Model-based Surgical Planning and Simulation of Cranial Base Surgery

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Abstract

Plastic skull models of seven individual patients were fabricated by stereolithography from three-dimensional data based on computed tomography bone images. Skull models were utilized for neurosurgical planning and simulation in the seven patients with cranial base lesions that were difficult to remove. Surgical approaches and areas of craniotomy were evaluated using the fabricated skull models. In preoperative simulations, hand-made models of the tumors, major vessels and nerves were placed in the skull models. Step-by-step simulation of surgical procedures was performed using actual surgical tools. The advantages of using skull models to plan and simulate cranial base surgery include a better understanding of anatomic relationships, preoperative evaluation of the proposed procedure, increased understanding by the patient and family, and improved educational experiences for residents and other medical staff. The disadvantages of using skull models include the time and cost of making the models. The skull models provide a more realistic tool that is easier to handle than computer-graphic images. Surgical simulation using models facilitates difficult cranial base surgery and may help reduce surgical complications.

Key words: cranial base surgery, simulation, skull model, computed tomography, meningioma

Introduction

Optimal craniotomy or craniectomy for maximal visualization of operative field as well as knowledge of the extent of a lesion and of its relationships with adjacent critical structures is imperative for such complex neurosurgical procedures as cranial base surgery. Progress in computer technology and medical image processing techniques has enabled stereoscopic display of anatomical structures from computed imaging data. Three-dimensional (3D) imaging, which allows image manipulation and surgical simulation on screen, or virtual reality surgical simulators will become an indispensable part of neurosurgical training. It is anticipated, however, that the full development of such facilities will take more than a few years. Another option for preoperative simulation is the use of custom-made plastic models of the patient’s anatomy. We describe our experience with surgical planning and simulation using models in cranial base surgery.

Clinical Materials and Methods

I. Patients

The clinical features of the seven patients are summarized in Table 1. One patient had a jugular foramen chondrosarcoma. Three patients had meningiomas; in the petroclival region, the cavernous sinus, etc.

Table 1 Clinical summary of seven patients with cranial base tumors

<table>
<thead>
<tr>
<th>Case No.</th>
<th>Age/Sex</th>
<th>Lesion</th>
<th>Surgical approach</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>52/M</td>
<td>pteroclival chondroma</td>
<td>anterior transpetrosal</td>
</tr>
<tr>
<td>2</td>
<td>65/M</td>
<td>foramen magnum meningioma</td>
<td>transcondylar and C-1 laminectomy</td>
</tr>
<tr>
<td>3</td>
<td>40/M</td>
<td>jugular foramen chondrosarcoma</td>
<td>lateral suboccipital and infralabyrinthine</td>
</tr>
<tr>
<td>4</td>
<td>44/F</td>
<td>cavernous sinus meningioma</td>
<td>fronto-temporo-orbitozygomatic</td>
</tr>
<tr>
<td>5</td>
<td>57/F</td>
<td>foramen magnum pachymeningitis</td>
<td>lateral suboccipital and C-1 lamiectomy</td>
</tr>
<tr>
<td>6</td>
<td>43/F</td>
<td>pteroclival meningioma</td>
<td>lateral suboccipital</td>
</tr>
<tr>
<td>7</td>
<td>13/F</td>
<td>parasellar chondroma</td>
<td>fronto-temporo-orbitozygomatic</td>
</tr>
</tbody>
</table>
and the foramen magnum, respectively. Two patients had chondromas; one in the parasellar region and the other in the clival region. One patient had pachymeningitis in the foramen magnum region.

II. Model manufacturing

Computed tomography (CT) scans of each patient were obtained at a slice thickness of 2 mm, table shift of 2–3 mm/sec, and image intervals of 1 mm with a TCT-9005 (Toshiba Co., Tokyo). Continuously acquired CT scans were output to either magnetic tape or a magneto-optical disc for transfer to a workstation for image processing and interpolation. The slice thickness (2 mm) of the CT scans used in this study was larger than the maximum layer interval (0.4 mm) of the stereolithography system. Therefore, to obtain a smoother surface more closely approximating the actual anatomy, data interpolation was performed. Scans were linearly interpolated to obtain a 0.2-mm slice interval, followed by binary processing of original CT scans and interpolated scans to delineate only bony tissue.\(^5\) Then, contour extraction was performed using these binary images to delineate the margins of the bones. The data thus obtained were transferred to the workstation of a stereolithography system. The stereolithographic apparatus which we used was a photocurable plastic modeling machine, JSC-2000 (D-MEC, Ltd., Tokyo).

Figure 1 shows the basic components of the stereolithographic apparatus. The apparatus is composed of a controlling computer, an ultraviolet laser with optics, galvanometer-coupled mirrors, a liquid polymer tank, and a movable platform within the tank. Model fabrication starts with the tank full of liquid plastic and the data in the controlling computer. The first layer of the model is created when the platform is lowered into the liquid and raised to a level just below the surface of the viscous liquid polymer. The laser, combined with a shutter and two computer-controlled galvanometer mirrors, draws the first slice. Whenever the laser strikes the surface of the liquid, the plastic solidifies. Correct control of the platform movement, liquid viscosity, and position of the laser results in the solid plastic ridge adhering to the platform. After the layer is fully drawn, the platform and newly solidified layer are submerged in the liquid and then raised enough to form another 0.2- to 0.4-mm layer of liquid on the previously solidified plastic. The next layer is then traced with a laser and the dipping process repeated. This process allows the solid model to be built up of a succession of layers.\(^5\) The complex structure of the skull base, which has a hollow portion, can be accurately reproduced.

III. Surgical planning and simulation

Surgical approaches and areas of craniotomy were evaluated using the fabricated skull models. In preoperative simulations, hand-made models of the tumors, major vessels and nerves were placed inside the skull models. Skull models were stabilized by a Mayfield head clamp and craniotomy or craniec tomy procedures were performed using actual surgical tools. Neuronavigator (Mizuho Co., Tokyo) was used as a navigation system. The accuracy of the navigation system was tested by preoperative application of the system to the skull models. Models of tumors were surgically removed piece by piece under a microscope. The bone defect was evaluated for reconstruction.

Results

The complex structure of the skull base, which has a hollow portion, could be accurately fabricated using the stereolithography apparatus. Accurate reproduction of enlarged cranial base foramens and mastoid air cells with bone destruction was achieved. However, the sellar and upper clival regions were not well reproduced due to artifacts in the CT scans.

Surgery in all seven patients was uneventful with no permanent postoperative neurological deficits. In two patients with meningiomas, which involved major vessels and cranial nerves, safe dissection was so technically difficult that the tumor was only partially removed in spite of a wide operative field.
Illustrative Cases

Case 1: A 52-year-old male had left abducens nerve palsy for 13 years. CT showed a partially calcified mass lesion in the left petroclival region. Magnetic resonance (MR) imaging demonstrated a mass lesion with compression of the pons (Fig. 2 left). A plastic skull model was made and hand-made models of the tumor, the internal carotid artery, and cranial nerves III, V, and VI were placed inside. The surgical approach was evaluated using a fabricated skull model. An anterior transpetrosal approach was selected. In simulation, the skull model was stabilized with a Mayfield head clamp and the craniectomy site and the orientation of the tumor were checked by the navigation system. Craniotomy and craniectomy were performed and the model of the tumor was surgically removed piece by piece both above and below the cranial nerve V (Fig. 2 right).

At surgery, the craniotomy was performed, then
the zygomatic arch was removed and the dura of the middle fossa was elevated. The anteromedial part of the petrous bone was drilled and the dura and the tentorium were incised. The tumor, located medially to the trigeminal nerve, was seen exactly as modeled in the simulation. The tumor was subtotally removed. The histological diagnosis was chondroma. Postoperative MR imaging showed a small amount of residual tumor on the clivus which was followed up conservatively.

Case 2: A 65-year-old male had occipital headaches and tingling sensations in both hands for 6 months. CT showed a mass lesion in the foramen magnum. MR imaging demonstrated a large mass lesion on the ventral side of the foramen magnum displacing the medulla posterolaterally and involving the left vertebral artery (Fig. 3 left). Angiography demonstrated a mass lesion of sun-burst neovascularity fed by the anterior meningeal artery and the ascending pharyngeal artery. A plastic skull model was made and hand-made models of the tumor, the vertebral arteries, the sigmoid sinus, the brain stem, and the cerebellum were positioned inside. The extent of bone removal required was evaluated using the model. A left lateral suboccipital craniectomy with C-1 laminectomy was performed. Removal of the bone of the condylar fossa and the posteromedial one third of the occipital condyle was adequate for removal of the tumor (Fig. 3 center, right).

The tumor was removed through a transcondylar approach. The tumor was firm and vascularized. Although the operative field was wide, it was difficult to dissect the tumor tissue safely from the lower cranial nerves and the major vessels. The tumor was removed only to the extent required to allow decompression of the brain stem. The postoperative course was uneventful except for subcutaneous fluid collection, which was subsequently treated by a ventriculoperitoneal shunt.

Case 3: A 40-year-old male had right facial nerve palsy for 3 years. CT showed enlargement of the right jugular foramen and calcification. T2-weighted MR imaging demonstrated a hyperintense dumbbell-shaped mass lesion and displacement of the internal carotid artery. A plastic skull model was made and hand-made models of the tumor and the internal carotid artery were positioned. The surgical approach was evaluated using the skull model. A lateral suboccipital and infralabyrinthine approach was chosen. In simulation, craniectomy was performed and the model of the tumor was surgically removed piece by piece under a microscope. The bone defect was measured for reconstruction.

At surgery, a craniectomy was performed. The tumor and associated bone destruction were seen exactly as modeled in the simulation. The tumor was subtotally removed. The tumor capsule attached to the extracranial internal carotid artery and cranial nerves IX, X, and XI was not resected. The bone defect was repaired with ceramic bone fragments, fibrin glue, and fat tissue from the lower abdomen. The histological diagnosis was chondrosarcoma. Postoperative MR imaging showed possible residual tumor which was treated by focal irradiation after surgery. The patient has been well both neurologically and cosmetically for 3 years.

Discussion

Stereolithography is a recently developed constructive process for the manufacture layer-by-layer of plastic models using an ultraviolet laser to catalyze the polymerization of a liquid plastic solution. By avoiding the tool path problems inherent in conventional computer-aided milling devices, stereolithography allows full details to be built into complex structures. This technology allows for reproduction of exact anatomic models that detail internal as well as external anatomy. A computer-aided design (CAD) system is employed to create objects as mathematical constructs and render them for display on a CAD computer as either wire-frame drawings or surface-shaded solids. Improvements in image study and CAD in recent years have greatly increased the accuracy of plastic skull models.

In complex surgical procedures, surgical planning can benefit from 3D images of an individual patient's anatomy. However, common 3D imaging does not allow image manipulation and surgical simulation on screen before surgery. The potential for generating 3D structural models from CT scans was conceived as early as 1980. A few years later, milled models were fabricated from 3D CT data. The use of skull models in craniofacial surgery and plastic surgery enabled various simulations of operations for congenital craniofacial anomalies, dentofacial deformities, and maxillofacial defects after trauma or tumor resection. Prediction of the resulting changes and preparation of prostheses, which are needed to reconstruct deformities or defects, are greatly aided by the creation of exact models.

We have adopted stereolitographic plastic skull models for preoperative planning and simulation of cranial base surgery. Optimal craniotomy or craniectomy for maximal visualization of operative fields can be determined in individually tailored skull models using actual surgical tools. Anatomical configurations and relationships in cranial base bony structures, such as the jugular tubercle, occipital
condyle, and jugular foramen, vary among individuals. It is important to estimate the extent of drilling of these bony structures before actual surgery. Anatomical variations must be accurately modeled for operative procedures to be realistically simulated. In addition, the presence of extradural tumors such as chordomas and chondromas, which are often associated with bone destruction, makes intraoperative orientation under a microscope much more difficult. Simulations provide the surgeon with accurate mental images of the anatomy that will be encountered. Intraoperative use of navigation systems is also helpful, but the guidance of navigation systems cannot be relied on exclusively since such systems do not provide warnings of possible malfunctions.

Simulations using models and navigation systems facilitate difficult skull base surgery and can reduce surgical complications. The other advantages of using skull models include an increased understanding by the patient and family and improved educational experiences for residents and other medical staff.

The disadvantages of using skull models include the time and cost of making the models. Furthermore, hand-made models of the tumors, major vessels and nerves placed inside the skull models may not provide exact reproductions. Current 3D MR imaging of intracranial structures with 3D computed imaging of the skull may be superior to hand-made models inside the skull model if used only for observation. For surgical simulation, however, skull models are considered superior to currently available computer-generated screen images; once skull models are made, they provide a more realistic tool that is easier to handle than computer graphics. Use of these models may be a transitional stage until the capabilities of computers are significantly expanded. Advances in computer hardware and software could lead to new surgical simulation techniques that are even more similar to the actual surgical procedure.

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References


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Commentary

Authors Masamitsu Abe, Kazuo Tabuchi, Masaaki Goto, and Akira Uchino should be commended for a

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very useful report under the title: “Model-based Surgical Planning and Simulation of Cranial Base Surgery.” The authors very clearly showed that “model-based surgical planning” is very practical from several aspects: For understanding the actual surgery of clinical cases, for teaching purposes (students) as well as for training purposes and also for overcoming the gap of understanding of surgical act between the doctors and family members as well as other medical stuff. It is no doubt that “model-based surgical planning” as is presented in this report, has practical value for understanding the location and extension of the pathology. And not only this. This does also help to appreciate the relationship between the normal vascular and neural structures and tumorous lesion. It is no doubt, superior visualization of the whole situation at the skull base in comparison with the 3D computer presentation. One can see a significant impact of model-based on surgical planning and simulation of cranial base surgery, on the concept of surgical procedures from the practical point of view and the understanding of the whole course of surgical procedure.

It goes without saying that the impact of this pre-surgical study and planning will be even greater if the individual using it, is familiar with the actual anatomy and if he or she has obtained this knowledge from the study of specimens in the laboratory.

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The authors have presented a new technique to make an individual plastic skull model by stereolithography from three-dimensional CT images. The stereolithography system presented here is a constructive process for the manufacture layer-by-layer of plastic models using an ultraviolet laser to catalyze the polymerization of a liquid plastic solution. The technique enables us to reconstruct the precise skull base structures containing brain tumors that vary between individuals. The major advantages of the plastic skull model are to give us visual information about surgical approach and area of craniotomy and to enable us to experience real skull base drilling preoperatively using real surgical tools just like cadaver dissections. Surgical procedures, however, cannot be determined by only the relationship between the tumor and adjacent bony skull base structures. Characteristics of the tumor itself such as consistency and vascularity, surrounding brain structures, major vessels (both arteries and veins), and cranial nerves are more important critical determinants. Indeed, although the operative field was wide and adequate for surgery using the skull model, the tumor was firm and vascularized and removed partially as mentioned in Case 2. Therefore, I really hope that a precise skull base model including tumor size and vascularization, and the surrounding brain, blood vessels, and cranial nerves will be available in the near future by advanced computer technology for ideal preoperative planning and surgical simulation. Finally, with further new methods of treatment, the matter of the time and cost of making the models will be brought to a reasonable conclusion.

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This article describes the potential value of preoperatively performed skull models for assessment of surgical planning and simulation in patients with cranial base lesions. The authors obtained excellent surgical results with a series of 7 patients using the computer-generated three-dimensional plastic skull model from CT bone images. This skull model allowed them to better decide the most appropriate surgical approach, evaluate the degree of operative risk for the patient during surgery, and improve educational experiences for residents. The article is of interest, nevertheless the time and cost of making the model are involved and the model may not provide precise reconstruction of the major vessels and nerves located in the lesions. This type of modeling will have a real impact on surgical planning and simulation in patients with cranial base lesions.

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