A Multicenter Experience With Image-Guided Surgical Navigation: Broadening Clinical Indications in Complex Craniomaxillofacial Surgery

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Purpose: Image-guided surgical navigation, or computed tomography (CT)–guided surgery, is a technology used by many specialties to reduce complications and improve surgical outcomes. Its use has become widespread in neurosurgical intracranial and otolaryngological skull base procedures. The authors hypothesize that CT image-guided surgical navigation has a wide scope of utility in complex craniomaxillofacial procedures. With time and experience, its use will further advance the safety and efficacy of craniomaxillofacial surgery.

Methods: A multicenter retrospective study at the University of California-Los Angeles, New York University, University of Pittsburgh, and the University of Kansas Medical Center was conducted. All craniomaxillofacial procedures using CT image-guided surgical navigation were reviewed.

Results: Twenty subjects were identified who underwent a total of 26 CT-guided navigation procedures (6 cases were bilateral). Subunits reconstructed included: the upper face (n = 5), middle face (n = 7), and lower face (n = 6). Two additional patients used CT navigation to reconstruct multiple facial subunits. In all 20 subjects, the image-guided system correctly identified the surgical anatomy to less than 2 mm. There were no perioperative complications. Long-term follow-up demonstrated no revisionary procedures were required to date.

Conclusions: Computed tomography–guided navigation is a safe and effective tool with multiple applications in craniomaxillofacial surgery. Indications for its use in complex craniomaxillofacial procedures continue to broaden. Further experience with this technology will continue to expand its clinical utility in craniomaxillofacial surgery.

Key Words: Image-guidance, image-guided surgery, CT-guided surgery, surgical navigation, craniofacial surgery

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Craniomaxillofacial reconstructive techniques have improved significantly over the past half century. This has allowed clinical indications to broaden and the specialty to expand. A surgeon's training and experience are the most important tools used to avoid undesired morbidity and mortality with these procedures. Improvements in technology have further advanced patient safety and surgical efficacy. However, complications still occur, even in the hands of the most experienced craniofacial surgeon.[1,2]

Computed tomography (CT) image-guided navigation is an intraoperative tool used by many surgical specialties to improve outcomes and reduce complications.[3–8] This technology allows a surgeon to identify anatomic landmarks in real-time based on preoperative CT imaging. Its use has become common in complex neurosurgical intracranial and otolaryngologic skull base procedures.[9–12] To date, its use in craniomaxillofacial surgery has been somewhat limited despite operating on similar anatomy.[13–16]

The importance and understanding of surgical anatomy is paramount to successful craniomaxillofacial surgery. Anatomic variations are common in the head and neck, and the anatomy is often abnormal in subjects who require complex craniomaxillofacial procedures. The use of image-guided surgical navigation can help localize complex craniomaxillofacial anatomy. We hypothesize that CT image-guided surgery is a useful tool in complex craniomaxillofacial reconstructions and may help prevent complications. We demonstrate select utilization of this technology in a multicenter case review.

METHODS

A multicenter retrospective chart review was performed. All subjects who underwent craniomaxillofacial procedures using CT image-guided navigation between July 1, 2010, and August 31, 2012, at the University of California-Los Angeles Medical Center, New York University-Langone Medical Center, the University of Pittsburgh Medical Center, and the University of Kansas Medical Center were included. Medical records were reviewed to collect patient demographics, radiographic imaging, operative reports, postoperative complications and follow-up. A minimum of 6 months of follow-up was required for inclusion in the study.

Surgical Technique

Preoperatively all subjects undergo a fine cut noncontrast maxillofacial CT scan with 0.5 to 1 mm slice cuts. These images are uploaded to either the Brainlab Image Guidance System (BrainLAB, Feldkirchen, Germany) or the Medtronic Surgical Navigation System (Medtronic, Minneapolis, MN) depending on the institution. Intraoperative registration is performed at the beginning of each procedure. A point merge technique is used to confirm accuracy of the CT navigation system. With this technique, several discreet surface anatomic landmarks, such as the radix, nasal tip, and medial/lateral canthi are selected and registered before surgery. Recalibration is performed for any discrepancies greater than 1 mm.

Surgical Indications and Anatomic Subunits

Intraoperatively, the CT navigation system is used to identify key anatomic landmarks. Accuracy is determined by identifying a surgical anatomic landmark on the patient with a blunt navigation probe. The anatomic accuracy of this point is then compared and measured to that point displayed on the image guidance system in the axial, coronal, and sagittal planes. Surgical decisions are based on these identified landmarks.

Subjects were divided into 4 groups based on the anatomic location of their craniomaxillofacial procedure. The groups included the upper, middle, lower, and panfacial subunits. The upper face subunit included subjects who underwent surgery above the orbit. The middle facial group had surgery involving the orbit, nose, the zygomaticomaxillary complex, and the upper jaw. The lower facial subunit involved surgery on the mandible. The panfacial group had complex procedures that involved all 3 subunits.

RESULTS

Twenty subjects were identified for inclusion in this study. Twenty-six distinct procedures were performed, as 6 subjects underwent bilateral procedures. The subjects ranged from 6 to 64 years of age. Twelve subjects (62.5%) were men and 8 (37.5%) were women. The average follow-up was 18.6 months. All patients had at least 6 months of follow-up. There were no adverse events intraoperatively or complications in the postoperative period. To date, no subject has required a revisionary procedure. The etiology of disease that required craniomaxillofacial surgery included congenital anomalies (n = 14, 70%), trauma (n = 4, 20%), and tumor (n = 2, 10%). The CT image-guided navigation was able to accurately identify surgical landmarks within 2 mm in all subjects. The indications for CT image-guided navigation utilization are summarized in Table 1.

Facial Subunit Utilization and Outcomes

Five subjects underwent upper facial reconstruction. This included 2 subjects with pneumosinus dilatans requiring setback of the anterior table of the frontal sinus (Fig. 1), 2 subjects with trauma-related frontal sinus fractures, and one subject requiring fibrous dysplasia resection and orbit/forehead/skull base reconstruction (Fig. 2). In this group, the CT image-guided navigation accurately identified the anatomic boundaries of the frontal bone, frontal sinus, and anterior skull base to a distance within 1 to 2 mm. In all cases, the frontal sinus was correctly identified, and it was either entered or avoided successfully without inadvertent injury.

TABLE 1. Indications for Image-Guided Surgery

Upper Facial Subunit	n = 5
Pneumosinus dilatans	2
Frontal sinus fracture	2
Fibrous dysplasia	1
Midface subunit	n = 7
Treacher Collins reconstruction	2
Redo LeFort 3 advancement	2
Enopthalmos after meningioma resection	1
Orbital neurofibromatosis	1
Unilateral orbital box osteotomy	1
Lower facial subunit	n = 6
TMJ bony ankylosis release	4
Condylar reconstruction in unilateral mandibular hypoplasia	2
Panfacial trauma	n = 2

TMJ indicates temporomandibular joint.

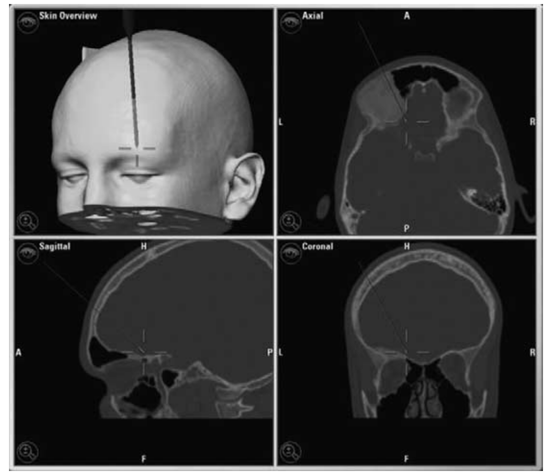

FIGURE 1. The blunt probe is used to mark out the borders of the frontal sinus during pneumosinus dilatans anterior table setback.

Seven patients underwent CT image-guided procedures involving the midface. Midface procedures included: 2 cases of bilateral lateral orbit, zygomatic arch and midface reconstruction for Treacher Collins, 2 cases of redo LeFort 3 osteotomy advancement, 1 case of enophthalmos repair after meningioma resection involving the orbital floor and lateral wall, 1 case of orbital neurofibromatosis excision, and 1 subject who underwent a unilateral orbital box osteotomy to correct orbital dystopia. Image-guided navigation was used to successfully locate the anatomic location of the skull base, orbit walls, and zygomatic arch to within 1 to 2 mm in all cases. There was no inadvertent injury to the orbit or its contents in this group.

Six subjects underwent lower facial reconstruction including 4 cases of bilateral temporomandibular joint bony ankylosis release (8 temporomandibular joints) and 2 cases of condylar reconstruction in unilateral mandibular hypoplasia. Computed tomography image–guided navigation was used to localize the skull base and its surrounding structures. The skull base, glenoid fossa, and mandibular condyle were accurate within 2 mm in each case. There was no inadvertent injury to the soft tissues exiting the skull base or entry into the cranial fossa (Fig. 3).

Two subjects underwent repair of panfacial fractures involving simultaneous reconstruction of upper, mid, and lower facial fractures. These cases require a special bone anchored navigation array for registration and localization. Both subjects had accurate anatomic localization to within 2 mm in each facial zone. Localization was used to identify obscured anatomical structures for adequate reduction and fixation in areas of highly complex and sensitive

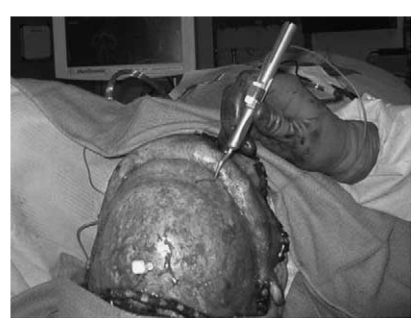

FIGURE 2. Intraoperative view. After resection of the patient's fibrous dysplasia, the probe demonstrates resection to the level of the tumor edge. The probe was additionally used to avoid accidental entrance into the frontal sinus.

FIGURE 3. The blunt probe is used to identify the skull base while operating on the temporomandibular joint. During dissection, the probe is used to identify key landmarks and minimize trauma to local structures.

facial anatomy (eg, around the optic nerve or skull base). There were no inadvertent soft tissue or bone injuries in this group.

DISCUSSION

Today, complex craniomaxillofacial procedures are routinely performed at most major medical institutions and complications are less common. This is due, in part, to the implementation of protocols that include broad-spectrum antibiotic coverage, improved airway management, and advanced diagnostic imaging.[17,18] However, the role of preoperative planning and precise surgical technique cannot be understated. Computed tomography image–guided navigation is a tool that can aid in the planning and surgical execution of complex craniomaxillofacial procedures by translating preoperative CT images into real-time information.

Several case reports and small studies have introduced this technology over the past decade.[19–21] Lübbers et al[22] characterized clinical indications for surgical navigation to include disease that abutted or involved the bone, including trauma and tumor. Reconstructions were based on the contralateral ''normal'' side, thus excluding bilateral disease. Austin et al[23] broadened the clinical utility of image-guided navigation by including intraorbital navigation, tumor resection, osteotomy design, craniotomy design, and pathology localization without the limitations of unilateral disease or limitations to 1 portion of the face.

As previously discussed, CT image-guided surgery has already demonstrated increased safety in the fields of neurosurgery and otolaryngology.[9,12,13,15] Recent studies have demonstrated its utilization and benefit in orbit trauma and reconstruction.[19,24] These studies denote its use to identify important anatomic landmarks within the orbit, such as the posterior maxillary shelf at the time of orbital floor implant placement. The current study further expands its utilization during orbit surgery. In our study, CT image guidance was used to confirm the surgeon's exact location within the three-dimensional orbit. Additionally, it was used to confirm accurate anatomic placement of lateral orbital bone grafts. Furthermore, osteotomies required for orbital box osteotomy were safely planned and executed using the landmarks identified by the navigation system.

Upper third facial surgery is made difficult by the presence of a frontal sinus in most but not all adults.[25,26] Safely avoiding or safely entering the frontal sinus is often the ultimate goal of upper facial procedures. Computed tomography–guided navigation is much more accurate than traditional techniques to localize the frontal sinus such as transillumination or templates cut from a 6-ft Caldwell plain film. Taub et al[27] previously described using CT navigation for frontal sinus localization in a subject with pneumosinus dilitans. Their description involved the placement of fiducials, or surface markers before intraoperative anatomic registration. This is a step that is not necessary with current image guidance systems. We agree with their conclusion that this technology minimizes the potential risk of intracranial injury or postoperative infection from intranasal violation.

The indications for the use of CT image guided navigation continue to expand. With rapid advancement of the navigation devices and software as well as improvements in imaging technologies, the field continues to progress rapidly. Although the clinical utility of this technology continues to expand, we recognize some of the current limitations and areas for future growth. Some of the biggest barriers for adoption of this technology are availability, cost, and added operative time. This technology already exists at many institutions and is routinely used by neurosurgeons and otolaryngologists for intracranial and skull base procedures. The cost per individual case for disposable registration material is nominal, generally less than \$200, and the registration process takes less than 5 minutes. Additionally, there are ''add-on'' CPT codes for the use of a navigation technology to reimburse the surgeon for their additional time. In early systems, the size of the navigation array often interfered with the surgeon's access to the surgical field. Today, navigation systems use a minimally sized array that consists of a small sticker device placed on the forehead or a small 2×1 cm bone anchored device screwed into the cranium. Although positioning and experience of the operating room personnel must be accounted for, currently it causes only minimal or no interference with the surgical field. Finally, the use of this technology no longer requires rigid fixation of the head as newer machines have the ability to follow head position.

The authors recognize that this study is not a prospective randomized trial. Unfortunately, no two patients are the same. Each case represents a unique circumstance thereby limiting the ability to compare these cases to a control group. Additionally, the ability to randomize a patient to use of CT-guided navigation versus the current standard of practice is also fraught with difficulty. The authors use CT-guided navigation when indicated by the patient's individual circumstance; therefore any attempt at randomization would be a disservice to the patient. The authors continue to collect data related to secondary correction procedures and accuracy of reduction.

CONCLUSIONS

Craniomaxillofacial surgery is a complicated surgical specialty and its procedures possess the possibility of significant morbidity and mortality. Accurate anatomical localization is a critical component of surgical planning and execution. Utilization of intra-operative CT-guided navigation is applicable to a multitude of craniomaxillofacial procedures and improves surgical anatomic accuracy. Further research is needed to fully delineate the indications and limitations of image-guided surgical navigation in craniomaxillofacial procedures.

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