Cranionavigator Combining a High-speed Drill and a Navigation System for Skull Base Surgery
—Technical Note—

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Abstract
Drilling of the skull base bone without damaging the important inside structures and with the correct orientation is very difficult even with the help of the anatomical landmarks. Monitoring of the location and direction of the drill tip and indications of the removed part of the bone during the drilling procedure enhances safety and achieves less invasive neurosurgery. We have developed a novel cranionavigator by combining a high-speed drill with a neurosurgical navigation system. To reduce the positional error to less than 1.5 mm, the position sensor (magnetic field sensor) must be attached 5 cm from the metallic fan portion of the drill and the sensor kept at least 10 cm away from the operating microscope. Simulation studies with the cranionavigator using two dried skulls and three cadaver heads were performed before clinical application. Clinically, this surgical instrument was used in four patients with the skull base tumor. The cranionavigator helped to safely drill the skull base bone in a shorter time by dynamic and real-time display of the precise operating site and extent of bone drilling on the preoperative computed tomography scans or magnetic resonance images. The cranionavigator is a very helpful instrument for skull base surgery in the hands of neurosurgeons with extensive expertise and anatomical knowledge.

Key words: navigation, high-speed drill, skull base surgery

Introduction
Frameless, stereotactic techniques have become more common and are now widely used in neurosurgery and ear, nose, and throat surgery. The combination of surgical tools and the neurosurgical navigation system may enable neurosurgeons to achieve easy and safe access to deep-seated lesions. Various types of neurological navigation systems are available. The multi-joint arm-guided system is simple and reliable, but may restrict the surgical field and the surgical procedure. The acoustic detection system and the optical sensor system are very accurate, but spatial tracking can be interrupted when the light or sound path is blocked by the surgeon or surgical instrumentation in a crowded or deep surgical field, so continuous monitoring of surgical instruments is difficult. Thus, these systems are more suitable for tracking a microscope, endoscope, or pointing needle rather than a drill or suction tube in the center of the surgical field. The computer-assisted neurosurgical navigation system (CANS Navigator) using the magnetic field modulation system allows real-time monitoring of surgical manipulation even in the crowded and deep surgical field of skull base surgery. However, the detection system is disturbed by metallic instruments, particularly those made of iron. The CANS Navigator available in the market uses only a suction tube on which the magnetic field sensor is attached. The real-time monitor shows the surgical track, as the accumulation of the tip positions of the suction tube, and indicates the extent of the surgical manipulation. Attachment of the sensor to the drill instead of the suction tool would allow precise and safe bone drilling with real-time monitoring of the tip position and the removed bone in the skull base surgery, in which there is no intraoperative positional change of the skull base target. Here, we describe a modifi-

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cation to the CANS Navigator for use with the high-speed drill, here named the cranionavigator.

**Technique**

The three-dimensional digitizer in the CANS Navigator (Shimadzu, Kyoto) is susceptible to interference by metal conductors because of the induced magnetic fields. The influence of the metallic drill on the positional accuracy in the CANS Navigator was studied to determine the best position for attachment of the sensor. The drill (Midas Rex, Fort Worth, Tex., U.S.A.) was positioned at various locations between the fixed magnetic source and sensor to assess the effect on the measured coordinates of the sensor (Fig. 1). The drill portion of the Midas Rex contains a metallic fan, which may affect the magnetic field of the navigation system. Positioning of this fan portion between the fixed magnetic source and sensor, especially in contact with the sensor, caused the maximum change in the measured coordinates of the sensor. However, this change was less than 1.5 mm when the fan portion was located more than 5 cm apart from the sensor (Fig. 1). Based on these results, the sensor was attached to the drill 5 cm from the fan (Fig. 2).

Simulation studies using two dried skulls and three cadaver heads were performed before surgical application. Four fiducial markers (colored pencil lead tip) were located on the dried skull surface or cadaver scalp at the midline parietal vertex, mastoid tip, nasion, and occiput, and then computed tomography (CT) scans were taken. The image data were transferred to the navigation system via an image scanner and stored in the computer. The dried skull or cadaver head was fixed with a Mayfield skull clamp made of carbon fiber resin to which the magnetic field source is attached. Immediately

![Fig. 1](image-url)  
**Fig. 1** Effect of the metallic high-speed drill on positional accuracy in the computer-assisted neurosurgical navigation system (CANS Navigator; Shimadzu Co., Kyoto). The distance (d) error between the fixed magnetic source (A) and sensor (B) was minimum when the metallic fan portion (asterisk) of the drill, which affected the magnetic field, was more than 5 cm from the magnetic sensor (upper and lower). —: no placement of the drill between the source and sensor.
before surgery, the position of the dried skull or cadaver head was calibrated by pointing to each fiducial marker in sequence with the calibration probe. Posterior retrolabyrinthine petrosectomy was then carried out under guidance from the combined CANS Navigator and high-speed drill. During the surgical procedure, the discrepancy between the real target position and the position on the CT scans was estimated for evaluation of the system accuracy (Fig. 3).

The mastoid antrum, even when poorly pneumatized, could be confidently opened to expose the inside solid angle without damage to the labyrinth by drilling under cranionavigator guidance. The position and direction of the drill tip could be monitored in real-time during the drilling procedure. The positions of the tip of the drill were recorded in memory and accumulated to form the “surgical track,” shown as red dots on the CT scans. Thus, the removed part of the petrous bone was displayed as the accumulation of red dots on the CT scans (Fig. 3). The positional discrepancy between the real targets and the CT scans was correlated with the distance between the magnetic source attached to the Mayfield head clamp and the sensor mounted on the drill. However, the error was within 1.5 mm regardless of the depth as long as the cranionavigator was used in the operative field, and could be minimized to less than 1.5 mm by keeping the magnetic sensor more than 10 cm from the objective lens of the surgical microscope when using the drill. Other metallic surgical instruments such as the bipolar coagulator, suction tubes, spatulas, or retractor did not interfere with the accuracy of the CANS Navigator.

Representative Cases

Clinically, the cranionavigator was used in the treatment of four patients with skull base tumor (2 petroclival meningiomas, 1 trigeminal schwannoma, and 1 frontal base lymphoepithelioma) using the Dolenc,5) petrosal,1) transpetrosal,10) and basal frontal approaches13) (Table 1). Preoperatively, CT (bone window level) was performed after fixing small radiopaque markers to the four fiduciary points on the patient’s head, and magnetic resonance (MR) imaging was performed after fixing spherical capsules filled with enhancement material to the same points. In the operating room, the patient’s head was fixed with the Mayfield skull clamp made of carbon fiber to which the magnetic field source was attached and positional calibration carried out as before.
Case 1: MR imaging revealed a huge petroclival meningioma (Fig. 4 left). Staged operations were planned for removal of the tumor. In the first surgery, the anterior part of the tumor was removed through the combined Dolenc\textsuperscript{5} and Kawase approaches\textsuperscript{10}. The cranionavigator was very helpful for drilling the pathologically thickened sphenoidal ridge and temporal basal bone, and correctly identifying the location of the optic canal, the petrosal segment (C\textsubscript{5}) of the internal carotid artery, and trigeminal nerve (Fig. 5). Removal of the anterior clinoid process, temporal fossa, petrous apex, and upper portion of the clivus were confidently accomplished with the cranionavigator by monitoring the location and direction of the drill tip. In the second surgery, the retrolabyrinthine transpetrosal approach was employed for removal of the residual posterior part of the tumor. The mastoid process and petrosal bone were safely and easily removed under guidance from an interactive surgical navigation system, with real-time identification of the location of the semicircular canals and fallopian canal. Posterior petrosectomy successfully exposed the solid angle with the preservation of hearing and facial nerve function by keeping the inside labyrinth structures intact (Fig. 6), and the residual tumor was subtotally removed except for the intracavernous portion (Fig. 4 right).

Case 2: Neuroimaging showed frontal extension of lymphoepithelioma. The basal frontal approach\textsuperscript{13} was employed to remove the huge recurrent tumor extending into the frontal lobe from the nasal cavity through the frontal skull base and bordering laterally on the left optic canal. The cranionavigator was used to find and protect the left optic nerve, and to avoid the risk of disorientation in the nasal cavity. The cranionavigator was useful to optimize craniotomy design and enabled verification of the location of the drill tip in real-time on both the CT scans and MR images during the drilling procedure. Before resecting the skull base tumor and after drilling the anterior skull base, the magnetic sensor was attached to the suction tube. The extension of both bony drilling and tumor removal was displayed during the operation as shown by the surgical track (Fig. 7).

**Table 1.** Clinical summary of four cases of skull base surgery using the cranionavigator

<table>
<thead>
<tr>
<th>Case No.</th>
<th>Age/ Sex</th>
<th>Tumor</th>
<th>Surgical approach</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>48/F</td>
<td>petroclival meningioma</td>
<td>Dolenc approach + transpetrosal approach (1st surgery), petrosal approach (2nd surgery)</td>
</tr>
<tr>
<td>2</td>
<td>68/M</td>
<td>lymphoepithelioma (frontal base)</td>
<td>basal frontal approach</td>
</tr>
<tr>
<td>3</td>
<td>52/F</td>
<td>petroclival meningioma</td>
<td>petrosal approach</td>
</tr>
<tr>
<td>4</td>
<td>27/M</td>
<td>trigeminal schwannoma</td>
<td>transpetrosal approach</td>
</tr>
</tbody>
</table>

**Fig. 4** Case 1. Preoperative magnetic resonance (MR) image showing a huge petroclival meningioma (left), and postoperative MR image showing subtotal removal of tumor except for the intracavernous part (right).

**Case 1:** MR imaging revealed a huge petroclival meningioma (Fig. 4 left). Staged operations were planned for removal of the tumor. In the first surgery, the anterior part of the tumor was removed through the combined Dolenc\textsuperscript{5} and Kawase approaches\textsuperscript{10}. The cranionavigator was very helpful for drilling the pathologically thickened sphenoidal ridge and temporal basal bone, and correctly identifying the location of the optic canal, the petrosal segment (C\textsubscript{5}) of the internal carotid artery, and trigeminal nerve (Fig. 5). Removal of the anterior clinoid process, temporal fossa, petrous apex, and upper portion of the clivus were confidently accomplished with the cranionavigator by monitoring the location and direction of the drill tip. In the second surgery, the retrolabyrinthine transpetrosal approach was employed for removal of the residual posterior part of the tumor. The mastoid process and petrosal bone were safely and easily removed under guidance from an interactive surgical navigation system, with real-time identification of the location of the semicircular canals and fallopian canal.

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Fig. 5 Case 1. Navigational displays during drilling of the anterior clinoid process (left), the petrous apex (center), and the temporal base (right).

Fig. 6 Case 1. Postoperative computed tomography scans (bone-window level) showing the anterior clinoid process, temporal base, petrous bone and apex, and upper portion of the clivus could be removed without nerve or vascular damage under the guidance by the cranionavigator.

Fig. 7 Case 2. Intraoperative navigational displays during the frontal base drilling and tumor removal. Both computed tomography (CT) scans and magnetic resonance (MR) images were used. left: axial CT scan, center: coronal MR image, right: sagittal MR image.
neural and vascular trauma by guidance in the close vicinity of delicate structures at the skull base. The cranionavigator is helpful to make a minimal and precise craniotomy and to prevent inadvertent injury of the vital and delicate anatomical structures in the petrous bone during the drilling procedures of the skull base surgery. Attachment of the sensor to the various surgical tools allowed us to safely and confidently monitor surgical procedures in the pathological structures even when the normal anatomy was lost.

The surgeon’s impression of the present four cases with skull base tumor indicated that the cranionavigator was very useful for performing the operations strictly as planned preoperatively and for selecting the surgical route that avoids important structures. In Case 1, the surgeon had to refer to the cranionavigator to find and identify the carotid artery and trigeminal nerve which were buried in the thickened temporal bone and to accomplish safe unroofing of the optic canal in the 1st operation, and to expose the solid angle with preservation of hearing and facial nerve function by keeping the inside labyrinthine structures intact in the posterior petroectomy. In Case 2, the cranionavigator minimized the risk of optic nerve injury during the drilling the thickened frontal base. In Cases 3 and 4, the tracking of skull base drilling made it easier and safer for the surgeon to preserve the nerve function and to avoid inadvertent vascular injury.

Drilling of the skull base bone may not always be safe even under the guidance of the cranionavigator. The neuronavigation system indicates the relative position of the probe on the preoperative tomographic images, so special attention should be paid to interpreting the probe display when the brain is distorted, cerebrospinal fluid is lost, or a large mass of tumor is being removed. Several methods can resolve this problem, including combining functional monitoring with the electrophysiological stimulator or Doppler flowmeter and visual monitoring with the navigation system or further positional correction by intraoperative CT. However, this problem may not be serious during skull base surgery. This new instrument can be very useful during skull base surgery in the hands of neurosurgeons with extensive experiences and anatomical knowledge.

References


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Commentary

The authors present a new navigation system for skull base surgery. The magnetic sensor is mounted on the hand piece of the drill at 5 cm distance from the tip of the drill. The positional error of localizing the different structure is around 1.5 mm. A series of four patients with skull base tumorous pathologies is presented in whom the cranionavigator was practically used.

In skull base surgery one should be familiar with all the grooves, the canals and different reliefs of the bone structures and at the same time with the course of the vascular and neural structures through the skull base as well as with the pneumatization of the individual skull base bones. Even by knowing all these details in the skull base at the normal bones one may still have difficulties in localizing some of those structures in the skull base, which is infiltrated by tumorous pathologies. By coupling the CT and MR images of the skull base in the intraoperative situation, one may be confronted with much fewer difficulties in avoiding an opening of the pneumatocoele in the anterior clinoid process or penetrating with the drill into the bony sinuses and creating a connection between the endo- and splanchnocranium, in particular in the anterior half of the central skull base. The cranionavigator may be also very useful for avoiding lesion of the ICA in the petrous canal, and the seventh and eighth nerves while drilling the wall of the inner auditory canal from the middle fossa, penetration into the semicircular canal(s) or to the inner ear as well as avoiding damage to the facial nerve in the canal while working in the posterior half of the petrous bone and in the mastoid.

It would be very naive to believe that a surgeon with the help of the any cranionavigator only, but without precise knowledge of the anatomy of the region, and without laboratory practice or without experience in surgery of the skull base, would be able to operate on tumorous and vascular lesions by using the cranionavigator only. The cranionavigator will help those surgeons who are familiar with anatomy and are experienced in dealing with the pathologies at the skull base in such a way that they will be able to advance with the drilling towards critical structures much faster than they were able to do without this tool.

The cranionavigator will facilitate resection of the bone and will bring the surgeon faster to the critical area(s) where the final “rubbing” of the bone will be necessary in order to expose the critical structures. It is now thought that the positional error of the tip of the drill will be less and less in the future, and it is hoped that the cranionavigator will be a very important tool for surgeons dealing with skull base pathologies in order to work under less stress and to shorten the time of surgical procedures without risking damage to an important structure of the region.

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Development of the surgical navigation system is increasing the accuracy of neurosurgical orientation. In the navigation system, real-time monitoring equipped with a surgical tool will be useful, as used in the facial nerve monitoring system combined with micro-dissector. This paper introduced a surgical tool combined with a surgical drill and CANS navigator, using the magnetic field modulation system, and analyzed the correct position of the magnetic sensor with minimum effect of the metallic fan in the drill. This drill system will be useful for resection of the temporal bone, not being shifted by surgical manipulation as seen in the soft tissues. However, the usefulness may depend on the spatial accuracy. Considering the diameter of the facial canal is 1–2 mm, an accuracy of less than 1 mm should be expected. A spatial error of more than 2 mm may be inferior to our microanatomical knowledge.

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This simply designed system combining a high-speed drill and CANS navigator enables precise and safe bone drilling of the skull base in skull base surgery. In the CANS navigator system, a 3-D digitizer utilizes a low-frequency magnetic field to detect the 3-D coordinates, so the influence of metal conductors on induced magnetic field was one of the serious problems. The authors studied the influence of the metallic drill on the positional accuracy to determine the best position for attachment of the sensor. They carried out simulation studies using two dried skulls and three cadaver heads before clinical application. The optimal distance between the drill and the sensor was fixed to minimize the positional error, which could allow this system to be helpful in the management of skull base lesions. Furthermore, this system could be used without limiting the operative field or interfering with the surgical procedure. In usual intracranial navigation surgery, positional inaccuracy due to brain shift or distortion is one of the difficult problems. Neurosurgical navigation is a more useful adjunct in the operative management of patients with...
skull base lesions, because skull base bony structures are little displaced or distorted. Though skull base bony structures are quite complicated in anatomical detail, including important organs, nerves or vessels, this system is helpful to make a precise and safe bone drilling of the skull base without inadvertent injury of those important neural or vascular structures. However, as authors mentioned, it may not always be safe even under guidance of this system. This system becomes quite useful in the hands of skilled neurosurgeons with extensive experience and anatomical knowledge. Because the sensor was attached to the drill itself, I am anxious about positional change of the sensor or mechanical damage of the instrument due to drill vibration. This system was only used in 4 clinical cases with skull base tumor. Further clinical use of this system is required to prove it to be truly safe and useful in skull base surgery.

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Traditionally, the skull base surgeon uses standard landmarks, bony and soft tissues, to operate in this region. In most instances this method is sufficient to achieve one's goals. However, in certain situations where the anatomy may be so distorted, the navigational tools will be very helpful. Perhaps this is most useful in cases where the surgeon knows beforehand that a total tumor resection may not be possible. In such cases using the frameless navigational unit, an aggressive debulking may be performed, meeting the precise goals of the surgeon. In the normal situation the surgeon could only guess as to how much tumor removal has been achieved unless an intraoperative MRI or CT scan could be performed. The frameless unit provides real-time information, eliminating the guesswork. The frameless unit can also be a valuable teaching tool for a less experienced surgeon. However, we have all experienced failure of equipment during an operation. The surgeon must be thoroughly knowledgeable of the normal and distorted anatomy and familiar with the traditional methods to be prepared for such events. It must be always remembered that this is only an ancillary tool and not indispensable so that one gets dependent on it.

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