

# Skull base training and education using an artificial skull model created by selective laser sintering

Masahiko Wanibuchi · Masafumi Ohtaki ·  
Takanori Fukushima · Allan H Friedman ·  
Kiyohiro Houkin

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## Abstract

**Introduction** Practicing skull base approaches on cadavers affords the surgeon a chance to learn complex anatomical relationships and to practice surgical skills. However, there are ethical or legal problems in obtaining cadaver material in some countries. In addition, there is always risk of transmitting infections with cadaveric material. In order to get around these problems, we created a whole skull model which reproduces the detailed anatomy within the skull base using a selective laser sintering (SLS) technique.

**Materials and methods** The first author's head was scanned using multidetector-row computed tomography. The data were reconstructed and converted into the standard triangulation language file system. Powdered material comprised of polyamide nylon and glass beads was laser-sintered in accord with the data derived from the head CT. The model was dissected under a surgical microscope using a high-speed drill, suction, and other surgical instruments.

**Results and discussion** The appearance of both inner and

outer cranial surfaces, including sutures, foramens, fissures, and protrusions, were clearly demonstrated. The artificial mastoid did not melt from the heat of the drill when a mastoidectomy was performed. The anatomical structures inside the mastoid and of paranasal sinuses were accurately reproduced in the model.

**Conclusion** The model created using SLS should be very useful for the teaching skull base approaches avoiding the ethical, legal, and infection problems inherent in cadavers.

**Keywords** Mastoidectomy · Microsurgical anatomy · Selective laser sintering · Skull base surgery · Skull model

## Introduction

Laboratory training is essential for understanding the microsurgical anatomy and acquiring surgical skills necessary for skull base approaches. Fine drilling technique is especially important. Many dissection courses are held to train neurosurgeons, but legal and ethical concerns limit the availability of cadaveric material in some countries. Even in countries where cadavers are available, surgeons not working in hospitals with skull base laboratories only have access to the cadaveric heads for the limited duration of the course. In addition, there is always the risk of transmitting known and unknown infectious agents from cadavers.

In recent years, selective laser sintering (SLS) has been used to create models of the temporal bone used to teach surgeons how to perform a mastoidectomy [1, 3–7]. SLS is a rapid prototyping technology that can be used to produce complex-shaped parts in a rapid fashion. SLS employs a laser beam to solidify powder materials such as polycarbonate, nylon, steel, or rubber building up the model in layers.

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M. Wanibuchi (✉) · K. Houkin  
Department of Neurosurgery, School of Medicine,  
Sapporo Medical University,  
South-1, West-16,  
Sapporo, Hokkaido 060-8543, Japan  
e-mail: wanibuti@sapmed.ac.jp

M. Ohtaki  
Department of Neurosurgery, Obihiro Kousei General Hospital,  
Obihiro, Japan

T. Fukushima  
Carolina Neuroscience Institute,  
Raleigh, NC, USA

T. Fukushima · A. H. Friedman  
Division of Neurosurgery, Duke University Medical Center,  
Durham, NC, USA

The process for building our model begins with powdered material comprised polyamide nylon and glass beads. This combination affords the model properties similar to real bone. SLS constructed models have two desirable characters, thermostability and the ability to simulate detailed structures within boney cavities. These characteristics of the materials make the model suitable for drilling without melting and for reproducing the detailed anatomical structures encountered within the skull. We have tried to produce a model of the skull for practicing skull base approaches for education the young neurosurgeons.

## Materials and methods

The first author's head and neck from the fifth cervical vertebrae to the vertex of his skull of the head was scanned using Aquilion 64<sup>®</sup> (Toshiba Medical Systems, Japan), multidetector-row computed tomography. A total of 834 slices was obtained using the following parameters: a 0.5-mm slice width, a helical pitch of 0.641, an image production interval of 0.3 mm, X-ray tube voltage and current of 120 kV and 300 mA, respectively, a field of view of 199.68×199.68 mm, a pixel size of 0.390×0.390, and a scan speed of 0.5 s/rotation.

The DICOM data were reconstructed using the software named Mimics<sup>®</sup> (Materialise Japan Co., Ltd., Yokohama, Japan). The data were converted into the standard triangulation language (STL) file system. The powder material comprised of 30% to 90% by weight of a synthetic resin (polyamide nylon) and 10% to 70% by weight of inorganic filler (glass beads) was laser-sintered according to the STL data. The powder of the synthetic resin comprised fine particles in a spherical shape with an average diameter of 5 to 200 μm. The sintered layers were accumulated with a pitch of 0.1 mm using SLS method. We created several models changing its ratio of polyamide nylon and glass beads in order to obtain the feeling of the real bone. Several neurosurgeons and otolaryngologists tried iterations of this model. The model of the final version resulted from their observations was dissected under a surgical microscope, a high-speed drill, suction, and other surgical instruments. This model was manufactured by Ono & Co., Ltd., Tokyo, Japan. The company has the patent of process for producing this artificial bone model.

## Results

### Appearance

The appearance of the head model is shown in Fig. 1. All the sutures, coronal, squamosal, lambdoid, parietomastoid,

occipitomastoid, and sagittal were clearly demonstrated (Fig. 1a). The pterion and the asterion were also observed. Extracranial protrusions, fissures and fossas, such as the spine of the sphenoid bone, the lateral and medial laminae of the pterygoid process, the hamulus of the pterygoid process, and the pterygopalatine fossa were accurately reproduced (Fig. 1b). The landmarks used for a mastoidectomy, the spine of Henle, Macewen's triangle, and the supramastoid crest were also identified (Fig. 1b).

A model cut in the midsagittal plane (Fig. 1c) demonstrated the frontal, sphenoid, and ethmoid sinuses and the superior, middle, and inferior nasal conchae. The indentations and depressions made inside the calvaria by the venous sinuses, the middle meningeal artery, and the arachnoid granules were also accurately reproduced.

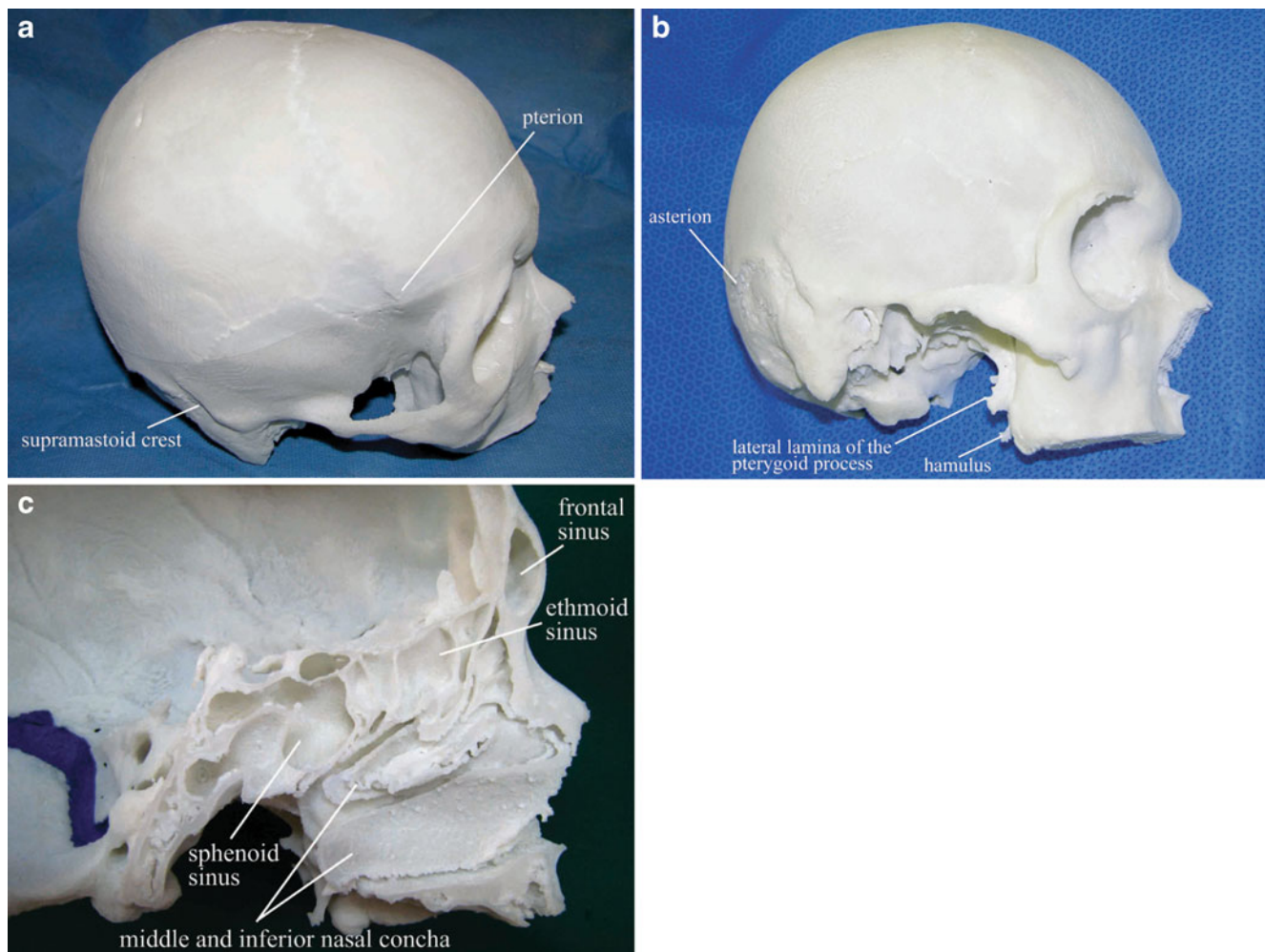
### Skull base structures

Foramens, canals, and fissures such as the anterior and posterior ethmoid foramen, the superior and inferior orbital fissures, the foramen rotundum, the foramen ovale, the foramen spinosum, the jugular foramen, the hypoglossal canal, and the carotid canal were clearly observed (Fig. 2a). The foramen ovale and spinosum were patent leading to the infratemporal fossa. The foramen rotundum communicated to the pterygopalatine fossa (Fig. 2b). The internal auditory canal was also accurately reproduced. The transverse crest and Bill's bar at the fundus of the internal auditory canal were observed (Fig. 3).

### Structures in the mastoid

The skull model when drilled had the same feeling as human bone. This was the most characteristic feature of this skull model. The model did not melt even when drilled using a diamond burr high speed drill. The anatomical structures inside the mastoid including the sigmoid sinus plate, the semicircular canals, the ossicles of the middle ear, and the fallopian canal were identified (Fig. 4a). These structures are made of hardened polymer. The hardness of these structures is easily distinguished when dissecting with a high speed drill. In addition to tactile sensation of the hard bone, the color injection into the fallopian canal and the venous sinus is useful for identifying its location. The sigmoid sinus plate appeared as a blue protrusion when the inner wall of the sinus was colored in blue. The fallopian canal appeared as a yellow protrusion when the inside of the canal was colored in yellow.

Further drilling of the ossicles demonstrated the ampulla of the superior, lateral and posterior semicircular canals, the common crus, and the inside of the fallopian canal (Fig. 4b). The promontory and the round window were also identified through the facial recess over the fallopian



**Fig. 1** The appearance of the head model. **a** All the sutures, coronal, squamosal, lambdoid, parietomastoid, occipitomastoid, and sagittal sutures and the pterion and the asterion were clearly demonstrated. **b** Extracranial protrusions, fissures and fossas, such as the spine of the sphenoid bone, the lateral and medial laminae of the pterygoid process, the hamulus of the pterygoid process, and the pterygopalatine fossa were accurately reproduced. The landmarks used for a

mastoidectomy, the spine of Henle, Macewen's triangle, and the supramastoid crest were also identified. **c** A cut of the model in the midsagittal plane demonstrated the frontal, sphenoid, ethmoid sinuses, and the superior, middle, and inferior nasal conchae. The indentations and depressions made inside the calvaria by the venous sinuses and the middle meningeal artery and the arachnoid granules were also accurately reproduced

canal (Fig. 4b). The hollow structures such as the mastoid antrum and air cells are filled with powder that was easily removed by irrigation and suction or compressed air. The powder which fills these structures in the place of air is brighter than the hardened bone and easily identified by the surgeon. We found that the cranium could be used for practicing craniotomy techniques. As with the mastoid, turning a flap with a craniotome did not result in melting of the bone.

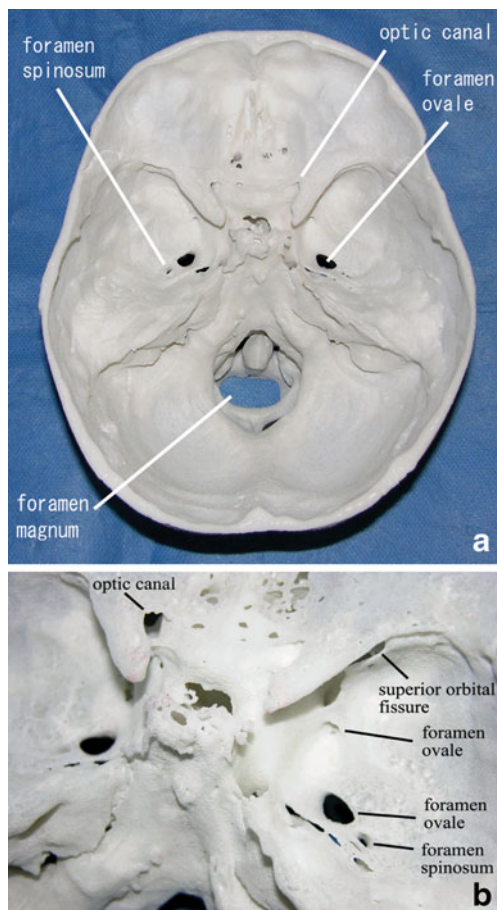
## Discussion

Rapid prototyping (RP) is a method used to create a 3D simulated model from liquid plastic or powder material.

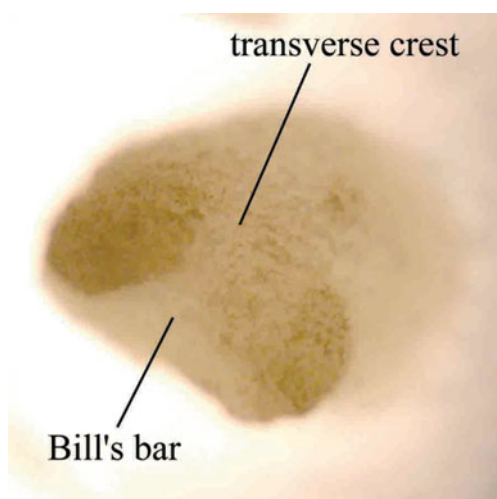
This technique is used for the production of complex-shaped parts. RP technology is a generic designation including the four technologies: SLS, stereolithography (SLA), fused deposition modeling, and 3D printing. RP technology has been extensively used to design and manufacture prototypes for the automotive industry, toy manufacturers, gold equipment manufacturers, and shoe manufacturers. In recent years, it has been applied to the medical field.

SLA that polymerizes and solidifies liquid resin using laser technology has been applied to create models of the mandible and the ear in order to better plan surgical procedures and to design prosthesis for bone defects [2, 8]. In the past, these models were not suitable for drilling, as the plastic from which they are made melted when heated.

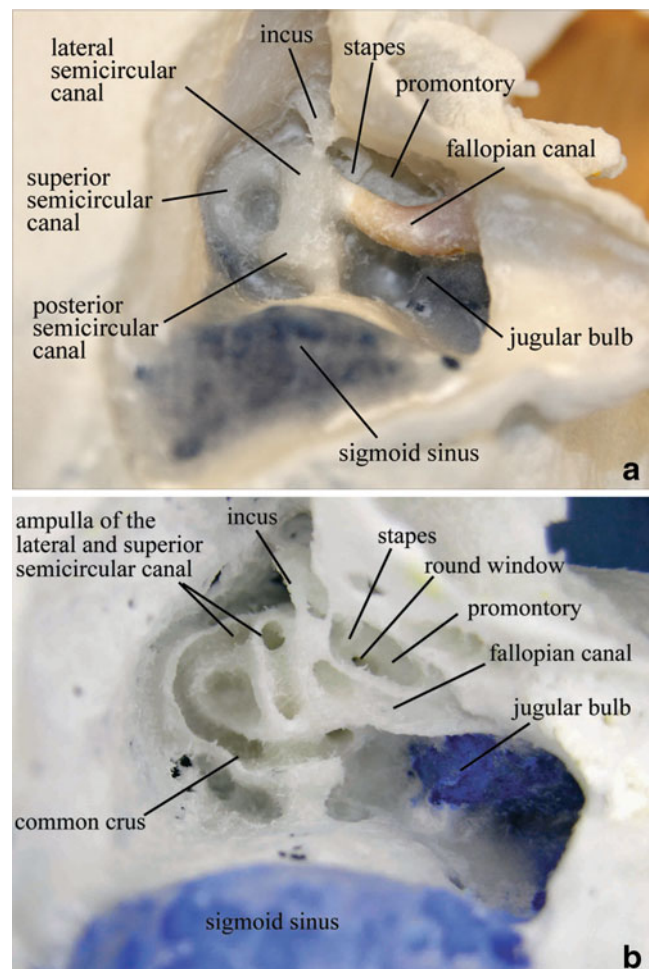




**Fig. 2** Skull base structures. **a** All foramen, canals, and fissures such as the anterior and posterior ethmoid foramen, the superior and inferior orbital fissures, the foramen rotundum, the foramen ovale, the foramen spinosum, the jugular foramen, the hypoglossal canal, and the carotid canal were clearly observed. **b** The foramen ovale and spinosum were patent leading to the infratemporal fossa. The foramen rotundum communicated to the pterygopalatine fossa



**Fig. 3** The fundus of the internal auditory canal. The internal auditory canal was also accurately reproduced. The transverse crest and Bill's bar at the fundus of the internal auditory canal were observed



**Fig. 4** Anatomical structures in the mastoid. **a** The anatomical structures inside the mastoid including the sigmoid sinus plate, the semicircular canals, the ossicles of the middle ear, and the fallopian canal were identified. The sigmoid sinus plate appeared as a blue protrusion when the inner wall of the sinus was colored in blue. The fallopian canal appeared as a yellow protrusion when the inside of the canal was colored in yellow. **b** Further drilling of the ossicles demonstrated the ampulla of the superior, lateral and posterior semicircular canals, the common crus, and the inside of the fallopian canal. The promontory and the round window were also identified through the facial recess over the fallopian canal

The SLS method used to make the models described in this article employs a laser beam to solidify powder materials building up the model in layers. Engineers can choose from materials such as polycarbonate, nylon, steel, or rubber depending on to the purpose the model is to serve. We selected powder comprised of polyamide nylon and glass beads to create the skull model in order to capture the characteristics of thermostability and the ability to simulate detail structures within cavities.

Taking advantage of these properties, a detailed skull model that is suitable for drilling can be created. The model will not melt when drilled using a diamond or a cutting bit

in a high speed drill. The anatomical structures within the mastoid and the paranasal sinuses are accurately reproduced. Since the skull model accurately reproduces intramastoid and the anterior skull base structures, it is very useful not only for practicing skull base surgery but also for the education of medical and nursing students, residents, and participants in a dissection course [11].

The model can be dissected with video observation at academic meetings to demonstrate techniques and finer points of anatomy to the participants. In some countries, a major advantage of using the model is that it obviates ethic and legal restrictions and there is no risk of the transmission of infection. The completely disinfected model could be handled and scrutinized in the operating room or on the physician's desk. Unlike a cadaver head, the model's shelf life is not limited.

We created the model from a scan of the first author's head. Because the model is an engineering product, we can create similar models of consistent quality. Suzuki et al. created a model from the cadaveric temporal bone using SLS method in 1994 [9]. Levy et al. and Suzuki et al. produced a rapid prototyping temporal bone model from computed tomography data of a normal human [10, 11]. A model can also be produced from the scan of a patient with a pathological condition. There are reports of using such a model to facilitate the preoperative assessment of various techniques to treat the condition. Such models have been used to facilitate laryngeal surgery, craniomaxillofacial reconstruction, and abdominal aortic aneurysm repair on treatment of acetabular fractures [1, 3–7]. The replicated model allows for the direct manipulation and study of abnormal anatomy prior to surgery.

There are some differences between this model and cadaver bone. When drilling, the surgeon will note that drilling the model is similar but not exactly the same as drilling a patient's skull. The polymer and glass bead combination is slightly harder than real bone. The bone dust created is slightly sticky. The dust accumulates and the surgeon will need to remove the accumulated dust on occasion. We experimented with various ratios of nylon and glass beads in an attempt to make the surgeon's perception of the material closer to that of actual bone. Since the model is bright white, the surface of the model appears glaringly bright to the surgeon working through the operative microscope. The light on the microscope should be dimmed. The powder not hardened by the laser remains in the mastoid air cells and the paranasal sinuses. After opening these cavities, the powder is easily removed using a suction or jet of compressive air. Differentiation of the powder from surrounding structures is easy, as the powder is soft and lighter in color. In addition, we must consider some limitations of this model. We cannot train or teach the unpredictability of actual surgical fields and the visual and

tactile feedback of handling living brain and dissecting around the neurovascular structures.

## Conclusion

We can perform a surgical training at anytime, anywhere without any ethic and legal problems or infection. The model can be applied not only for the surgical training but also for educating the young neurosurgeons.

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## Comments

This is an interesting paper demonstrating the use of selective laser sintering to develop a skull model useful for skull base lab educational experience. While this has been applied in otology for this purpose, this paper educates the neurosurgical readership: the precise composition of the material that will simulate drilling of the skull base in a

laboratory experience. This is a useful model to simulate skull base anatomy and drilling, especially important in those regions of the world where access to cadaveric specimens is limited. I commend the authors for bringing this to our attention.

W.T. Couldwell  
Utah, USA

This is an interesting report describing the development of a whole skull model reproducing the anatomic features of the cranial base. The sophisticated technology adopted produced detailed and realistic modeling of the relevant bony structures. There are many practical limitations in some countries in obtaining cadaveric specimen for

practicing skull base approaches, which is important not only for teaching residents but also for already trained neurosurgeons. This paper adds another useful piece of information on the potential advantages of new educational tools in neurosurgical training and clinical practice.

Nevertheless, at the state of the art, from the strictly educational point of view, this technique cannot exactly reproduce the unpredictability of actual surgical fields; neither can substitute the visual and tactile feedback of handling living brain and dissecting around the neurovascular structures.

Domenico d'Avella  
Luca Denaro  
Padova, Italy