Real-Time Navigation-Guided Drilling Technique for Skull Base Surgery in the Middle and Posterior Fossae

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J Neurol Surg B 2018;79(suppl S4):S334–S339.

Abstract

Objective The usefulness of the bony surface registration method for navigation system image-guided surgery in the lateral or prone position has been reported. This study was performed to evaluate the efficacy of our new real-time navigation-guided drilling technique with bony surface registration for skull base surgery in the middle and posterior fossae.

Methods The study included 29 surgeries for skull base tumors that required drilling of the petrous bone between January 2015 and December 2017 in Shinshu University Hospital. A navigation system was used for drilling of the petrous bone as follows: (1) some labyrinthine structures were marked by color in the source image and superimposed on the navigation image on the workstation preoperatively; (2) bony surface registration was performed with a three-dimensional (3D) skull reconstruction model in the operating room; (3) the petrous bone was drilled under navigation guidance with real-time view-through confirmation of 3D color-marked labyrinthine structures with observation under a microscopic operative view.

Results Real-time identification of some structures in the petrous bone was performed, and adequate and precise drilling of the petrous bone was achieved without the risk of labyrinthine perforation or stress. Using this method, surgeons do not need to alternate their gaze between the surgical field and the navigation screen.

Conclusions Due to the development of bony surface registration, this new technique is useful for drilling petrous bone in the middle and posterior fossa skull base surgeries.

Keywords

- navigation system
- image-guided neurosurgery
- bony surface registration
- skull base surgery
- petrous bone

Introduction

Navigation technology has been widely used in neurosurgery and functions as the core of multimodal three-dimensional (3D) databases. It is an essential technology for skull base surgery in which the operative field is deep and narrow, and has several critical structures, including vessels, and nerves.^{1–4} Facial surface matching registration is difficult in the middle or posterior fossa skull base surgery with the

patient in the lateral or prone position because of the direction of the face, skin shifting, and adhesive facial monitoring tape. This represents a very serious problem because accurate registration is essential for precise navigation.^{2,3} Therefore, navigation systems are not commonly applied in the middle or posterior fossa skull base surgery with the patient in the lateral or prone position.^{1,3} To resolve this problem and facilitate application of navigation systems to skull base surgery in the lateral or prone position, we

received

January 21, 2018

accepted after revision

June 6, 2018

published online

July 17, 2018

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Stuttgart · New York

DOI <https://doi.org/10.1055/s-0038-1667044>.
ISSN 2193-6331.

developed a new bony surface registration method that enables highly precise navigation in the middle and posterior fossa skull base surgery.³

Drilling of the petrous bone in the middle and posterior fossa skull base surgery, for example, in the lateral suboccipital approach or transpetrosal approach, is one of the most important procedures for success in these surgeries. However, no standardized intraoperative techniques have been developed to protect the labyrinth.⁵ Imaging guidance may be useful for drilling of bony structures in skull base surgery because accurate navigation is possible without intraoperative brain shift. On the other hand, use of a navigation system for drilling in skull base surgery makes it necessary for the surgeon to alternate their gaze between the surgical field and the navigation screen. This motion is stressful and problematic for the surgeon. In this study, we developed and assessed the efficacy of a simple new technique based on navigation-guided drilling with bony surface registration for the middle and posterior fossa skull base surgery.

Materials and Methods

Real-Time Navigation-Guided Drilling Technique for Petrosectomy

The navigation system used in this study was the Curve Dual Display (Brainlab, Munich, Germany), which is a commonly used optimal navigation system and consists of an infrared camera, navigation probe, reference array, and software. Image-guided surgery with the navigation system is generally divided into four steps: patient imaging, input patient data, registration, and navigation. All procedures are important for accurate navigation. In particular, when drilling

petrous bone in the middle or posterior fossa skull base surgery, we use the navigation system in planning, bony surface registration, and navigation-guided drilling.

Planning: preoperative computed tomography (CT) scans (the LightSpeed VCT Vision 64-column CT scanner with thin-cut imaging, 0.63 mm, GE Healthcare, Little Chalfont, England) and magnetic resonance (MR) images (MAGNETOM Avanto 1.5-T or Trio 3-T MRI unit, Siemens Healthcare, Erlangen, Germany) of the entire face and head were used in the navigation system. The patient's digital imaging and communications in medicine data of these neuroimages were registered on a workstation, and some anatomical landmarks in the petrous bone, including the trigeminal nerve, internal carotid artery (ICA), cochlea, internal auditory canal (IAC), vestibule, and semicircular canal, were colored and highlighted. A 3D model was made on a workstation and transferred to the navigation system preoperatively (►Fig. 1a).

Bony surface registration: in the operation room, after induction of general anesthesia, the patient was placed in the lateral position, and the head was fixed using a head fixation system with a reference array. The software allows us to adjust the threshold to define a specific bone-density value (150 HU). Accordingly, a 3-D skull reconstruction image can be obtained. After skin flapping and before craniotomy, a surface matching point was recognized using an infrared camera with a pivoting method. Multiple surface matching points were distributed all over the exposed skull as triggers for converting the 3D shape, and bony surface registration was completed by exposing the skull surface in a sterile environment (►Fig. 1b).³ After the completion of surface matching, registration enables the Cranial 2.1

Fig. 1 (a) Some anatomical landmarks in the petrous bone, including the internal carotid artery (red), semicircular canal (yellow), greater superficial petrosal nerve (green), mastoid air cell (light green), petrosal vein (purple), jugular vein (blue), and tumor (brown), were colored and highlighted in a three-dimensional (3D) model made on a workstation. (b) After skin incision and exposure of the skull, surface matching on the entire exposed skull, “bony surface registration,” was performed using a pivoting method before craniotomy. (c) Intraoperative photographs showing the view of the 3D color image of labyrinthine structures, which was superimposed onto the actual microscopic operative view using the present view-through system.

software to map the patient's preoperative imaging with the data obtained from the real-time anatomy of the patient's head and to verify the navigation accuracy.

Real-time navigation-guided drilling technique: due to preoperative planning and bony surface registration, real-time identification of some structures in the petrosal bone can be performed under direct vision. The 3D color image of the labyrinthine structures was superimposed onto the actual microscopic operative view using the present view-through system, and drilling of the petrosal bone was performed under real-time navigation guidance with confirmation of color-marked labyrinthine structures while viewing the microscopic operative field (►Fig. 1c).

Clinical Experiment

From January 2015 to December 2017, the real-time navigation-guided drilling technique was used for drilling the petrosal bone in 29 patients at Shinshu University Hospital. The patients ranged in age from 17 to 77 years (mean: 48.9 years), and 14 were women. The lateral position was applied in all patients. The histological diagnoses included schwannoma ($n = 23$), meningioma ($n = 3$), cavernous angioma ($n = 2$), and mature teratoma ($n = 1$). Details of the patients' demographic characteristics are presented in ►Table 1.

Results

Bony surface registration provided highly precise navigation in skull base surgeries even with the patient in the lateral position. A new real-time navigation-guided drilling technique that we have developed enabled surgeons to see labyrinthine structures beyond tissue barriers in real time in the

microscopic operative field using a navigation system, and adequate and precise drilling of the petrous bone was achieved without any complications related to this method in all cases. There was no evidence of labyrinthine injury in any of the patients, and surgeons did not need to alternate their gaze between the surgical field and the navigation screen.

Illustrative Case

A 53-year-old man presented with gait disturbance and cognitive dysfunction due to hydrocephalus, and right hearing disturbance. MR images revealed a right huge cerebellopontine angle tumor (►Fig. 2a, b), and tumor resection was planned through the lateral suboccipital approach with continuous neurophysiological monitoring, including auditory brainstem response and facial motor evoked potential.

First, we performed preoperative neuroimaging of the patient using a workstation, and landmarks in the petrosal bone, including ICA, semicircular canal, common crus, jugular vein, and tumor, were colored and highlighted after obtaining head MR images that included the whole face. A 3D model of his head was made on a workstation and transferred to the navigation system (►Fig. 3a). Intraoperatively, the patient was placed in the lateral position under general anesthesia. After exposing the skull surface, bony surface registration was performed with surface matching with exposed occipital bone.³ The posterior lip of the petrous bone was drilled out with a high-speed drill under a real-time navigation guidance in the microscopic operative view to identify the nerves following resection of the tumor at the cisternal portion (►Fig. 3b). Due to preoperative planning and bony surface registration, real-time identification of some structures in the petrosal bone was completed without any trouble. The patient tolerated the procedure well. He woke up immediately after surgery without new neurologic deficits. An adequate drilled area of the posterior lip of the petrous bone was confirmed on postoperative bone CT (►Fig. 4b, c). Postoperative MR images revealed subtotal resection of the tumor, and the ventricle was reduced in size (►Fig. 4a). Gait disturbance and dementia improved significantly, but right hearing disturbance remained. No new neurologic deficits appeared after the surgery. Histopathological diagnosis of the resected lesion was vestibular schwannoma.

Discussion

This new technique helps the surgeon to perform precise drilling of the petrosal bone without any stress according to our preliminary results.

Image Guidance for Skull Base Surgery

Sufficient anatomical knowledge and a high level of surgical skill are necessary for successful skull base surgery, which is technically demanding, and the outcome of surgery has a great impact on the patient's quality of life.² Navigation methods that can improve the surgeon's intraoperative orientation and situational awareness provide an additional

Table 1 Master table showing details of the patients included in the study

	Cases, n
Diagnosis	
Schwannoma	23
Meningioma	3
Cavernous angioma	2
Mature teratoma	1
Position	
Lateral	29
Tumor location	
Cerebellopontine angle	22
Petroclivus	2
Middle fossa	3
Brainstem	2
Operative approach	
Lateral suboccipital approach	22
Anterior petrosal approach	7

Fig. 2 Preoperative images. (a, c) T1-weighted images with gadolinium enhancement and (b) heavy T2-weighted images showing a cerebellopontine angle tumor with brainstem compression. (d) Bone CT (computed tomography) image indicated that the internal auditory canal was eroded due to the tumor.

layer of safety and accuracy in resection of skull base lesions.⁴ Furthermore, use of a navigation system reduces stress on the surgeon during the operation, although skull base surgery, including the endoscopic endonasal approach, has a heavy mental workload even for experienced surgeons.⁶ Bir et al reported that interactive surgical navigation is useful in the operative management of skull base meningiomas to decrease recurrence rate, blood loss, and length of hospital stay, and to improve recurrence-free survival and performance status.⁷

Skull base surgery is divided into three types of procedure: anterior, middle, and posterior fossa skull base surgeries. Navigation systems have been shown to improve the accuracy of surgery on the anterior skull base.² These systems help in locating the frontal sinus during bone opening and are useful to avoid injury to the optic nerves, ICA, and anterior cerebral and middle cerebral arteries.⁷ In addition to endoscopic endonasal skull base surgery, additional information provided by the navigation system is crucial for the success of surgery.⁶ In addition, accurate navigation is possible as it is easy to complete precise registration with surface matching using the patient's face for anterior skull base surgery in the supine position. Thus, navigation has been shown to be a useful adjunct for neurosurgeons to localize supratentorial anterior skull base pathologies, and it

Fig. 3 (a) Planning of navigation on a workstation was performed preoperatively, and a three-dimensional model of the head, including the labyrinthine structures, was made. (b) The posterior lip of the petrous bone was drilled out with a high-speed drill under a real-time navigation guidance in the microscopic operative view.

Fig. 4 Postoperative images. (a) T1-weighted image with gadolinium enhancement showing gross total resection of the tumor. (b, c) Bone CT (computed tomography) images indicating adequate drilling out of the posterior lip of the internal auditory canal.

has become a standard technology used worldwide in anterior skull base surgery.¹ For middle and posterior fossa skull base surgery, navigation also helps to locate the major arteries and nerves during surgical procedures. Cranial nerves are unlikely to be identified using existing imaging techniques, but bony structures associated with their courses can be identified and explored carefully using a navigation system.⁷ However, navigation techniques are not commonly used for surgery in the middle and posterior fossae, and little is known about their possible applications.¹ One reason for this is that accuracy is not ensured. Although precise registration of CT and MR images is crucial for precise navigation in surgical interventions, registration is sometimes incomplete in patients in the lateral or prone position due to the direction of the face, skin shift, and adhesive facial monitoring tape.² Even if the occipital scalp is used for surface matching, this does not reduce registration error because there are few surface landmarks in the flat occipital scalp. Furthermore, its shape is distorted in the supine position during preoperative neuroimaging due to the pressure transferred from the pillow. We previously reported that bony surface registration resolved this problem.³ This method may be useful in a navigation system image-guided surgery even with the patient in the lateral or prone position. Another reason is that the necessity of the navigation system is questionable because the presence of several landmarks, including the cochlear line and digastric point, has been reported.⁵ Anterior petrosectomy can be performed more efficiently using the cochlear line as a key landmark to preserve the cochlea.⁵ Understanding the exact morphology of the temporal bone increases the success of maximal removal of the posterior wall of the IAC while minimizing morbidity secondary to violation of the bony labyrinth.⁸ However, the high degree of interindividual variation in the relationships between surface structures and internal anatomy is a matter of some concern. Therefore, use of a navigation system in the middle and posterior fossa skull base surgery would be beneficial. Navigation should be considered as a useful tool not only for anterior skull base surgery but also for operations in the middle and posterior cranial fossae.

Drilling Technique in Skull Base Surgery

Adequate drilling of the petrous bone is essential for the success of middle and posterior fossa skull base surgery, such as that through the lateral suboccipital approach for vestibular schwannoma and the anterior petrosal approach for brainstem lesions. For example, the integrity of the labyrinthine structures, including the posterior semicircular canal or common crus, is a major determinant of the success or failure of hearing preservation when drilling the posterior wall of the IAC through the retrosigmoid approach.⁹ In other words, drilling of the petrous bone during skull base surgery puts the integrity of the labyrinthine structures at a risk due to their anatomical variability and the absence of intraoperative landmarks to indicate their precise location in the petrous bone.⁹

Several techniques have been reported for drilling of bone at the skull base. A technique based on making meticulous

measurements on preoperative high-resolution CT scan is useful for drilling of the petrous bone.⁹ In a cadaver-based study, Pillai et al also used frameless navigation using high-resolution CT and bone-implanted reference markers as a roadmap for safe drilling the posterior wall of the IAC.¹⁰ The difference in bone density between the petrous bone and the cochlea can also aid in determining the location of the cochlea. However, there are no reliable anatomical landmarks for intraoperative guidance of drilling even if meticulous measurements are taken.⁹ Surgeons may face an unexpected difficulty in applying these concepts in the surgical field during actual operations.⁵

Navigation was thought to be helpful in the middle and posterior fossa skull base surgery to achieve precise drilling of the petrous bone and to increase the safety of these approaches.^{1,11} Moreover, the development of the bony surface registration technique allowed navigation with the patient in the lateral or prone position. However, using a navigation system, surgeons are required to rotate the dimension of the monitor to match the microscopic surgical field because the positional information is indicated on the navigation monitor. This is an issue that cannot be ignored.

The main advantage of this technique is that it achieves volumetric navigation in contrast to the conventional point-to-point navigation. It is highly intuitive and does not require the surgeon to visualize the 3D orientation of MR and CT images in one's mind. The image with petrosectomy is superimposed onto the actual microscopic surgical view using the present view-through system, thus helping the surgeon to perform accurate petrosectomy.¹² It extends augmented reality images directly onto the real surgical images, thus helping the surgeon to integrate these two dimensions intuitively. Visualization is therefore performed on the microscopic view as the petrous bone was translucent, and the internal structures can be seen through the bone. Being able to see beyond tissue barriers with the navigation system provided additional safety for the patient, with accurate localization of the labyrinthine structures in the petrous bone in real time. Use of this technique, including making a 3D model, would also be a useful preoperative and intraoperative simulation in surgical management of the middle and posterior fossa skull base lesions.⁷

Watanabe et al also developed a similar augmented reality-based navigation system with whole-operation-room tracking and emphasized its usefulness in neurosurgery.¹² The advantage of this system over conventional systems is that it enables volumetric view-through navigation with minimal blind spots.

Limitations

One of the limitations of this study is that evaluation of the usefulness of this technique is still subjective and dependent on the experience of the surgeon. Randomized control trials are required to compare the true effectiveness of this technique with other methods. Another limitation is that it is time-consuming to make the 3D model. Planning in this method took approximately 2 hours. In addition, the

projected 3D model in the operative field may disturb the actual petrous bone surface, and surgeons may find it problematic.

Conclusions

Real-time navigation-guided drilling technique with bony surface registration is useful for skull base surgery in the middle and posterior fossae. This is a simple technique based on preoperative planning and intraoperative diligence of the neurosurgeon in drilling within the parameters decided preoperatively. This study indicated that the use of the navigation system allowed effective surgical planning, better visualization of tumors and adjacent anatomical structures, and enhancement of surgical confidence.

Disclosures

The authors have no personal financial or institutional interests in any of the drugs, materials, or devices discussed in the article. All authors, who are members of The Japan Neurosurgical Society (JNS), have registered online Self-reported COI Disclosure Statement Forms through the Web site for JNS members.

Patient Consent

The patient and next of kin/guardian consented to the submission of this original article to the journal.

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