The Accuracy of an Electromagnetic Navigation System in Lateral Skull Base Approaches

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Objectives/Hypothesis: Image-guided optical tracking systems are being used with increased frequency in lateral skull base surgery. Recently, electromagnetic tracking systems have become available for use in this region. However, the clinical accuracy of the electromagnetic tracking system has not been examined in lateral skull base surgery. This study evaluates the accuracy of electromagnetic navigation in lateral skull base surgery.

Study Design: Cadaveric and radiographic study.

Methods: Twenty cadaveric temporal bones were dissected in a surgical setting under a commercially available, electromagnetic surgical navigation system. The target registration error (TRE) was measured at 28 surgical landmarks during and after performing the standard translabyrinthine and middle cranial fossa surgical approaches to the internal acoustic canal. In addition, three demonstrative procedures that necessitate navigation with high accuracy were performed; that is, canalostomy of the superior semicircular canal from the middle cranial fossa,1 cochleostomy from the middle cranial fossa,2 and infralabyrinthine approach to the petrous apex.3

Results: Eleven of 17 (65%) of the targets in the translabyrinthine approach and five of 11 (45%) of the targets in the middle fossa approach could be identified in the navigation system with TRE of less than 0.5 mm. Three accuracy-dependent procedures were completed without anatomical injury of important anatomical structures.

Conclusion: The electromagnetic navigation system had sufficient accuracy to be used in the surgical setting. It was possible to perform complex procedures in the lateral skull base under the guidance of the electromagnetically tracked navigation system.

Key Words: Navigation system, electromagnetic, lateral skull base, temporal bone.

Levels of Evidence: N/A.

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INTRODUCTION

Image-guided surgical navigation has become a popular tool to help surgeons accomplish complex surgical objectives with minimal tissue injury, particularly in endoscopic sinus surgery and neurosurgery.1,2 Surgical navigation tracks the location of surgical devices and gives feedback to the surgeon by showing the location on the patient’s radiographic images. Correct tracking of the device location is an important factor underlying the accuracy of the navigation systems. Currently, optical and electromagnetic tracking strategies are widely used.

The optical tracking system, which is currently the most popular, uses retroreflective spheres on the tracking device. The optical tracker has two sets of infrared emitters and cameras and detects three-dimensional coordinates of the retroreflective spheres. By using three or more spatially distributed spheres forming a specific shape, the tracking software detects the three-dimensional location and orientation of the device. This straightforward strategy is robust against electromagnetic interference and offers 0.5-mm spatial resolution and up to 60 Hz of temporal resolution (product specification provided by NDI, Waterloo, ON, Canada). Each device to be tracked needs at least three spheres with a certain spatial distribution, for example, > 55 mm of separation from one sphere to another in one system (NDI). All spheres must maintain optical access while tracking. In reality, however, the optical access is often interrupted during surgery by other devices, staff movement, and the surgeon’s hands. The retroreflective spheres are usually attached at the rear of the surgical device to avoid blocking the surgeon’s view. This increases the distance between the spheres and the tip of the device to be located by the navigation computer. The large size of the set of retroreflective spheres and the distance between the spheres and the tip of the device to be blocked are disadvantages of the optical tracking strategy because small locational errors at the
The electromagnetic tracking strategy, which is acquiring more popularity, uses small sensor coils in an electromagnetic field created by an emitter. The advantage of the electromagnetic tracker is that the sensor is small (as small as 0.3 mm in some models) and optical line of sight is not required. Electromagnetic sensors can be embedded near the tip of the surgical devices, a factor that makes electromagnetic trackers more accurate, although the tracking resolution of the electromagnetic system, that is, 0.8 mm to 1.4 mm spatial and 40 Hz temporal (NDI product specifications), is not as high as that of optical trackers. The clinical use of the electromagnetic tracking systems has been limited due to the instability of the magnetic field, created by metal, rotating drills, or surgical lights. Developments in hardware and software have helped stabilized the magnetic field and improved the accuracy and stability of electromagnetic tracking.3,4 As a result, the electromagnetic system is now used more commonly in endoscopic paranasal sinus and anterior skull base surgeries.5–7 However, the use of electromagnetically tracked navigation systems in lateral skull base surgery, dealing with smaller surgical targets requiring more accuracy and stability of the device tracking, is controversial, if not slightly negative.8,9 Nevertheless, improvements in the accuracy and stability of the tracking device require reevaluation of electromagnetic tracking in lateral skull base surgery. In this study, we evaluated the accuracy of a new commercially available electromagnetic navigation system in lateral skull base surgery on cadaveric specimens.

MATERIALS AND METHODS

Preparation

A total of 25 formalin-fixed cadaveric temporal bones were dissected in a surgical setting equipped with a navigation system (Fig. 1A). We placed seven titanium screws (see Fig. 1B and 1C for locations) on each head as fiducial markers for the navigation. Axial computed tomography (CT) scans of each temporal bone were completed (GE LightSpeed 16, GE Healthcare, Wauwatosa, WI). Computed tomography datasets were obtained in 512 × 512 pixels at a resolution of 0.46 mm/pixel and a slice thickness of 0.63 mm.

The StealthStation i7 integrated navigation system fitted with AxiEM electromagnetic field emitter (Medtronic, Louisville, CO) was used for this study. The reference marker (cranial dynamic reference frame) was screwed on the ipsilateral forehead. The AxiEM magnetic field emitter (Medtronic) was fixed on the side of the surgical table directly adjacent to the head in order to obtain a stable magnetic field covering the head.

The head was registered to the navigation system using paired-point method of the seven fiducial markers. During the registration process, the navigation system estimated the error and displayed a sphere showing the area where an error of less than 1 mm was expected (Fig. 1B and 1C). The algorithm for drawing the sphere was not disclosed by the manufacturer. However, the center of the sphere was obviously placed at the centroid of the fiducials markers (Fig. 1B and 1C). After a few pilot trials, we selected positions for the seven fiducial markers (Fig. 1B and 1C) to provide an accuracy sphere that covers the entire temporal bone.

Surgical Procedures for the Evaluation

The arteries and veins of two of the 25 cadaveric temporal bones were injected with a red or blue colored silicone rubber, Thinner 200, and RTV catalyst (Dow Corning Corp., Midland, MI) prior to dissection. Photographs taken during the bone dissections were used in Figures 2 and 3, but these bones were not included in the navigational error measurement described below because dissection of these bones did not follow the surgical procedure as precisely as those of the cadaveric temporal bones.

Twenty temporal bones were dissected under the surgical microscope with 3× to 40× optical magnifications using neurotological instruments and a surgical drill (Midas Rex Legend, Medtronic Powered Surgical Solutions, Fort Worth, TX). We performed two traditional temporal bone approaches, translabyrinthine (Fig. 2) and middle fossa (Fig. 3) to the internal acoustic canal (IAC). The translabyrinthine approach began with a conventional mastoidectomy. The retrofacial air cells were drilled, and the sigmoid sinus was followed toward the jugular bulb. The bone between the jugular bulb and labyrinth...
was removed, exposing the cochlear aqueduct medially. Labyrinthectomy was performed to reach the IAC. Next, the same cadaver was re-registered with the same fiducial markers after repositioning the head. The temporal dura was elevated after standard temporal craniotomy, the middle meningeal artery was divided, and the bone over the IAC was removed. The meatal, labyrinthine, and tympanic segments of the facial nerve were exposed. The bone was drilled anterolateral to the tympanic segment to expose the middle ear cavity, cochleariform process, and head of the malleus. An anterior petrosectomy was completed to expose the petrous carotid artery and Eustachian tube.

**Target Registration Error**

The distance between the landmark on the CT dataset and the coordinates indicated by the tracking system when pointing to the corresponding landmark with the tip of the
Fig. 3. Accuracy measurements during right middle fossa approach. (A) Middle fossa approach. The yellow square in the inset shows the area of view. (B) The tip of the probe is on the middle meningeal artery, just lateral to the V3. Red colored area shows the course of the internal carotid artery. (C) Navigation screen with the probe on the middle meningeal artery. The axial, coronal, and sagittal views are shown in the left upper and lower corners and right column. (D) The probe is positioned on the geniculate ganglion, adjacent to the cochlea at the origin of the greater petrosal nerve. (E) Navigation screen with the probe at the geniculate ganglion. The axial, coronal, and sagittal views are shown in the left upper and lower corners and right column.

A. = artery; Aud. = auditory; Car. = carotid; CN = cranial nerve; Cochlear. = cochleariform; Eust. = eustachian; Gang. = ganglion; Gen. = geniculate; Gr. = greater; Int. = internal; Lat. = lateral; Men. = meningeal; Mid. = middle; N. = nerve; Pet. = petrosal; Post. = posterior; Proc. = process; Sup. = superior; Temporomandib. = temporomandibular; Tens. = tensor; Tymp. = tympani.
probe represents the target registration error (TRE), which is a reliable indicator of the navigational accuracy.10,11 We measured the TRE while performing the translabyrinthine and middle fossa approaches at 28 selected landmarks that could be detected by CT and also during surgery. Seventeen landmarks were approached during the translabyrinthine procedure and 11 during the middle fossa approach (Table I).

The StealthStation i7 Integrated Navigation System (Medtronic) automatically calculates the distance between the tip of the probe and the specified point on the CT. We collected this distance as TREs. The software program of the navigation system does not allow inputting specific coordinates of the landmarks, nor outputting detected coordinates of the tip of the probe. The measurement was done based on the finger-pointed landmark on the navigation computer. Thus, the measurement is susceptible to human errors, specifically in the finger-pointing process where it is easy to point several pixels away from the intended landmark. The TRE at each landmark was measured three times, and the average value of the three measurements was collected for further analysis to minimize human errors. All surgical instruments were removed from the magnetic field during measurement.

### Statistical Analysis

Statistical analysis was performed using Prism 6 for Mac (GraphPad Software, San Diego, CA). All analyzed values are presented as mean ± standard deviation. Student paired t test or analysis of variance (ANOVA) were used to examine whether there was a significant difference between pairs or among groups of more than two, respectively. Tukey’s posthoc test was used to identify any significant difference between each pair following ANOVA analysis. The difference was considered significant if the probability value (P) was less than 0.05.

### Additional Surgical Procedures

Finally, we performed three demonstrative procedures that require accurate image guidance on three additional cadaveric temporal bones under the navigation system: 1) middle fossa canalostomy of the superior semicircular canal, 2) middle fossa cochleostomy, and 3) transmastoid infralabyrinthine petrosectomy.

### RESULTS

The overall average TRE at 28 landmarks was 0.49 ± 0.05 mm. Among the 28 targets, TRE was less than 0.5 mm in 16 (57%) target points. There were no differences in TREs in different surgical procedures. TRE was less than 0.5 mm at 11 of 17 (65%) targets in the translabyrinthine procedure and five of 11 (45%) targets in the middle fossa approach. The averages of TREs associated with the translabyrinthine and middle fossa approaches were 0.49 ± 0.14 and 0.50 ± 0.15 mm, respectively. There was no significant difference among the TREs in different targets (P = 0.11) (Fig. 4).

The three demonstrative procedures were successfully completed. The canalostomy of the superior semicircular canal could be completed directly from the middle cranial fossa without widely exposing the surrounding air cells (Fig. 5). The cochleostomy from the middle cranial fossa was accomplished without injuring the IAC or the facial nerve (Fig. 6). The infralabyrinthine petrosectomy could be performed without injuring the jugular bulb, carotid artery, cochlea, or IAC. It was possible to complete the petrous apicectomy (Fig. 7) with confidence that only a thin cortical layer of bone remained.

### DISCUSSION

The accuracy of an electromagnetic navigation system in lateral skull base surgery was examined during established surgical procedures performed in a landmark to landmark fashion. However, surgical landmarks have individual variations in size and location and are often absent or modified by anomalies or previous surgery. For example, the arcuate eminence is one of the important landmarks in the middle cranial fossa that corresponds to the position of the superior semicircular canal, but there are often some differences in the position of the

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**TABLE I.** Anatomical Targets for Translabyrinthine Approach (A) and Middle Fossa Approach (B).

<table>
<thead>
<tr>
<th>A. Translabyrinthine Targets</th>
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<tr>
<td>Spine of Henle</td>
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<td>Sinodural angle</td>
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<tr>
<td>Mastoid segment of facial nerve</td>
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<tr>
<td>Lateral semicircular canal</td>
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<tr>
<td>Posterior semicircular canal</td>
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<tr>
<td>Superior semicircular canal</td>
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<tr>
<td>Subarcuate artery</td>
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<tr>
<td>Short process of incus</td>
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<tr>
<td>Incudostapedial joint</td>
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<tr>
<td>Pyramidal eminence</td>
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<tr>
<td>Round window overhang</td>
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<tr>
<td>Vestibule</td>
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<tr>
<td>Common crus</td>
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<tr>
<td>Ampulla of superior semicircular canal</td>
</tr>
<tr>
<td>Cochlear aqueduct</td>
</tr>
<tr>
<td>Jugular ridge</td>
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<td>Transverse crest</td>
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<tr>
<th>B. Middle Fossa Targets</th>
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<tbody>
<tr>
<td>Arcuate eminence</td>
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<tr>
<td>Cochleariform process</td>
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<tr>
<td>Malleus head</td>
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<tr>
<td>Cochlea</td>
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<tr>
<td>Geniculate ganglion</td>
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<tr>
<td>Tympanic segment of facial nerve</td>
</tr>
<tr>
<td>Labyrinthine segment of facial nerve</td>
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<tr>
<td>Bill’s bar</td>
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<tr>
<td>Eustachian tube</td>
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<tr>
<td>Foramen spinosum</td>
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<td>Petrous carotid artery</td>
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Laryngoscope 127: February 2017

Komune et al.: Electromagnetic Navigation in the Skull Base
two structures.\textsuperscript{12} In our dissections, the arcuate eminence was almost always located lateral to the superior semicircular canal. Thus, knowledge of the anatomical landmarks as average anatomy or textbook anatomy is necessary but no longer sufficient to perform surgery to the current standard. Preoperative imaging and surgical tracking devices make it possible to confirm patient-specific anatomy during surgery. Computer-aided surgery (CAS), including surgical simulation and/or navigation, deals not with average anatomy but with patient-specific anatomy. In this regard, CAS is the surgical version of personalized medicine.

The most common concern while using surgical navigation system is its accuracy. The demand for navigational accuracy is extreme in temporal bone surgery, requiring errors of less than 0.5 mm. In many clinical settings, this accuracy requirement almost reaches the navigation system's inherent limit defined by the physical resolution of the CT dataset (e.g., 0.46 mm in our study). Multiple studies have shown that optically tracked navigation systems have achieved submillimetric accuracy in lateral skull base procedures, both in the clinical\textsuperscript{13} and laboratory\textsuperscript{14–21} settings, but there are fewer studies of the accuracy of magnetically tracked navigation. Miller et al. reported that the middle of the IAC and arcuate eminence could be identified within an error of 2.31 mm and 1.86 mm, respectively, with the InstaTrak 3500 Plus electromagnetic image guidance system (General Electric, Fairfield, CT).\textsuperscript{22} In this study, an electromagnetic navigation system (StealthStation i7 Integrated Navigation system, Medtronic) was accurate enough to be used in lateral skull base surgery, with an average TRE of 0.49 mm. The three demonstrative approaches under navigation were successfully performed without apparent damage to the target and surrounding structures (Fig. 5, 6, and 7).

In optical tracking, the retroreflective spheres should be attached to the patient and to the surgical device. The fact that the electromagnetic navigation system is smaller and free from the issue of optical interference provides it with at least two advantages over the optical tracking system: usability and accuracy. The small tracking sensor embedded in the device is more user-friendly than having a device with large tracking spheres attached at the rear of the device. In addition, having a tracking sensor near the tip of the device contributes to more stable and accurate tracking. These features apparently compensate for the lower tracking resolution of the current electromagnetic system, although electromagnetic systems are still susceptible to noise in the electromagnetic field caused by metallic instruments or some surgical light. We did not measure TRE while other metallic devices are moving or while drilling, which may decrease accuracy. In general, metal around the surgical field, including drills and retractors, potentially decreases the accuracy of the electromagnetic system. Thus, the tip of the navigation stylus can be used when metallic devices are temporarily kept away. Hermann et al. reported that they used the AxiEM neuronavigation system Medtronic Powered Surgical Solutions, Fort Worth, TX with the electromagnetic navigation, and there was no need to remove the retractor in sites deeper than the craniotomy margin.\textsuperscript{23} The susceptibility of this system to the inaccuracies caused by metallic instruments should be subjected to further examination.

![Fig. 4. Target registration errors. The target registration errors at the anatomical targets during the translabyrinthine approach (A) and middle fossa approach (B) to the internal acoustic canal. Black dots and vertical bars represent mean ± SD at each measured target, 20 measurements each; A = artery; CN = cranial nerve; Lat. = lateral; Post. = posterior; Seg. = segment; Semicirc. = semicircular; SD = standard deviation; Sup. = superior; TRE = target registration error.](image-url)
In this study, we used invasive fiducial markers on the temporal bone, forehead, and contralateral mastoid tip. The reference post was also invasively screwed on the skull, which provides better accuracy in lateral skull base surgery. However, less invasive methods for registration and referencing are reported to provide near-comparable accuracy.

Fig. 5. Opening the left superior semicircular canal in a middle fossa approach. (A) After keyhole craniotomy and elevation of the middle fossa dura, the probe was placed at the arcuate eminence. (B) The navigation screen showing the trajectory to the superior semicircular canal in the axial (left upper corner), coronal (left lower corner), and sagittal planes (right column). (C) Endoscopic view: Drilling the bone along the same trajectory exposes the superior semicircular canal, which has been opened. (D and E) Computed tomography images before (D) and after dissection (E). Inserts show axial views of the left temporal bone. The yellow lines in inserts show the sagittal plane and the blue line shows the coronal plane. The red dashed arrow points to the semicircular canal. Arc. = arcuate; Aud. = auditory; Emin. = eminence; Int. = internal; Mid. = middle; Sup. = superior.
CONCLUSION
The electromagnetic navigation system was sufficiently accurate to be used in the surgical setting. The fact that the tracking sensors are smaller in electromagnetic tracking may provide some advantages over the optically tracked navigation systems.

Acknowledgment
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Fig. 7. Access to the left petrous apex through a left infralabyrinthine approach. (A) After conventional mastoidectomy, the bone between the posterior semicircular canal and jugular bulb is drilled to expose the cochlear aqueduct. (B) Navigation screen showing the probe on the cochlear aqueduct on the axial (left upper corner), coronal (left lower corner), and sagittal planes (right column). (C–E) Axial (C), oblique coronal (D), and sagittal (E) CT images before drilling to extend the approach to the petrous apex. The red dashed arrow shows the trajectory to the petrous apex (C). (D and E) The yellow lines in insets show the oblique coronal CT cut (D) and the sagittal cut (E). The red star marks the target area. (C–E) Axial (F), oblique coronal (G), and sagittal (H) views after extending the drilling to the petrous apex. Inserts: Yellow lines in G and H show the level of the oblique coronal (G) and sagittal (H) CT cuts. The red star marks the target in the petrous apex. Red dashed arrows in F indicate the trajectory to the petrous apex. A. = artery; Aud. = auditory; Car. = carotid; CN = cranial nerve; Int. = internal; Jug. = jugular; Post. = posterior; Sig. = sigmoid.
This work was conducted in the Department of Neurosurgery, University of Florida, College of Medicine, Gainesville, Florida, U.S.A.

BIBLIOGRAPHY