Comparison of 3 Optical Navigation Systems for Computer-Aided Maxillofacial Surgery

E. Bradley Strong, MD; Amir Rafii, MD; Bettina Holhweg-Majert, MD, DMD; Scott C. Fuller, MD; Marc Christian Metzger, MD, DDS

Objective: To compare the accuracy of 3 computer-aided surgery systems for maxillofacial reconstruction.


Setting: The University of California, Davis, Department of Otolaryngology computer-aided surgery laboratory.

Participants: Four fresh cadaveric heads.

Main Outcome Measure: Mean target registration error.

Results: The StealthStation was the most accurate (mean [SD] target registration error, 1.00 [0.04] mm), followed by VectorVision (1.13 [0.05] mm) and then Voxim (1.34 [0.04] mm). All values met statistical significance (P < .05).

Conclusions: Measurable accuracy differences were found among the navigation systems evaluated. The StealthStation was the most accurate. However, the differences are small, and the clinical significance for maxillofacial reconstruction is negligible.


The use of open reduction and internal fixation for the treatment of facial fractures was popularized in the 1970s and 1980s. It remains the standard of care for most facial fractures. However, symmetric repair of complex facial fractures (ie, orbital fractures, secondary naso-orbito-ethmoid or zygomaticomaxillary complex fractures) remains extremely challenging. In these situations, surgeons have turned to computer-aided surgery (CAS) planning software and intraoperative navigation to assist with repair of these complex injuries.1-3

The planning software allows the surgeon to import 2-dimensional computed tomographic (CT) data and generate a precise 3-dimensional, virtual representation of the skull. The proposed surgical repair (eg, osteotomies, bony reductions) can then be performed in a virtual environment. Finally, these virtual reconstructions can be imported into an intraoperative navigation system to guide the repair in real time.

All intraoperative navigation systems incorporate a computer digitizer to track the location of the patient and instruments in space. Four different digitizer modalities have been developed: optical, electromagnetic, electromechanical, and ultrasonographic. Optical tracking is most commonly used. Optically based systems can be either active or passive. Active tracking systems use infrared, light-emitting diodes attached to the patient’s head and to the surgical instrumentation. As long as the light-emitting diodes stay within the line of sight of the digitizer camera, the location of the patient and the surgical instruments are accurately presented on the computer monitor. Passive tracking systems use reflective spheres (instead of diodes) to reflect infrared light from an infrared emitter back to a receiver. Both the emitter and receiver are located in 1 digitizer camera. All instruments and headsets (whether active or passive) have a unique structural pattern of emitters and reflectors rigidly attached, which identifies each instrument. As long as the headset does not shift with respect to the patient, both the head and surgical probe can be moved freely in space without loss of accuracy.

Author Affiliations:
Department of Otolaryngology, University of California, Davis, Sacramento (Drs Strong, Rafii, and Fuller), and Department of Craniomaxillofacial Surgery, University Freiburg, Freiburg, Germany (Drs Holhweg-Majert and Metzger).
A registration process is necessary to accurately define the location of the patient for the CAS system. Registration allows integration of any given point \((x, y, z)\) on the actual patient with the identical point \((x', y', z')\) on the virtual patient. Registration is accomplished by identification of specific fiducial markers (ie, stable landmarks that can be identified on both the virtual and real patients) on the virtual patient as seen on the navigation system monitor. The identical fiducial markers are then identified by placing a surgical probe in the same locations on the actual patient. Either bony or skin surface landmarks can be used. Clinically, skin surface landmarks are most common. In a trauma setting, this requires that the patient have an up-to-date CT scan representative of the current anatomy. Significant resolution of facial swelling will change the patient’s surface anatomy, and registration cannot be performed. Registration accuracy is defined by the difference, in millimeters, between the virtual and real coordinates. Registration errors describe the inaccuracies inherent in superimposing the virtual patient onto the actual patient. These errors translate into discrepancies between where the navigation system shows that the instruments are located within the patient and where the instruments are actually located. The best measurement of this error is the target registration error (TRE). The TRE describes the discrepancy between the real and virtual location of any anatomical point or fiducial marker after registration is complete. Previous studies have evaluated registration protocols, clinical outcomes, and ease of use. However, a stringent comparison of optical intraoperative navigation system accuracy on cadaveric specimens has not been performed. This study compares the accuracy of 3 commercially available optical navigation systems in a cadaver model.

METHODS

Four fresh cadaveric heads were obtained from the Donated Body Program at the University of California, Davis. Institutional review board approval was not required. The specimens were prepared by applying 15 invasive fiducial markers (ie, titanium screws 1.5 mm in diameter and 18 mm long; Synthes, Paoli, Pennsylvania) to each skull at predetermined anatomical landmarks, evenly distributed over the anterior facial skeleton (Figure 1). After application, each screw head was removed to provide a more precise tip. The outer 6 screws were defined as registration fiducial markers and were used for specimen registration (green). The 9 central screws were defined as target fiducial markers and used to determine the TRE (blue) (Figure 1). All 4 specimens then underwent a thin-cut, axial CT scan. The scanning protocol was 1-mm, nonoverlapping cuts, without gantry tilt. This protocol was compatible with all navigation systems being tested.

The following commercially available optical CAS systems were evaluated: StealthStation (Medtronic-Xomed, Jacksonville, Florida), VectorVision (BrainLab, Munich, Germany), and Voxim (IVS Solutions, Chemnitz, Germany) (Figure 2). All navigation systems were equipped with an infrared digitizer camera and separate central processing unit. A FESSframe fixation device (Medtronic-Xomed) was used to stabilize the head registration arc for all systems (Figure 3). All reference arcs on the headset and surgical probes were tracked with passive reflectors.

ERROR MEASUREMENTS

Two independent observers (A.R. and M.C.M.) registered each of the 4 specimens on each CAS system using only the 6 registration fiducial markers. No skin surface mapping was used. Specific details of registration (eg, type of probe used for registration, software interface) are slightly different for each CAS system; however, the manufacturer recommendations were followed for each system. The registration procedure was then repeated by each observer for a total of 2 complete data sets on each CAS system. The TRE for each run was determined by sequentially placing the navigation pointer on each of the 6 registration fiducial markers. This placement defined the true location of the registration fiducial and surgical probe in space (ie, the probe was physically on the screw as determined by the observer). The CAS system then projected a virtual fiducial marker and surgical probe on the monitor. The distance between the virtual registration fiducial and the virtual surgical probe was measured and documented as the TRE for each fiducial marker.

MEAN TRE

A mean TRE was then determined by analyzing the mean error from all 72 target fiducial markers evaluated on each system (ie, 9 markers per specimen, 2 specimens per system, 2 runs per system, 2 observers total).

RESULTS

The mean TRE was defined as the mean error of all 72 points collected on 4 specimens by 2 observers perform-
ing 2 runs per system. For the StealthStation system, the mean (SD) TRE (ie, the distance between the actual surgical probe placement and the virtual location depicted by the navigation system) for all 72 points was 1.00 (0.04) mm (P < .05). For the VectorVision system, the mean (SD) TRE for all 72 points was 1.13 (0.05) mm (P < .05). For the Voxim system, the mean (SD) TRE for all 72 points was 1.34 (0.04) mm (P < .05). All TREs were found to be statistically significant using the Kruskal-Wallis test. Statistical analysis was performed to evaluate differences between observers or within evaluation by a single observer. No statistical significance was found (Mann-Whitney test P_{observer} = .70, P_{evaluation} = .16).

**COMMENT**

The concept of open reduction and internal fixation of facial fractures was popularized in the 1970s and 1980s. Although this remains the standard of care for most facial fractures, situations occur in which an accurate reduction is extremely challenging. This is particularly true for complex facial fractures, fractures that involve the orbit, and secondary reconstructions. In these situations, the premorbid facial symmetry can be difficult, if not impossible, to restore. To combat these challenging situations, surgeons have turned to CAS. Computer-aided surgery systems allow the surgeon to use thin-cut, axial CT data and generate accurate 3-dimensional skeletal reconstructions. These data sets can be manipulated preoperatively for surgical planning and projected intraoperatively as a surgical guide. Unfortunately, little has been published on the efficacy of this technique in maxillofacial reconstruction. This article evaluates the accuracy of 3 different optical navigation systems.

In general, all systems had similar ease of use. However, differences were found in the hardware and software (Table). All 3 systems offer fiducial marker registration with either invasive or noninvasive markers. They all offer a point-to-point registration modality in which the surgeon identifies specific fiducial markers (either anatomical or markers applied by the surgeon) on the virtual patient and then identifies the same fiducial markers on the actual patient. The CAS system then triangulates...
the location of the patient to within 1 to 2 mm. The VectorVision and StealthStation systems offer a second registration modality: skin surface matching registration. Skin surface registration on the VectorVision system is performed with a dedicated laser pointer (Z-Touch) that outlines a representative portion of the facial skin. No patient contact is required. Skin surface registration on the StealthStation is performed by moving a surgical probe across a similar area. Point collection (approximately 100-150 points) is easy and rapid, taking approximately 10 to 15 seconds for either system. All 3 systems require that the headset and surgical probe be maintained within the line of sight of the digitizer camera during registration and during surgery. This can be slightly cumbersome, but all systems performed equivalently.

**CENTRAL PROCESSING UNIT SOFTWARE**

The StealthStation system uses a Lenox-based format. It has a dedicated central processing unit located within the navigation device. Windows-based personal computers cannot function as planning stations. The navigation system itself or a dedicated Lenox-based personal computer must be used for preoperative planning. The VectorVision and Voxim systems use a Windows-based format. They have dedicated central processing units within the navigation device. However, the software is compatible with most Windows-based personal computers (Table).

**PREOPERATIVE PLANNING SOFTWARE**

All 3 systems can be used to segment (ie, separate) the soft and hard tissues by windowing of the Hounsfield units. They can also measure simple distances in the 2-dimensional format. BrainLab (VectorVision) is in the process of developing dedicated planning software that allows for segmentation and mirroring of the bony skeleton and measurement of angles and distances. At the time of publication, this software was the most advanced, rapid, and powerful software available for presurgical planning. However, it did require the use of 2 distinct programs: one to convert the CT data into a proprietary language and the second for data manipulation. The Voxim system uses a single program to both convert and manipulate the data. It has a robust capability for segmentation of soft and hard tissues, segmentation and mirroring of bone, and measurement of angles and distances in both 2-dimensional and 3-dimensional views.

**DATA IMPORT AND EXPORT**

All 3 systems import DICOM (Digital Imaging and Communications in Medicine) data sets and translate the information into proprietary languages used by each device. Data can be imported into all 3 systems using either a CD or a network connection. The StealthStation and VectorVision systems also offer import via optical disk. The Voxim and VectorVision systems offer USB (universal serial bus) import capability. The ease of data import was equivalent for all systems. However, when using a USB import with the VectorVision system, only 1 data set could be imported at a time because the memory stick was reformatted after each use. Data export is limited to the proprietary format for the StealthStation. The VectorVision system can export data in a proprietary format, STL, and DICOM. The Voxim system can export data in a proprietary format and STL and DXF (Table).

**OTHER FINDINGS**

The StealthStation and Voxim systems responded more rapidly than the VectorVision system during registration and intraoperative use. However, this finding could have been related to the specific system or central processing unit we were working with. The anatomical ac-

---

### Table. Overview of Software and Hardware Applications for Each of the 3 Computer-Aided Surgery Systems Tested

<table>
<thead>
<tr>
<th>Hardware</th>
<th>StealthStation</th>
<th>VectorVision</th>
<th>Voxim</th>
</tr>
</thead>
<tbody>
<tr>
<td>Infrared camera</td>
<td>Passive</td>
<td>Passive</td>
<td>Passive</td>
</tr>
<tr>
<td>Registration</td>
<td>Point to point</td>
<td>Point to point</td>
<td>Point to point</td>
</tr>
<tr>
<td>Software</td>
<td>Navigation system</td>
<td>Windows based</td>
<td>Navigation system</td>
</tr>
<tr>
<td>System conditions</td>
<td>Lenox based</td>
<td>Windows based</td>
<td>Windows based</td>
</tr>
<tr>
<td>Planning tools</td>
<td>Segmentation Measurements</td>
<td>Mirroring Measurements</td>
<td>Segmentation Measurements</td>
</tr>
<tr>
<td>View</td>
<td>3-Dimensional Multiplanar</td>
<td>3-Dimensional Multiplanar</td>
<td>3-Dimensional Multiplanar</td>
</tr>
<tr>
<td>Data source</td>
<td>CD Optical disk</td>
<td>CD Optical disk USB stick</td>
<td>CD USB stick Hard disk</td>
</tr>
<tr>
<td>Data import (DICOM)</td>
<td>Single program (import and manipulation)</td>
<td>DICOM conversion program Manipulation program</td>
<td>Single program (import and manipulation)</td>
</tr>
<tr>
<td>Data export</td>
<td>Own format</td>
<td>Own format</td>
<td>Own format STL, DXF</td>
</tr>
<tr>
<td>Graphics</td>
<td>Average</td>
<td>Good</td>
<td>Excellent</td>
</tr>
</tbody>
</table>

**Abbreviations:** CD, compact disk; DICOM, Digital Imaging and Communications in Medicine; USB, universal serial bus.  

*StealthStation (Medtronic-Xomed, Jacksonville, Florida), VectorVision (BrainLab, Munich, Germany), and Voxim (IVS Solutions, Chemnitz, Germany).*
Accuracy (ie, screen representation) of the StealthStation was acceptable. The VectorVision screen representation was good. The Voxim screen representation was excellent. Other specialty modalities include the following: image fusion (StealthStation, VectorVision, and Voxim), which allows for fusion of multiple CT or CT and magnetic resonance imaging data sets; advanced interfaces (VectorVision), which allows the direct connection with a microscope, endoscope, or C-arm; and radar sphere (Voxim), which allows automatic detection of the shortest vector to the target point, independent of surgical pointer axis. This can be an important tool for navigation in the orbital cavity, where the surgical probe cannot be placed perpendicular to all the anatomical structures being evaluated.

CONCLUSIONS

Although each CAS system had unique features, overall ease of use was equivalent. The StealthStation was found to be the most accurate (mean [SD] TRE, 1.00 [0.04] mm), followed by VectorVision (1.13 [0.05] mm) and Voxim (1.34 [0.04] mm). The clinical significance of these small differences in maxillofacial reconstruction is unclear. All 3 systems offered fiducial marker registration, whereas only the StealthStation and VectorVision offered surface registration. Only the Voxim and VectorVision systems offered dedicated digital manipulation software.

Submitted for Publication: March 28, 2007; final revision received October 12, 2007; accepted November 2, 2007.

Correspondence: E. Bradley Strong, MD, Department of Otolaryngology, University of California, Davis, School of Medicine, 2521 Stockton Blvd, Ste 7200, Sacramento, CA 95817 (edward.strong@ucdmc.ucdavis.edu).

Author Contributions: Dr Strong had full access to all the data in the study and takes responsibility for the integrity of the data and the accuracy of the data analysis.

Study concept and design: Strong, Hollweg-Majert, and Metzger. Acquisition of data: Strong, Fuller, and Metzger. Analysis and interpretation of data: Strong and Metzger. Drafting of the manuscript: Strong and Metzger. Critical revision of the manuscript for important intellectual content: Strong, Hollweg-Majert, Fuller, and Metzger.

Statistical analysis: Metzger. Administrative, technical, and material support: Strong, Hollweg-Majert, and Metzger. Study supervision: Strong and Hollweg-Majert.

Financial Disclosure: None reported.

Funding/Support: This study was funded by grant 90925871098 from the Association for the Study of Internal Fixation.

REFERENCES


