used to confirm accurate reduction of the malar buttress and restoration of orbital volume. (F) Postoperative 3D reconstruction. (G) Postoperative coronal CT scan demonstrating restoration of orbital volume with titanium mesh. (H) Postoperative appearance. (I) Postoperative appearance.
segments and internal orbit is confirmed in sequential fashion according to the following systematic protocol: malar eminence, infraorbital rim, lateral orbital rim, orbital floor, medial internal orbit/postero-medial orbital bulge, lateral internal orbit, posterior orbit/orbital apex, globe projection.

Maxillo-Mandibular Reconstruction

The loss of mandibular continuity or palatal integrity as a result of ablative tumor therapy or severe trauma is physiologically and psychologically debilitating. The utility of the free fibular osteocutaneous flap (FFOF) for mandibular reconstruction was recognized and subsequently popularized by Hidalgo in 1989. Since that time, a series of surgeons throughout the world have shown the FFOF to be a highly reliable flap for reconstruction of mandibular and maxillary continuity defects.

Despite wide acceptance, there has been some controversy over the method of fixation used to stabilize the fibular constructs, with some authors advocating miniplates and others advocating reconstruction plates. One of the advantages of reconstruction plates is that an accurate shape of the neomandible may be created by bending the plate to the native mandible. In situ plate bending is time consuming, however, and a gap is formed between the straight fibula and...
the curved mandible unless multiple osteotomies are performed. Increasing the number of fibular osteotomies further increases the complexity of the procedure and invites vascular complications. Additionally, in situ plate bending is not practical if tumor grossly invades soft tissue on the lateral mandible.

The use of stereolithographic models for plate adaptation before surgery has been used by the author for the past 5 years to aid in maxillo-mandibular reconstruction.10 The model may be used to remove tumor deformation and eliminate mandibular convexities, and thus minimize fibular osteotomies. In addition to correcting transverse problems related to mandibular reconstruction, favorable anteroposterior relationships can be achieved by placing the reconstruction plate/fibular construct in an optimal relationship relative to the opposite jaw, at the correct occlusal plane angle. This

Fig. 6. (continued)
will allow for more predictable implant-supported prosthetic rehabilitation and prevent overprojection of the mandible.

More recently, CAD/CAM software has been used to accomplish much of this “bench work” in a virtual environment (Fig. 7). All of the previously mentioned factors can be virtually altered and a stent is then constructed to provide a method for transferring the virtual reconstruction into reality.\(^47\) Hirsch and colleagues described the use of CAD/CAM technology to produce orthogonally ideal surgical outcomes for patients with segmental mandibular defects undergoing reconstruction with fibular free flaps.\(^48\) Using the Surgi Case CMF software (Leuven, Belgium), surgery is simulated on a computer workstation. The fibular and maxillary or mandibular osteotomies are transferred to a rapid prototyping instrument and a guide stent is constructed to allow for accurate placement of osteotomies (Medical Modeling, Inc, Golden, CO). The guide stent is sterilized and used during surgery (both fibular osteotomies and maxillary or mandibular osteotomies). In this fashion, the vascularized composite tissue is transferred into the appropriate anteroposterior, vertical, and transverse position, presumably with increased accuracy and efficiency (Fig. 8). Additionally, dental implants can be placed into the proper position based on optimal digital renderings. Proper positioning of the entire composite tissue construct is then confirmed intraoperatively using navigation. This “real time” intraoperative imaging also allows for immediate dental implant placement, and theoretically optimizes the chance for successful prosthetic restoration and decreases treatment time (Fig. 9).

### Cranial Reconstruction

Reconstruction of cranial defects (cranioplasty) may be performed using autogenous bone or a number of alloplastic materials. Bone cranioplasty should generally be performed whenever possible, although success rates are proportional to the size of the defect.\(^49\) However, if adequate bone is not available to cover the critical-sized defect, alloplastic cranioplasty is a viable option. Alloplastic cranioplasties may be performed with titanium (mesh or custom molded) and acrylics (polymethylmethacrylate),\(^50\) ceramics (hydroxyapatite cement),\(^51,52\) or high-performance thermoplastics (porous high-density polyethylene or polyetheretherketone [PEEK]).\(^53\) The ultimate choice of material depends on the size and location of the defect, the presence or absence of infection, the quality and quantity of soft tissue coverage available, and the proximity to the paranasal sinuses.

CAD/CAM software can be used to construct custom-milled titanium plates or patient-specific implants constructed from high-performance thermoplastics such as PEEK.\(^54,55\) The primary advantage of this technique over intraoperative molding of titanium mesh combined with hydroxyapatite, for example, is that it is potentially time saving and it provides an accurate, anatomic reconstruction of the defect. The significant disadvantage, however, is that it is difficult to manage the extradural dead space, when present, and the custom implants are expensive.

### Tumor Resection

Intraoperative navigation has been advocated as a means to delineate resection margins during exirgative tumor surgery in the craniofacial skeleton.\(^56-58\) Several reports have highlighted the value of this technology in improving the precision in which tumors are resected, while minimizing the amount of uninvolved tissues. In addition, surgery involving the skull base, pterygoid fossa, or infratemporal fossa, including temporomandibular joint (TMJ) ankylosis release,\(^59\) may be performed with an added degree of safety with respect to surrounding vital structures (Fig. 10). Finally, osteotomies may be accurately positioned based on a presurgical image so that preformed implants, bone grafts, or free flaps may be inset into the defect in an effort to increase operative efficiency and accuracy.

Surgery in the mandible deserves special mention because of the complexities of navigating a mobile structure. Accurate synchronization of the acquired CT data is made difficult because of the problems associated with determining a stable and reproducible mandibular position. There are three possible solutions to the problem.\(^60\) The first approach is to place the patient in intermaxillary fixation before the CT scan. This method, however, is not feasible for transoral surgery. The second method is to position the mandible in centric relation or centric occlusion, either manually or using a dental splint. The strategy is sensitive to relative movements of the mandible, which in turn undermines the accuracy of the intraoperative navigation. A third approach has been described that uses a special sensor frame that is mounted onto the mandible, thereby allowing surgeons to optically track the jaw’s position and to compensate for its continuous movement during surgery. Although time consuming, this method has the theoretical advantage of improved accuracy by monitoring the position of the
Fig. 7. A 29-year-old male with ossifying fibroma involving the anterior mandible. (A) Preoperative profile. (B) Preoperative panoramic radiograph. (C) 3-D CT image of the mandible, highlighting tumor deformation. (D) "Virtually corrected" 3-D CT image of the mandible, with tumor deformation removed and restoration of normal mandibular contours. (E) "Perfected" stereolithographic model with pre-bent reconstruction plate. (F) Intraoperative appearance of tumor before resection. (G) Intraoperative view following transoral tumor excision and application of pre-bent reconstruction plate. (H) Postoperative profile. (I) Postoperative panoramic radiograph.
mandible directly, rather than by its relative position to other fixed cranial structures.

Craniofacial/Orthognathic Surgery

Preoperative computer imaging and intraoperative navigation are useful for planning complex surgical movements of the craniofacial skeleton. Using recently designed CAD/CAM software, osteotomies may be planned and the jaws or other anatomic structures can be virtually repositioned in any plane of space. Maxillo-mandibular deformities of yaw, pitch, or roll can be accurately repositioned into a more esthetic and functional position based on the individual clinical situation. Although clearly not necessary for routine orthognathic procedures, its potential in achieving improved accuracy in treatment planning complex facial asymmetry cases is self-evident.

Xia and colleagues and Gateno and colleagues have described computer-aided surgical simulation (CASS) for use in treatment planning of complex cranio-maxillofacial deformities. The first step of the CASS process is to create a composite skull model. This is accomplished with a bite jig that is used to relate the

Fig. 8. Virtual planning for resection and fibular free flap reconstruction in a patient with osteoradionecrosis and pathologic fracture of the mandible. (A) Preoperative panoramic radiograph. (B) 3-D CT images a virtually planned resection with insertion of virtual cutting guides to assist in accurate placement of osteotomies. (C) Virtual fibula is inserted and cutting guides are designed to accurately transfer the virtual surgery into reality. (D) Virtual template of the reconstructed mandible with insertion of virtual reconstruction bar, which is then additively manufactured into an acrylic template or custom titanium reconstruction bar. (E) Stereolithographic model of unaltered mandible (clear model), the virtually reconstructed mandible (white model), and the reconstruction plate and acrylic template. (F) Unaltered stereolithographic model and mandibular cutting guide. (G) Intraoperative view with mandibular cutting guide. (H) Postoperative panoramic radiograph.
Fig. 9. A 67-year-old female with invasive mucosal melanoma involving the maxillary gingiva extending from the second molar to the contralateral second molar. (A) Preoperative appearance of lesion. (B) Virtual image based on CT data set of patient illustrating planned resection osteotomies. (C) Virtual reconstruction using a fibula (average female dimensions) illustrating inset with care to position fibular construct into a favorable position relative to the dental arch and into the pterygoid plates. (D) Virtual implants are placed into the virtual neomaxilla in a prosthetically favorable position relative to the opposing dental arches. (E) Stereolithographic model with neomaxilla template and dental implant stent additively manufactured based on the virtual reconstruction. (F) Navigated resection osteotomies. The virtual reconstruction is “back-converted” into the navigation system generating intraoperative navigation images that are used to transfer the virtual reconstruction into reality. (G) Resection specimen. (H) Closing-wedge fibular osteotomies are performed using cutting guides and templates from the virtual reconstruction. (I) Neomaxilla is formed from the fibula and implants are then placed using a stent constructed from the virtual images. (J) Accurate inset of the fibular construct is confirmed using intraoperative navigation. Planned anteroposterior and vertical position of the anterior neomaxilla is confirmed. (K) Following stabilization of the neomaxillary construct, the dental implants are placed under navigation guidance. (L) Postoperative panoramic image.
upper and lower dental casts to each other and to support a set of fiducial markers. The fiducial markers are then used to register the digital dental models to the 3-D CT skull model. After the bite jig is created, a CT of the patient’s craniofacial skeleton is obtained with the patient biting on the bite jig. Digital dental models are then created by scanning the plaster dental models with a laser surface scanner. The result is a computerized composite skull model with an accurate rendition of the bone and teeth. The second step of the CASS is to quantify the deformity with cephalometric analyses and virtual anthropometric measurements. The third step in the process is to simulate the surgery in the computer by moving the bony segments to the desired position. Using this software, the maxilla and mandible can be repositioned in all three planes of space. Hence, deformities of yaw, pitch, and roll can be accurately corrected in a virtual environment. The final step is to transfer the virtual plan to the patient through surgical splints and templates that are created using a specialized CAD/CAM technique.

The author’s preferred technique uses SimPlant OMS (Materialise Dental, Leuven, Belgium) in a fashion similar to the CASS described by Getano and colleagues. The patient is clinically examined in the usual fashion for orthognathic surgery and anthropometric measurements are obtained and analyzed. The bite jig is created (Fig. 11A), natural head position is virtually defined (Fig. 11B), plaster casts are obtained, and a CT scan with 1-mm cuts from the skull vertex to the clavicles is performed. Digital clinical photos, upper and lower stone casts, clinical anthropometric measurements, the acrylic bite jig, final occlusion registration, CT datasets, and the gyroscopic natural head position readings are then mailed to a software engineer for computer rendering (Fig. 11C) (Medical Modeling, Inc, Golden, Co). The software engineer then creates digital dental models by scanning the plaster casts with a laser surface scanner. The digital dental casts are “melded” to the digital CT skull using a best-fit model. A tentative surgical plan is outlined and taken to a “live” Web conference with the software engineer. The maxillary and mandibular osteotomies are performed and movements are made with the patient’s composite CT scan in the previously defined natural head position (Fig. 11E–G).
Deformities of yaw, pitch, and roll can be virtually corrected and accurately assessed using precise angular and linear digital measurements. Any inaccuracies in the virtual plan can then be corrected based on the virtual image analysis. Finally, the virtual reconstruction is transferred to the patient by construction of an intermediate and final splint using a CAD/CAM technique, which is mailed back to the surgeon before the planned procedure.

**Temporomandibular Joint Surgery**

Treatment of end-stage degenerative TMJ disease poses significant challenges to the surgeon...
Computer Planning in Cranio-Maxillofacial Surgery

Fig. 11. Computer-aided surgical simulation with Simplant OMS and Medical Modeling Corporation. (A) Registration of natural head position with fiducial markers and gyroscope. (B) Gyroscope natural head position readings showing pitch, roll, and yaw data. (C) Preoperative checklist with required data necessary for virtual planning. (D) SimPlant OMS order form. (E) CT data set with 3D reconstructions and virtual plan for a patient with severe mandibular deficiency, retrogenia, and short ramus height. Patient is treatment planned for counter-clockwise maxillo-mandibular repositioning using bilateral inverted L osteotomies, Le Fort I, and genioplasty. (F) The mandible is virtually repositioned according to the preoperative plan, midlines are confirmed, and accurate and symmetrical correction of pitch, roll, and yaw is verified. A virtual intermediate splint is constructed from laser scanned plaster casts, which is then milled into an acrylic intermediate splint using a CAD/CAM technique. (G) The maxilla is virtually repositioned and a final splint is constructed intermediate splint following virtual repositioning of the mandible according to the preoperative plan (right mandibular sagittal osteotomy and left mandibular inverted L osteotomy). (H) Final splint following virtual reposition of the maxilla (Le Fort I osteotomy) and chin (genioplasty). (I) Post-prediction 3-D cephalometric analysis. Midlines are confirmed and accurate and symmetrical correction of pitch roll and yaw is verified (J) post-prediction 3-D CT images (K) post-prediction tereolithographic model for analysis and pre-bending of reconstruction plate (L) insert pre-bent reconstruction plate to stabilize inverted L osteotomy with interpositional bone graft (M) intermediate splint in place (N) final splint in place (O) preoperative appearance, frontal view (P) preoperative appearance, lateral view (Q) preoperative occlusion (R) postoperative appearance, frontal view (S) postoperative appearance, lateral view (T) postoperative occlusion. ([d] From Medical Modeling, Inc, Golden, Co; with Permission.)
because of altered anatomy and carries the risk of injury to structures within the middle cranial fossa. Treatment is further complicated by the complex functional demands of the TMJ. Various methods have been described for total TMJ replacement, including gap arthroplasty with autogenous bone graft reconstruction, microvascular free tissue transfer, stock alloplastic condyle, and fossa prosthesis construction and custom, patient-specific TMJ condyle and fossa implants.

Traditionally, a two-stage approach has been used for total TMJ replacement in the presence of ankylosis or end-stage TMJ degeneration. Gap arthroplasties were performed, often with risk of neurovascular injury to structures in the middle cranial fossa, and a second-stage reconstruction was performed some time later. Navigation has been advocated for use in TMJ surgery for two primary reasons: (1) to promote safety during the ankylosis release, and (2) to
provide a predictable method by which one-stage ankylosis release and custom TMJ replacement can be facilitated. Malis and colleagues described a one-stage approach by which the navigation-assisted surgery is simulated on a stereolithographic model and a custom prosthesis is fabricated before surgery (Fig. 12).

**Dental/Craniofacial Implants**

Intraoperative navigation has for many years been advocated as a means to assist in the accurate placement of dental implants. For a number of reasons, however, widespread acceptance of this technology for routine dental implant–supported prosthetic rehabilitation has not occurred. The reasons for this are primarily related to cost of the
equipment in the context of the current US dental care delivery model—that being small, office-based private practices. The benefits probably do not outweigh the costs for routine cases of dental implantology. On the other hand, there are several important exceptions to this cost-benefit inequity, which are primarily related to completely edentulous and severely atrophic maxillo-mandibular rehabilitation\textsuperscript{78}, composite tissue reconstruction of the maxilla and mandible following ablative surgery or posttraumatic deformity\textsuperscript{57}, and for craniofacial implants used for prosthetic auricular reconstruction\textsuperscript{80}. 

Fig. 11. (continued)
SUMMARY

Preoperative computer design and stereolithographic modeling combined with intraoperative navigation provide a useful guide for and possibly more accurate reconstruction of a variety of complex cranio-maxillofacial deformities. Although probably not necessary for routine use, the author’s early experience confirms that of other surgeons with more than a decade of experience: computer-assisted surgery is indicated for complex posttraumatic or postablative reconstruction of the orbits, cranium, maxilla, and mandible; total TMJ replacement; orthognathic surgery; and complex dental/craniofacial implantology. Further study is needed to provide outcomes data and cost-benefit analyses for each of these indications.

Fig. 12. One-stage total temporomandibular joint replacement with custom alloplastic implants in a patient with giant cell foreign body reaction secondary to failed Teflon-proplast implants. (A) Preoperative lateral view. (B) Preoperative 3D CT image demonstrating condylar degeneration with loss of ramus-condyle height and retained Teflon-proplast implant. (C) Virtual plan for resection before construction of custom TMJ condyle and fossa implants. (D) Stereolithographic model demonstrating “waxed up” custom condyle and fossa TMJ implant (TMJ Implants, Inc). (E) Intraoperative view of submandibular approach to the ramus facilitated navigation-assisted ramus osteotomy at the precise level as the virtual plan. Note navigation pointer. (F) CT images of intraoperative navigation with measurement of distance between glenoid fossa and planned ramus osteotomy, facilitating accurate osteotomy placement. (G) Inset of custom fossa and condyle implants. (H) Postoperative lateral view.
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