Prediction of the Microsurgical Window for Skull-Base Tumors by Advanced Three-Dimensional Multi-fusion Volumetric Imaging

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Abstract

The surgery of skull base tumors (SBTs) is difficult due to the complex and narrow surgical window that is restricted by the cranium and important structures. The utility of three-dimensional multi-fusion volumetric imaging (3-D MFVI) for visualizing the predicted window for SBTs was evaluated. Presurgical simulation using 3-D MFVI was performed in 32 patients with SBTs. Imaging data were collected from computed tomography, magnetic resonance imaging, and digital subtraction angiography. Skull data was processed to imitate actual bone resection and integrated with various structures extracted from appropriate imaging modalities by image-analyzing software. The simulated views were compared with the views obtained during surgery. All craniotomies and bone resections except opening of the acoustic canal in 2 patients were performed as simulated. The simulated window allowed observation of the expected microsurgical anatomies including tumors, vasculatures, and cranial nerves, through the predicted operative window. We could not achieve the planned tumor removal in only 3 patients. 3-D MFVI afforded high quality images of the relevant microsurgical anatomies during the surgery of SBTs. The intraoperative déjà-vu effect of the simulation increased the confidence of the surgeon in the planned surgical procedures.

Key words: neurosurgery, presurgical simulation, skull base tumor, surgical anatomy, three-dimensional imaging

Introduction

Surgical removal of tumors located in the skull base, i.e., skull base tumors (SBTs), is complicated due to the obstruction of the surgical window by the cranial base, brain bottom, cranial nerves (CNs), and various important vessels. Therefore, understanding the spatial location of the anatomical structures surrounding SBTs is essential to obtain adequate tumor removal and avoid surgical complications. Three-dimensional (3-D) image-rendering techniques are now being used to obtain 3-D information of anatomical structures from the data of various imaging methods such as computed tomography (CT), magnetic resonance (MR) imaging, and digital subtraction angiography (DSA). These techniques in the neurosurgical field have improved the precision and safety standards of surgical procedures.

We have applied a 3-D multi-fusion volumetric imaging (MFVI) technique for the preoperative examination of patients with SBTs, which includes “volume rendering” and “image fusion” of various components such as tumor and CNs from MR imaging data, bony structures from CT data, and vessels from DSA data.

We present a comparison of the simulated craniotomy and bone resection using 3-D MFVI data and the microsurgical view from the simulated surgical window for individual patients obtained using the innovative imaging method and the actual surgical findings.

Patients and Methods

Presurgical simulation using 3-D MFVI was performed for 32 patients with SBTs, 13 males and 19 females aged between 19 and 71 years, between July
Fig. 1 Operating window of the software (Real INTAGE; Cybernet Systems Co., Ltd.) used to create, process, and review the three-dimensional multi-fusion volumetric imaging data.

Fig. 2 Representative process of preoperative simulation using three-dimensional multi-fusion volumetric imaging (3-D MFVI) for a right trigeminal neurinoma. A: Constructive interference in steady state magnetic resonance image showing a small round tumor within the right trigeminal nerve (CN-V) in the cistern (arrowhead). B: 3-D MFVI confirming the exact 3-D location. C: Planned temporal craniotomy and anterior petrosectomy were designed on the skull volume image (water blue). D–F: 3-D MFVI (D) showing removal of the temporal lobe after temporal craniotomy, with magnified view (E) including the tentorium (tent) and temporal base and predicted operative view (F). The predicted and actual surgical images were compatible in approaching to the tentorium and the area of the anterior petrosectomy (water-blue dotted line). G–I: After cutting the tentorium up to the free edge, the entire tumor and CN-V were exposed on the 3-D MFVI (G), and confirmed during the actual surgical approach (H). After total removal of the tumor, the location of the superior cerebellar artery (SCA) was also confirmed to be similar (G, I).

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extracted as volume data from the selected imaging data: for instance, tumor components from 3-D CT, MR-CISS, or MR-SPGR data; the skull from CT data; the brain and CNs from MR-CISS data; and vasculatures from MRA, CTA, and 3-D DSA data. This procedure was mainly performed by automatic data extraction of continuous voxels exhibiting similar intensity or density after adjusting for the window width and levels. Additional manual alignment was sometimes required for structure with partially unclear margin. Finally, all structural volumes were integrated onto the same space as the 3-D MFVI data.

To determine the best surgical route for approaching the tumor and to simulate the microsurgical view through the predicted operative window, a skull volume model of the actual craniotomy and bone drilling was made and 3-D MFVI data obtained (Fig. 2). This procedure was performed for 3-D skull data using a cutting tool from the software. The cutting area was determined by subtracting the simulated data from the original skull data. Sometimes, several different approaches were simulated in the same case. Using this technique, we planned the surgical route for tumor removal and predicted the resectable parts and the amount of residual tumor.

To evaluate the efficacy of simulation-guided bone resection, the results obtained from simulated 3-D MFVI and the 3-D skull data of postoperative CT were compared. Further, the tumor removal rates were evaluated from postoperative imaging findings.

### Results

Presurgical simulation of SBTs, location and pathology, and the surgical approach, modalities for 3-D MFVI creation, and the surgical findings are summarized in Table 1. One patient had double tumors of acoustic neurinoma and petroclival meningioma on the same side; both tumors were treated in one-

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stage operation. To create 3-D MFVI data, MR imaging and CT data were used in all patients. DSA data were used in patients in whom fine and detailed vascular information was required, and CTA or MRA data were used in other patients. We selected the appropriate surgical approach on the basis of various clinical factors and 3-D MFVI simulation results. Different patterns of craniotomy and bone resection were designed for each patient. The 3-D MFVI data required about 2–3 hours to create the skull data and simulate the bone resection for each patient.

Actual craniotomy and bone resection were accomplished based on the simulation results in all patients, except for the patient with 2 acoustic neurinomas for which the planned procedure to open the internal auditory canal (IAC) was not performed according to the intraoperative findings. For meningiomas and neurinomas requiring temporal bone resection, the extent of tumor resection by the transpetrosal or trans- or infralabyrinthine approach was planned on the basis of 3-D MFVI simulation, and the outcome was compatible with results of postoperative CT. For most neurinomas, intracanalicular tumors were exposed by evaluating the precise extent and projection of bone drilling based on the 3-D MFVI simulation results. During retrosigmoid craniotomy for acoustic neurinomas,
the position and shape of the jugular bulb were confirmed based on the 3-D MFVI simulation results, so ensuring safe and precise drilling of the posterior wall of the IAC (Fig. 3). For chordomas, extradural surgical corridors through the infratemporal route were predicted by 3-D MFVI simulation, and virtual endoscopy via endonasal route enabled examination of the tumor beyond the bony wall and determination of the exact locations of the distorted carotid arteries.

The tumor removal rate varied greatly from partial to total. Subtotal tumor removal (95%, 90%) was achieved in 13 patients, and partial tumor removal (90%) in 5 patients. However, the position of residual tumors agreed with the presurgical predictions in all but 3 patients in whom the tumor presented with extraordinary bleeding or unpredicted hard tumor tissues during removal.

Illustrative Case

A patient presented with foramen magnum meningioma manifesting as progressive gait disturbance. Neuroimaging examinations confirmed that the tumor was attached to the dural wall of the left anterior side of the foramen magnum (Fig. 4A, B). We planned to remove the tumor via the left lateral suboccipital route, and simulated the craniotomy with or without partial resection of the condyle and C1 laminectomy to form the optimum surgical window to remove the tumor (Fig. 4C–H). Of course, we considered that the articular condition of the condyle on 3-D MFVI is different from the actual state dislocated with head rotation in the positional setting. We decided to resect the medial part of the condyle, and obtained an extremely similar surgical view to that predicted by 3D-MFVI simulation. Finally, we accomplished the planned tumor removal (Fig. 4I).

Discussion

Simulating the surgical window using 3-D MFVI is a promising technique that can assist neurosurgeons in evaluation of realistic surgical views of the brain before surgery, in turn enabling safe and precise surgical removal of SBTs, which are commonly associated with anatomical complexities and difficulties. Preoperative viewing of the simulation might increase the surgeon’s confidence during operation as the so-called déjà-vu effect, consequently allowing smooth and safe completion of the procedure. Even experienced neurosurgeons tend to revise their surgical strategy after virtual reality simulation. Further, preoperative 3-D MFVI simulation can be used to determine the accessible routes for each individual according to the location and pathologic features of SBTs. We accomplished tumor removal by a procedure planned based on 3-D MFVI results in most patients. Postoperative neurological deficits were prevented in some patients by the partial removal of the tumor, which was planned before the operation, by taking into account the spatial relationships between CNs and the tumor. However, tumor removal was not accomplished to the planned extent in 3 patients due to unpredicted severe bleeding and tumor tissue hardness. Care should be taken to avoid such inevitable intraoperative incidents that cannot be predicted by high-quality anatomic evaluation.

For SBTs such as meningiomas or neurinomas, optimal bone resection must be performed only after thorough understanding of the lesion-bone relationship. Management of the temporal bone is often an important issue in obtaining good exposure of tumors and for removal of tumors with fewer restrictions. After taking into consideration the tumor location, vascular conditions, and hearing function, temporal bone dissection on 3-D MFVI was helpful to decide the area of actual dissection. Surgical removal of most neurinomas involves establishing the access route to the canal or the foramen in the cranial base and the management of the intracanalicular part of the tumors. By simulating craniotomy and bone drilling using 3-D MFVI, we could precisely determine the accessibility of the tumors in the canal or the foramen before surgery. Opening of the IAC through a retrosigmoid craniotomy for acoustic neurinomas should be performed only after understanding the 3-D relationship and the exact distance between the IAC and the jugular bulb, which is difficult to obtain from only 2-D images. Removal of a tumor located in the jugular foramen is associated with the risk of injury to the jugular bulb, which is also the main obstacle. Occipital bone resection to accurately expose the hypoglossal canal is also difficult because of the 3-D complexity of the bony structure. Prediction of the operative window with bone resection around the occipital condyle should take into consideration the difference of the articular conditions between on 3-D MFVI and the actual surgical head position, which is usually rotated to some degree. In patients with tumors invading into the cranial base, such as chordomas or meningiomas, 3-D MFVI simulation enables understanding of the shape of the damaged and dislocated bony walls, and further allows evaluation of the best surgical route that would enable maximum resection by using an appropriate ‘surgical corridor’ made by the tumor extension.
3-D imaging has found applications in various neurosurgical fields.\(^1\) This study showed that high-quality visualization by 3-D MFVI improved the understanding of the 3-D relationships between the tumor, important vessels, brain and CNs, and skull. We employed advanced image-analysis methods such as volume rendering to reconstruct 3-D volumetric data from a sequential 2-D dataset and image fusion to integrate multiple datasets into the same data. We previously reported that high-quality visualization by 3-D MFVI was recently developed and may be applied to future simulation systems. We require an interactive system employing a specific user interface to allow not only visual inspection but also tactile feedback to enable realistic virtual surgery. Some groups have already attempted to establish such simulation systems.\(^2\) We plan to establish the intraoperative use of this innovative technique in combination with the neuronavigation system, enhancing the accuracy of the surgical procedure.

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