Real-Time Imaging with the O-Arm for Skull Base Applications: A Cadaveric Feasibility Study

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Abstract

Introduction Although intraoperative imaging/navigation has established its critical role in neurosurgery, its role in cranial base surgery is currently limited. Due to issues such as poor bony resolution and accuracy, surgeons have to rely on anatomic landmarks that can be distorted by pathology when drilling out critical structures. Though originally developed for spinal application, we hypothesized that the O-Arm could address the above issues for use in cranial base procedures.

Methods A cadaveric study was performed in which heads underwent a preprocedure scan via the O-Arm, a fluoroscopic device capable of providing three-dimensional images through the use of cone-beam technology. Preprocedure scans were taken and then registered to a Stealth S7 machine (Medtronic, Inc., Minneapolis, MN, USA). Key cranial base landmarks were identified on these scans and then subsequently identified under direct visualization after (1) endoscopic endonasal dissection and (2) a middle fossa approach. We then quantified the difference in distance between the preplanned and identified structure during surgery. This difference was considered the error.

Results For anterior cranial fossa structures, the mean error was 0.25 mm (anterior septum), 0.27 mm (left septum), and 0.32 mm (right septum). For middle fossa structures, the errors were: 0.11 mm (foramen spinosum), 0.44 mm (foramen rotundum), and 0.21 mm (foramen ovale).

Conclusion Based on this preliminary cadaveric study, we feel the O-Arm can provide the necessary imaging resolution at the skull base to be employed for intraoperative navigation during cranial base approaches (open and endoscopic). This study warrants further investigation into its clinical use in patients undergoing similar surgical procedures.

Keywords

- intraoperative navigation
- O-Arm
- skull base

Introduction

The anatomy of the skull base is extremely dense with critical neurovascular structures.^{1,2} Approaches to cranial base pathology, benign or malignant, can often place these structures at risk due to inadvertent injury. In performing these complicated approaches, intraoperative identification of anatomic landmarks often guides bony resection; however, these landmarks can be distorted by the pathology of interest. This need

for anatomic mapping highlights the value of neuronavigation in supplementing a surgeon's anatomic understanding. Although image-guidance systems and intraoperative navigation have improved surgical speed and safety, they are mostly based on preoperative imaging. In addition, these images are obtained prior to positioning. As a result, pinning and positioning the patients will often distort the skin and overlying fiducials and thereby decrease the accuracy of the image guidance systems.

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Over recent years, there has been increasing emphasis on intraoperatively acquired three-dimensional (3D) imaging. More recently, several surgical fields, particularly spine surgery, have supplemented preoperative images with 3D intraoperative imaging.^{3–6} This technology has enabled spine surgeons to place hardware more precisely and confirm successful completion of surgical objectives before the conclusion of the operation. The O-Arm (Medtronic, Inc., Minneapolis, MN, USA) was recently introduced for such purposes.^{7–10}

We investigated the use of the O-Arm for skull base surgery. This technology is increasingly being studied in various intracranial operations, and the O-Arm was recently described in its use for deep brain stimulation.¹¹ We felt that changing the paradigm for acquiring images and registering after positioning would improve navigational and imaging accuracy when applied to skull base techniques. The 3D bony imaging would not only offer better understanding of complex and tortuous structures in relation to each other, but now would also potentially improve true accuracy to the surgeon to improve safety and efficiency for these difficult surgeries. In addition, the O-Arm would also provide real-time images throughout a procedure to provide immediate feedback with regards to the progress in surgery.

The primary goal of the current study was to determine the navigational accuracy precision of the O-Arm with regards to key anatomic landmarks commonly used in surgical approaches to the skull base. To determine the accuracy and precision of 3D intraoperative imaging in the anterior and middle cranial fossa, we correlated locations of surgical targets identified on preoperative imaging obtained with the O-Arm with the location identified during cadaver dissection.

Materials and Methods

A cadaveric study was performed on a series of 10 embalmed cadaver heads with no known intracranial or skull base pathology. The study was designed to assess navigational accuracy of the O-Arm with critical skull base landmarks. This accuracy was measured by average target registration error (TRE), which refers to the difference between corresponding points in the real world (i.e., cadaver) and the navigational dataset (i.e., O-Arm imaging data) after registration and scanning. The value of this data and its clinical relevance has been previously described in the literature.^{12,13}

O-Arm Navigation

The O-Arm is an intraoperative imaging device (►Fig. 1A, B) with a flat-panel detector that provides two imaging modalities: (1) two-dimensional (2D) fluoroscopic imaging and (2) 3D cone-beam computed tomography (CT) imaging. The fluoroscopic imaging modality acquires 2D images that are larger and more accurate than a conventional C-arm. As opposed to conventional fluoroscopy, the O-arm is also able to provide 3D imaging through a full 360-degree scan that is obtained over the course of 30 seconds; this is possible because the “C” shape can close into an “O” in the appropriate

Figure 1 O-Arm. (A) Image of O-Arm with remaining “operating room” equipment in place. (B) Image of surgeons performing endoscopic endonasal dissection with cadaver head in relation to O-Arm.

setting to allow for a cone beam CT based image. The imaging resolution of the O-Arm is $0.415 \text{ mm} \times 0.415 \text{ mm} \times 0.83 \text{ mm}$; the technical accuracy of the system is dependent on several factors (including the tools employed, registration accuracy, etc) while the tracking accuracy of the camera (NDI, Ontario, Canada) is 0.3 mm root mean square (RMS) obtained they can be transferred to a navigational workstation and fused with previously obtained imaging modalities (i.e., magnetic resonance imaging [MRI]).

Cadaveric Registration and Data Acquisition

Ten cadaver heads were studied for anatomic landmarks in the anterior and middle cranial fossa. After fixation in a radiolucent Mayfield clamp and attachment of a reference

Table 1 Anatomic Landmarks

	Anatomic Landmarks
Anterior cranial fossa	Anterior septum ^a
	Left septum ^b
	Right septum ^b
Middle cranial fossa	Foramen spinosum
	Foramen ovale
	Foramen rotundum

^aAnterior septum refers to the anterior intersection of the sphenoid septum with the anterior wall of the sphenoid sinus and planum sphenoidale.

^bLeft/right septum refers to the respective side of the posterior intersection of the sphenoid septum with the sella/carotid.

array, a 3D acquisition scan was performed via the O-Arm, which was then transferred to a Stealth S7 navigational workstation (Medtronic, Inc.). This predissection scan served the purpose of registering the cadaver specimen for navigation in lieu of fiducials as the scan is taken with the head in fixed relation to a reference array. This preprocedure imaging was also then analyzed by the surgeons (SR and ML) to determine the location of key anatomic landmarks in the anterior and middle cranial fossa (► **Table 1**); these anatomic landmarks would serve as the study points to determine TRE of the system at the skull base.

After noting surgical targets, dissections were then performed to identify each of the targets under direct visualization. This dissection was done independent of the navigational system and was based on the surgeon's anatomic understanding. For structures in the anterior cranial fossa and sella, a standard binasal endoscopic endonasal approach to the sella with middle turbinate resection was performed. After wide opening of the sphenoid sinus and mucosal stripping, the navigation probe was placed on the targeted structures. For the middle cranial fossa structures, an extradural subtemporal approach was performed via a "U"-shaped incision around the external auditory meatus.

Prior to the approaches, the points of interest were marked on the Stealth station. After performing our opening, we identified each point based on direct anatomic visualization. With the probe in place on each of the targeted structures, a screenshot was taken using navigation as the surgeon stabilized the probe. We then left the navigation probe in the specified point and repeated the cone beam CT with the O-Arm to confirm that we were in the correct location (► **Figs. 2 and 3**). For these scans, the navigation probe was stabilized with a holder to maintain the probe tip in a steady position. To determine accuracy (TRE), we measured the distance between the target identified in surgery with the navigation probe at the same preplanned target on the Stealth station. Each of these two points had a specific coordinate in three dimensions (x, y, z) that could be extracted from the Stealth station. We then calculated the distance between the two points by taking the square root of the sum of the difference in x coordinates squared, difference in y coordi-

nates squared, and difference in z coordinates squared. We then calculated the mean distance to determine the accuracy error of the O-Arm.

Results

For structures in the anterior cranial fossa, the mean error difference between preselected and visualized structures was as follows: anterior septum 0.25 mm (standard deviation 0.43 mm), left septum 0.27 mm (standard deviation 0.51 mm), and right septum 0.32 mm (standard deviation 0.40 mm). For the middle cranial fossa structures, the mean error difference between direct visualization and location based on navigation was as follows: foramen spinosum 0.11 mm (standard deviation 0.09 mm), foramen rotundum 0.44 mm (standard deviation 0.57 mm), and foramen ovale 0.21 mm (standard deviation 0.23 mm) (► **Table 2**).

Discussion

The anatomy of the cranial base is densely packed with critical structures within submillimeter distances from each other.¹⁴ Accordingly, surgery in this region is associated with the risk of significant morbidity/mortality by damage to these neurovascular structures. Successful resection of cranial base lesions, benign or malignant, requires the use of advanced surgical approaches that rely on intraoperative recognition of key anatomic landmarks. With more destructive lesions, such as chordomas, these landmarks can be distorted or hidden; increasing the chances of morbidity. Concurrently, in the modern neurosurgical era, there is an impetus to minimize soft-tissue morbidity through minimally invasive approaches (i.e., expanded endonasal endoscopy and keyhole craniotomies). These relatively new approaches now diminish visualization of anatomic landmarks that have been used by surgeons to navigate the skull base. As a result, there is now increasing reliance on neuronavigational systems to approach cranial base lesions that were once resected through larger approaches that provided more regional visualization. In light of the inherent risk of cranial base surgery and the growing role of neuronavigational systems for anatomic confirmation, there is a need for a real-time navigational system that provides submillimeter accuracy and visualization of the bony skull base. The goals of this study were (1) to determine the accuracy of the O-Arm, initially designed for spine applications, in imaging the anterior and middle cranial fossa; and (2) explore potential applications with modern and conventional surgical approaches.

Current Neuronavigational Systems and Skull Base Surgery

The development of modern neuronavigation systems has helped improve patient outcomes in many regards, such as allowing smaller incisions, tailoring craniotomies, and minimizing disruption of surrounding neurovascular structures. Although it is not a replacement for a surgeon's intimate understanding of anatomy, navigation plays a role in confirming intraoperative visualization and, perhaps, increases

Figure 2 Anterior cranial fossa navigation algorithm. (A) Screenshot of our planned target to the anterior superior point of the sphenoid septum done on the image guidance station. (B) Screenshot of neuronavigation image taken with probe along the anterior aspect demonstrating the capacity to navigate utilizing the O-Arm. (C) Intraoperative computed tomography image taken utilizing O-Arm with probe held in position at the anterior aspect of the sphenoid septum confirming that the probe was indeed in the position indicated by the image guidance station.

Figure 2 (Continued).

surgical efficiency. The benefits are well known and have been discussed in other publications.

Although neuronavigation has minimized risk associated with modern minimally invasive approaches, there are shortcomings and disadvantages that prevent 100% reliance on its utility. There are two primary issues of concern: (1) the difference between target registration and accuracy at the skull base and (2) the lack of real-time intraoperative feedback.^{15,16} The shortcomings of applying traditional neuronavigational systems to the skull base, particularly the temporal bone, have been addressed in the literature. Previous studies have demonstrated that registration error does not necessarily correlate with actual anatomic accuracy or global accuracy at the skull base. This is an artifact of errors in localizing the geometrical position of fiducials that are typically placed on the scalp over the convexity (typically where the skin is the least mobile). The reported error in accuracy with these systems in identifying the internal auditory canal have ranged from 0.9 mm to 2.4 mm. Previous authors have attempted to improve upon currently available systems with the use of CT imaging obtained preoperatively and the use of bone fiducials.¹⁷ The use of bone markers placed through the skin as opposed to traditional scalp fiducials have been used to circumvent this issue; however, the invasive nature of bone markers is not appealing and has prevented widespread adoption. In addition to these geometrical considerations, there are several other factors that can mitigate neuronavigational accuracy at the skull base: the mechanics of registration itself and slippage of the patient from pin fixation.

The lack of feedback during surgery, though not major, is another limitation of current neuronavigational systems; a reason why many surgeons still employ ultrasound for intra-axial lesions and why intraoperative imaging (CT or MRI) has been introduced. One could imagine that the availability of real-time imaging would be employed in cranial base approaches (such as the extended middle fossa and far-lateral transcondylar approaches) to ensure that an adequate amount of bone has been drilled. In light of these considerations, any navigational system that is employed for cranial base applications should not only provide submillimeter accuracy but also an accurate intraoperative assessment of bony anatomy.

The O-Arm and Cranial Base Navigation

The O-Arm is an intraoperative imaging device that fluoroscopically acquires 2D images more accurately than a conventional C-arm. In addition, with a full 360-degree scan performed over a short period of 30 seconds, 3D volumetric reconstructions can be performed. Primarily designed for an intraoperative assessment of osseous structures, it has primarily been applied to spinal applications, such as assessing pedicle screw placement. In addition to providing intraoperative 3D imaging, the O-Arm can provide CT imaging, which can be coupled with traditional neuronavigational systems. Avoiding the need to obtain special preprocedure imaging, registration is performed with a brief registration preprocedure scan that can be fused with a standard MRI obtained preoperatively.

Due to the need for an accurate intraoperative system that provides real-time navigation in the skull base, the goal of this study was to determine its accuracy in imaging key anatomic landmarks used during standard cranial base approaches to the anterior and middle cranial fossa. For both cranial fossa,

based on preprocedure O-Arm imaging, we attempted to identify key anatomic landmarks used during expanded endonasal approaches to the anterior skull base/sella and extended middle fossa approaches. Subsequently, the respective surgical approaches were performed (described earlier)

Figure 3 Middle cranial fossa landmarks. (A) Point 1: foramen spinosum. (B) Point 2: foramen ovale. (C) Point 3: foramen rotundum.

Figure 3 Continued.

and the navigation probe was placed on these landmarks under direct visualization. By calculating the error distance between the structures as identified on preoperative O-Arm imaging and direct intraoperative visualization, the error in accuracy of the O-Arm in imaging the skull base was determined.

Overall, the comparison in imaging-based and directly visualized targets revealed submillimeter differences, demonstrating an exciting potential role for the O-Arm in navigation of the skull base. This submillimeter error must be taken in the context of two issues: the sizes of the foramina/structures tested can be greater than 1 mm, and the tip of the navigational probe is 1 mm. Despite these issues, it is feasible to get submillimeter differences, since this final target registration error is a compilation of differences in three dimensions (x-, y-, and z- axis). Although the initial raw

images are based on 1-mm slices in the axial plane, submillimeter differences are possible in the other sagittal and coronal planes. Differences in millimeters of error in navigation in the real world can result in disastrous consequences when drilling in the skull base, such as the risk of injury to the petrous carotid during a petrosectomy. As this risk can be increased due to anatomic distortion from the pathology of interest, any navigational system employed must provide this accuracy. The submillimeter error in the O-Arm demonstrates its advantageous role in providing real-time intraoperative imaging and navigational guidance during cranial base approaches.

Considerations and Potential Applications

The current study demonstrates that the O-Arm is capable of imaging skull base structures with excellent accuracy and

Table 2 Mean Error of Anatomic Landmarks

	Anatomic Landmarks	Mean Error (Std. Dev.) Millimeters
Anterior cranial fossa	Anterior septum	0.25 (0.43)
	Left septum	0.27 (0.51)
	Left septum	0.27 (0.51)
Middle cranial fossa	Foramen spinosum	0.11 (0.09)
	Foramen ovale	0.21 (0.23)
	Foramen rotundum	0.44 (0.57)

resolution. There are several additional characteristics that lend well to intraoperative use. First, the fact that imaging is based on intraoperative cone beam CT imaging as opposed to conventional CT imaging results not only in less radiation exposure (particularly important for pediatric patients or where multiple images are taken) but also that specially-designed surgical instruments are not necessary (such as those needed for intraoperative MRI). Second, its short scan times (~30 seconds for 3D image acquisition and reconstruction) and portable and mobile nature minimize its impact on operating room workflow. Third and most important, the registration is done after the head is positioned. This obviates the concerns of the fiducials moving on the skin secondary to pinning. In addition, because the data for the registration is directly linked to the navigation system, it eliminates another potential point for processing error through intermediate computers. Last, because the registration is direct, if the head is inadvertently moved during the procedure or if the surgeon wants to verify his/her point during surgery, another scan can be performed and the surgeon will have a cone-beam-generated image to directly visualize his/her progress and will have a refreshed registered navigation system. Although these points are very exciting, there are certain limitations to the O-Arm. The resolution is limited when trying to visualize intra-axial and soft-tissue structures. In addition, similar to other intraoperative imaging systems, the O-Arm can be unwieldy at times and requires significant operating room space to be maneuvered. An additional and important consideration is the technical accuracy of the system. Although the navigational accuracy in the study has been demonstrated to be in the submillimetric range, the error of the technology needs to be factored—this includes the imaging resolution of the O-Arm ($0.415 \text{ mm} \times 0.415 \text{ mm} \times 0.83 \text{ mm}$) and the technical accuracy of the system. As mentioned earlier, the technical accuracy is dependent on several factors (including the tools employed, registration accuracy, etc).

Despite these disadvantages, the O-Arm could play a significant role for intracranial procedures. Based on the anatomic approaches performed in this study, the O-Arm could provide valuable improvements in accuracy and efficiency based on the principle of imaging and registering after positioning. Furthermore, the intracranial applications of the O-Arm could be expanded with progress in soft-tissue imaging.

Conclusion

The utility of conventional neuronavigational systems in cranial base approaches is limited by accuracy at the skull base and the lack of real-time feedback that could be used to guide bony drilling. The need for accurate skull base navigation is paramount, as there is a push in the modern era for minimally invasive approaches (i.e., endoscopic approaches) and the need to improve safety. Based on the current study that assessed accuracy with two standard approaches to the anterior and middle cranial fossa, the paradigm of imaging and registering after positioning with

the O-Arm provides excellent accuracy for its preliminary application in skull base procedures. Further improvement in soft-tissue imaging could potentially expand the role of the O-Arm for other intracranial applications. However, prospective clinical trials are necessary to ultimately delineate the role of this technology in the surgical approaches to the skull base.

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