



Rapid Communication

Modern Applications of Computer Bioengineering in Maxillofacial Surgery: Image Guided Surgical Navigation and CAD/CAM Custom Implants

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Summary

Orbital reconstruction is a common craniofacial surgical procedure that presents many technical challenges. The recent integration of computer engineering and advanced surgical techniques has greatly improved outcomes in maxillofacial reconstruction. Data collected from pre-operative magnetic resonance imaging (MRI) or computed tomography (CT) radiographs can be processed to help surgeons create a “diagnostic blueprint” of an injury prior to surgery. Additional computer engineered technologies such as virtual surgical planning (VSP), computer-aided design/computer-aided manufacturing (CAD/CAM) custom implants, and intra-operative image guided surgical navigation further support improved surgical outcomes. Although these technologies represent the forefront of the synthesis between information technology and surgery, future refinements are required before widespread utilization is possible in all aspects of craniofacial surgery.

Keywords

Image guided surgery; Surgical navigation; Orbital reconstruction; CAD/CAM

Introduction

Orbital (i.e. eye socket) reconstruction is among the most common maxillofacial procedures performed, as 25% of facial traumas involve orbit fractures [1]. The anatomy of the orbit has an intricate composition of seven bones which protect the globe with both rigid strength and shock absorbing properties. Maxillofacial injuries which disrupt “normal” orbital anatomy often impact vision and ocular function. Reconstructive surgery to restore orbit anatomy and ocular function can be challenging for both experienced and inexperienced surgeons alike. Recent advances in computer engineering and information technologies have greatly improved surgical techniques and outcomes in maxillofacial reconstruction.

Successful orbital reconstruction requires anatomic restoration of the pre-injury shape and volume of the eye socket. Several factors limit a surgeon’s ability to accomplish this goal. First, surgical access to

the orbit is typically limited by small “anatomically hidden” incisions within the eyelids. These small 2-3 cm incisions provide modest visualization of fracture patterns and orbital contents. Second, the ocular globe and surrounding fat limit surgical dissection, especially to the posterior orbit. The posterior shelf of the orbital floor is an important surgical landmark 4 cm deep in the orbit. It is commonly misidentified by surgeons due to poor lighting, narrow field of vision, and anatomic obstruction by the ocular globe. Furthermore, many surgeons have apprehension when dissecting posteriorly in the orbit as they are within close proximity to the optic nerve [2]. For these reasons, intricate pre-operative planning and precise surgical execution is necessary for successful outcomes.

Orbital Reconstruction Workflow

Today, complex orbital reconstructive surgery begins with pre-operative virtual surgical planning (VSP). VSP uses computer engineered “segmentation” techniques to “mirror” select anatomic structures such as the orbit. Segmentation is performed by selecting the “normal” contralateral anatomy and radiographically transposing it over the desired injured anatomy (Figure 1a). This creates a “reconstructive blueprint” to aid surgical planning. A variety of commercial software systems are available, including Proplan CMF, Surgicase CMF, Simplant Pro, and Mimics [3]. In addition, pre-operative radiologic DICOM (Digital Imaging and Communications in Medicine) data can be converted to STL (STereoLithography) files for the creation of 3-D printed medical models (Figure 1b). Medical models provide the craniofacial surgeon with an exact replica of the injured anatomy that also serves as a “hands on” reference guide in the surgical theater.

In the case of severe orbit injuries, VSP is further used to design “custom” anatomic implants via computer aided design/computer aided manufacturing techniques (CAD/CAM). CAD/CAM is new technology gaining popularity in modern maxillofacial surgery. CAD/CAM implants are generated via DICOM data which is converted to STL files for implant fabrication (Fig. 1c). Commercial CAD/CAM software systems include Procera (Nobel Biocare), Etikon (Straumann), CAMStructure (Biomet 3i), and Atlantis (Astra Tech) [4]. Benefits of these CAD/CAM programs over standard, conventional orbital implants include: (1) superior anatomic implant precision, (2) simpler implant fabrication protocols, and (3) minimal human intervention and variation [4].

At the time of reconstruction, image guided surgical navigation is a new technology that has begun to improve maxillofacial surgical outcomes at several medical institutions [5]. Surgical navigation integrates pre-operative radiographic images (CT or MRI scans) with “real-time” stereotactic instrument localization (Figure 2). This provides identification of desired anatomic positioning during dissection in three directional planes (frontal, axial, sagittal) to within 1-2 mm. When surgical navigation is utilized, the pre-operative DICOM file is uploaded into a commercially available navigation system as manufactured by Medtronic, Stryker, or Brainlab. At the time of surgical repair, the patient is positioned on the operating table with their head rigidly fixed relative to a dynamic reference frame (DRF) or array. The DRF defines the coordinate space of the operating

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field and is recognized by the navigation computer via a camera using infrared (IR) or electromagnetic (EM) signaling.

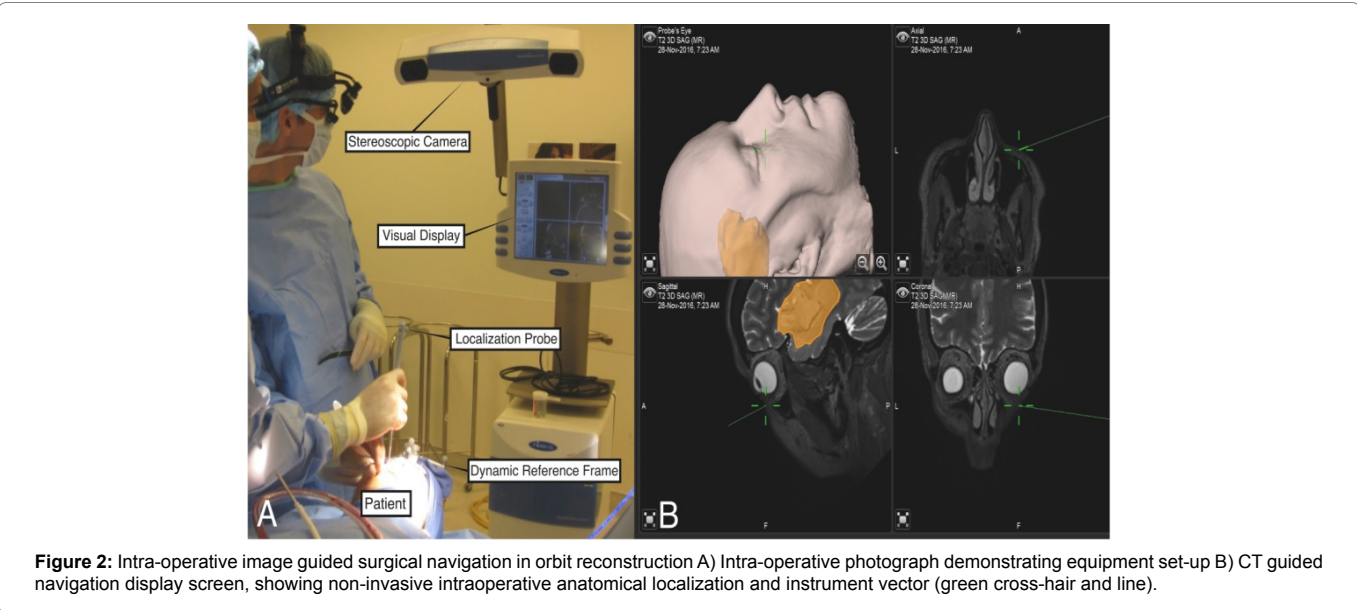
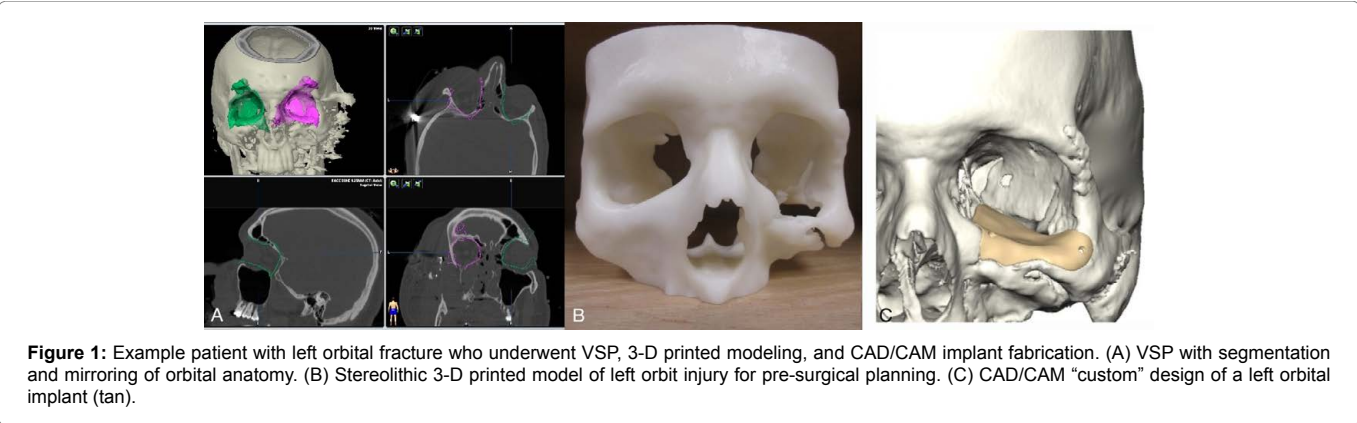
Accurate registration of the patient’s surgical anatomy must be obtained prior to commencement of the surgical procedure. This is a computational process by which the CT/MRI data is synchronized to the patient within the operative coordinate space. This can be done using many techniques, but most commonly it is accomplished using fiducials or a fiduciary system based upon the matching of reproducible surface anatomic landmarks [6]. To register the patient’s surgical anatomy, the surgeon touches reproducible facial structures with a tracked probe within the surgical field as requested by the software, which calibrates the patient’s anatomy to the CT/MRI anatomy. The final component of surgical navigation is accurate tracking of a surgical probe or select instrumentation. The surgeon navigates by placing the surgical probe or instrument on the desired anatomic area or structure of interest. The surgeon can then visualize the instrument’s real-time position overlaid on the pre-operative CT/MRI images displayed on the navigation computer in the sagittal, coronal, and axial planes (Figure 2).

Utilization of surgical navigation in orbit reconstruction has been demonstrated to both improve patient safety and reconstructive success [5]. A more recent utilization of surgical navigation is the anatomic

placement of CAD/CAM implants and the precise conformation of their location. Previous work by our group demonstrated that image guided surgical navigation is accurate to within 2 mm when used in maxillofacial orbital reconstruction [7]. An important concept to realize about CAD/CAM implants is that they are only anatomic if they are accurately placed within the orbit. Malposition of a CAD/CAM implant by as little as 2-3 mm may result in an unacceptable aesthetic result, poor ocular function, vision loss, or blindness (Figure 3a). As such, utilization of image guided surgical navigation in conjunction with CAD/CAM implants is the ideal approach to ensure precise anatomic reconstruction (Figure 3b).

Limitations

There are several limitations of this technology that prevent its universal application in maxillofacial surgery; however advances in computer engineer and information technology will solve many. A primary limitation of these technologies is their expense. As such, not all medical institutions have access to the equipment described. Surgical navigation and 3-D printing technologies also are bulky requiring large spaces and significant training of both surgeons and supportive staff. First generation navigation systems use IR signaling between the operating field and the navigation computer. “Line of sight”



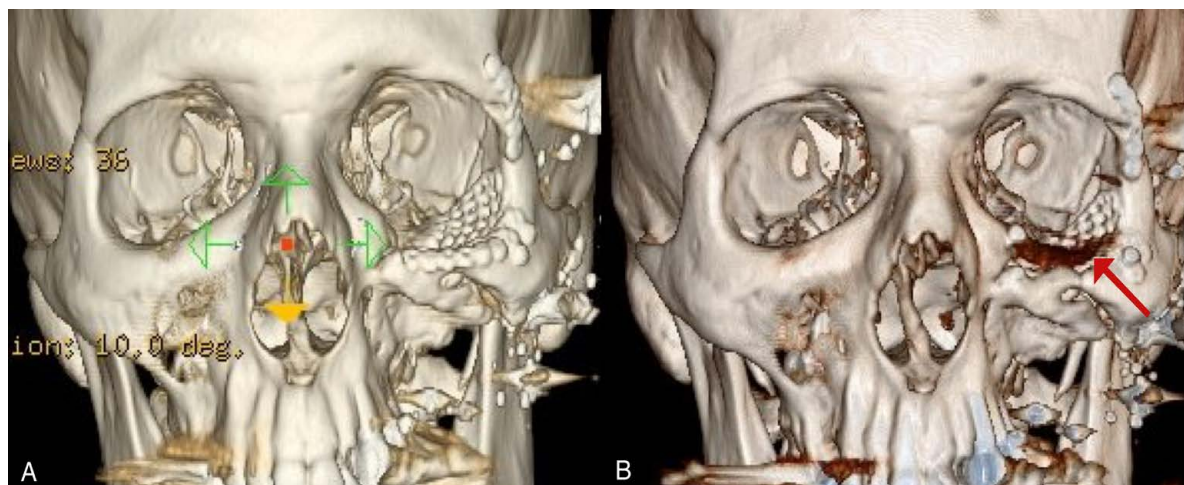


Figure 3: Post-operate CT scans of a patient following left orbital reconstruction. (A) Poorly placed “standard” left orbit implant (B) Corrective revision surgery utilizing CAD/CAM “custom” implant anatomically placed with the assistance of surgical navigation (red arrow).

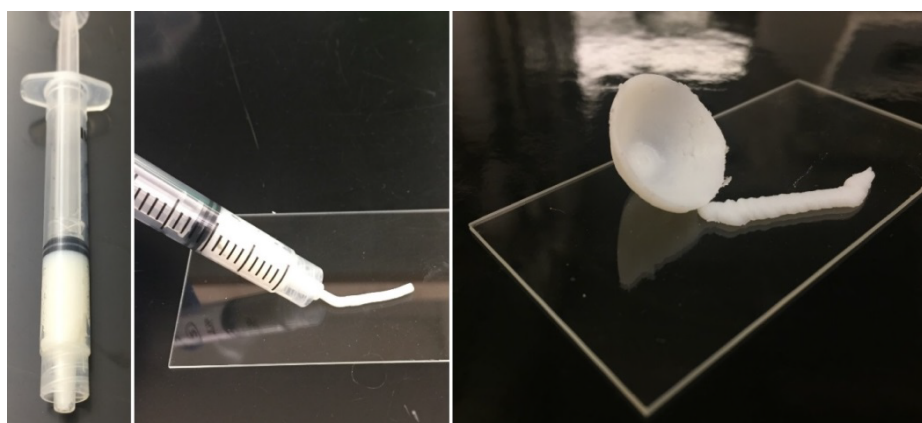


Figure 4: Depiction of a paste-like hydrogel being syringed, shaped, and crosslinked to form a concave structure that could be used as a future orbital implant.

issues often arise that obstructs the system’s view of either the surgical instrumentation or the DRF. These challenges are compounded by early DRFs being bulky and cumbersome, frequently interfering with a surgeon’s positioning or surgical access in maxillofacial procedures. Finally, the head-DRF relationship must remain stable throughout the procedure, or the navigation will become inaccurate. These problems have led to the development of new EM signaling systems which avoid “line of sight” problems and smaller DRFs which can be directly anchored to bone, dentition, or skin [8,9].

Two other concerns drastically impact surgical navigation’s accuracy. First, soft tissue swelling and edema usually accompany any maxillofacial injury. This can negatively impact the reliability and accuracy of surgical navigation especially if the amount of edema changes between the time of the pre-operative radiographic imaging and surgical intervention. Second, current navigation systems only provide information based upon pre-surgical anatomy. Surgical manipulations of soft tissues and bony structures are not appreciated by the navigation computer. This has prompted the development of intra-operative CT/MRI with direct DICOM uploading into navigational software during neurosurgical procedures [10]. Future generations of surgical navigation systems will allow updating of

the surgical anatomy as the procedure progresses, maintaining the accuracy of navigation.

Future Directions

Future advances in orbit reconstruction lie in bioengineering and implant fabrication. Modern implants are inert and composed of materials such as porous polyethylene or polyether ether ketone (PEEK). Future biomaterials may consist of “paste-like” hydrogels that can be readily 3-D printed to form custom CAD/CAM implants using STL data [11-13]. “Paste-like” hydrogels combined with 3-D printing capabilities allow for the creation of complex structures (Figure 4). These novel materials can potentially offer osteoconductive (implant material serves as a scaffold for native bone growth and formation) and/or osteoinductive (implant material induces stem cells to differentiate into living mature bone cells) properties to help restore normal maxillofacial bone anatomy.

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