Dissectable Modified Three-Dimensional Temporal Bone and Whole Skull Base Models for Training in Skull Base Approaches

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ABSTRACT

Training in dissection of the skull base is essential for anatomical understanding and correct surgical techniques, but chances for cadaver dissection are limited, so a substitute is very desirable. Modifications of commercially available three-dimensional (3D) temporal bone and whole skull base models made from surgically dissectable artificial bone are proposed to include artificial dura mater, venous sinuses, carotid artery, and cranial nerves as educational tools for training in skull base surgery. These 3D models precisely reproduce the surface details and inner bony structures such as the cranial foramina, inner ear organs, air cells, and so on. Dura mater and venous sinuses are made from silicone, cranial nerves from rubber fibers, and the internal carotid artery from vinyl tube. Simulations of skull base techniques were performed on these models using a high-speed drill under the operating microscope. The dissected models were evaluated by bone density computed tomography scans to confirm the areas of bony removal. The three steps of reconstruction of the skull base model, dissection, and observation of the dissected model promote clear understanding of the 3D anatomy and acquisition of surgical techniques in the skull base.

KEYWORDS: Skull base surgery, temporal bone, cavernous sinus, surgical anatomy, training model

Skull base surgery techniques are accepted as a standard neurosurgical approach to treat cerebrovascular diseases and deeply seated brain tumors. However, the skull base consists of complex

three-dimensional (3D) bony structures that contain dura mater, venous sinuses, cranial nerves, and arteries. In particular, the temporal bone containing the inner ear organs and sphenoid bone with

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the cavernous sinus is a key location of skull base surgery. Therefore, understanding of the unique anatomical complexities and the surgical techniques in the skull base is relatively difficult. Experience with cadaver dissection is essential to understand such complicated anatomy and develop the required surgical skills, but opportunities to participate in cadaver dissection are limited, so training models are also needed.

A 3D-temporal bone model (OMeR-Version 3; Ono & Co., Ltd., Tokyo, Japan) made from polyamide nylon and glass beads was originally produced for education and training in otological surgery.¹ Surgical maneuvers in otology are basically limited to the inside of the temporal bone. In contrast, neurosurgical skull base surgery is intended to expose the dura mater, venous sinuses, and foramina of the cranial nerves and blood vessels. We previously described a temporal bone model and whole skull model for training in skull base surgery.^{2,3} These 3D models are manufactured by the rapid prototyping method using selective laser sintering (SLS) technology based on 3D computed tomography (CT) data.⁴ The SLS method can reproduce the precise 3D shape of an object including its inner structures by laser sintering and fusing of powder layers. However, the feeling of drilling the artificial bone of these original models was somewhat "sticky" and lacking in the "crispy" touch experienced during skull bone drilling.^{2,3} Recently, new temporal bone and skull base models (Ono & Co., Ltd.) have been produced from improved artificial bone that is more suitable for surgical drilling.

Here we describe how to construct a 3D temporal bone model and 3D whole skull base model by adding colored silicone to the inner surfaces of the commercial models to simulate the dura mater and venous sinuses including the cavernous sinus, rubber or sponge to represent the cranial nerves, and vinyl tubing to represent the internal carotid artery (ICA). Surgical drilling under an operating microscope and evaluation of the removed bone using bone density CT were performed. The proposed new training system,

consisting of constructing the skull base model, simulation of the skull base surgery, and final evaluation by CT, definitely facilitates the understanding of the complicated 3D anatomy and the acquisition of surgical techniques in the skull base.

MATERIALS AND METHODS

Construction of the Modified 3D Temporal Bone Model

The 3D temporal bone model (OMeR-KEZLEX-TMB-R-L; Ono & Co., Ltd.) reproduces the surface details needed for temporal bone skull base surgery, such as the zygomatic process, external acoustic meatus, styloid process, mastoid process, Henle's spine, Macewen's triangle, temporal line, supramastoid crest, asterion, digastric groove, foramen ovale, foramen spinosum, hiatus facialis, arcuate eminence, petrous ridge, jugular tubercle, internal acoustic canal, jugular foramen, hypoglossal canal, sigmoid sulcus, occipital condyle, and so on (Fig. 1). This model also reproduces the inner bony structures such as the mastoid antrum, mastoid air cells, semicircular canals, fallopian canal, carotid canal, cochlea, and so on.

Blue silicone (hydrophilic vinyl polysiloxane impression material; Exafine Regular Type; GC Corporation, Tokyo, Japan) was brushed onto the inner surface of the model to model the transverse, sigmoid, superior petrosal, and inferior petrosal sinuses and the jugular vein (Fig. 2A). The silicone material consists of two components, which should be mixed with retarder fluid (GC Corporation) to delay the hardening time. Brown silicone (Exafine Injection Type; GC Corporation) was brushed to model the artificial dura mater (Fig. 2B). Yellow rubber fibers were used to model the facial and cochlear nerves in the internal acoustic canal, the glossopharyngeal, vagal, and accessory nerves in the jugular foramen, and the hypoglossal nerve in the hypoglossal canal (Fig. 2C). Red vinyl tube was used to model the intrapetrous portion of the ICA

Figure 1 Prototype three-dimensional temporal bone model (OMeR-KEZLEX-TMB-R-L; Ono & Co., Ltd., Tokyo, Japan) showing the surface details of the temporal bone. (A) Lateral view of the temporal bone model. (B) Superior view of the temporal bone model. (C) Posterior view of the temporal bone model. AE, arcuate eminence; AM, external acoustic meatus; AS, asterion; DG, digastric groove; FO, foramen ovale; FS, foramen spinosum; HC, hypoglossal canal; HF, hiatus facialis; HS, Henle's spine; IAM, internal acoustic meatus; JF, jugular foramen; JT, jugular tubercle; M, mastoid process; MT, Macewen's triangle; OC, occipital condyle; PR, petrous ridge; SC, supramastoid crest; SP, styloid process; SS, sigmoid sulcus; TL, temporal line; Z, root of zygoma.

(C6) in the carotid canal and the middle meningeal artery in the foramen spinosum (Fig. 2D).

Construction of the Modified 3D Whole Skull Base Model

The 3D whole skull base model (OMeR-KEZLEX-SKB-L; Ono & Co., Ltd.) contains all bony structures that are landmarks of skull base surgery, such as the anterior clinoid process (ACP), optic canal, optic strut, posterior clinoid process, superior orbital fissure (SOF), foramen ovale, foramen spinosum, hiatus facialis, orbit, ethmoid sinus, sphenoid sinus, and so on (Fig. 3). The cavernous sinus is the key structure in the skull base, situated between the periosteal layer of the dura mater (inner wall) and the meningeal layer (dura propria) of the dura mater (outer wall). Therefore, these two layers of the dura mater were reproduced in the whole skull base model.

The periosteal layer of the dura mater and the periorbita of the orbit were modeled with yellow silicone (hydrophilic vinyl polysiloxane impression material; Exafine Hard Type; GC Corporation), and the venous sinuses, such as the cavernous sinus, sphenoparietal sinus, intercavernous sinus, venous confluence, basilar plexus, and other venous sinuses, were modeled with blue silicone (Exafine Regular Type; GC Corporation) (Fig. 4A). The periosteal bridge was formed by fusing the two yellow silicone layers of the periorbita and the periosteal layer in the middle fossa at the lateral part of the SOF. The meningeal layer of the dura mater except around the cavernous sinus was modeled with brown silicone (Exafine Injection Type; GC Corporation) brushed onto the periosteal layer (Fig. 4B). The C1 to C5 portions of the ICA were modeled with red vinyl tube and the C6 portion in the carotid canal with red rubber tube (Fig. 4B).

The olfactory nerve, optic nerve with chiasma, and trigeminal nerves with Gasserian ganglion were modeled with yellow sponges. The other cranial nerves were modeled with yellow rubber fibers. The abducens nerves were positioned

Figure 2 Process to modify the three-dimensional temporal bone model. (A) Transverse, sigmoid, superior petrosal, and inferior petrosal sinuses, jugular vein, and venous confluence are modeled with blue silicone. (B) Dura mater is modeled with brown silicone brushed onto the inner surface of the model. (C) Facial, cochlear, glossopharyngeal, vagal, accessory, and hypoglossal nerves are modeled with yellow rubber fibers positioned in the corresponding canals. (D) Intrapetrous portion of the internal carotid artery is modeled with red vinyl tube placed in the carotid canal. The middle meningeal artery is modeled with red rubber fiber positioned in the foramen spinosum. FO, foramen ovale; HC, hypoglossal canal; IAM, internal acoustic meatus; IC, internal carotid artery; IPS, inferior petrosal sinus; JF, jugular foramen; MMA, middle meningeal artery; SPS, superior petrosal sinus; SS, sigmoid sinus; TS, transverse sinus; VC, venous confluence; VII, facial nerve; VIII, cochlear nerve; IX, glossopharyngeal nerve; X, vagal nerve; XI, accessory nerve; XII, hypoglossal nerve.

from the venous confluence (corresponding to Dorello's canal) and along the C4 portion of the ICA and then passed into the SOF. The ophthalmic division (V1), maxillary division (V2), and mandibular division (V3) of the trigeminal nerve were placed in the SOF, foramen rotundum, and foramen ovale, respectively. The trigeminal root was attached to the trigeminal impression in the tip of the pyramidal bone. The oculomotor nerve and trochlear nerve were placed parallel to the V1. The other cranial nerves were positioned in the corresponding foramina (Fig. 4C). The middle meningeal artery was modeled with red rubber fiber and placed into the foramen spinosum. Finally, the lateral wall of the cavernous sinus (dura propria) was

modeled with brown silicone (Fig. 4D). The semi-transparent layer under the dura propria was not reconstructed in this model.⁵

Dissection of Modified Models for Surgical Simulation

The modified temporal bone model was retained in a temporal bone holder (Sando-Davis; Nagashima Medical Instruments Co., Ltd., Tokyo, Japan) and the modified whole skull base model with Mayfield's tri-pins. Artificial bone dissection was performed using a high-speed drill under an operating microscope. These 3D modified models were evaluated

Figure 3 Prototype three-dimensional whole skull base model (OMeR-KEZLEX-SKB-L; Ono & Co., Ltd.) showing the fine structures in the skull base. (A) Superior view of the whole skull base model. (B) Oblique lateral view of the whole skull base model. ACP, anterior clinoid process; CL, clivus; FO, foramen ovale; FR, foramen rotundum; FS, foramen spinosum; OC, optic canal; OS, optic strut; PCP, posterior clinoid process; SOF, superior orbital fissure; SW, sphenoid wing.

with the simulated posterior transpetrosal approach,^{6,7} Kawase's approach,⁸ and epidural cavernous sinus surgery (Dolenc's technique⁹) to assess the value as a substitute for cadaver dissection. The areas of the removed bony structures were evaluated by bone density CT.

Figure 4 Process to modify the three-dimensional whole skull base model.

Figure 4 (Continued) (A) Periosteal layer of the dura mater and periorbita of the orbit are modeled with yellow silicone. The dural sinuses such as the cavernous sinus, intercavernous sinus, and basilar plexus are modeled with blue silicone. (B) The meningeal layer of the dura mater is modeled by brushing brown silicone on the periosteal layer. The internal carotid artery (C1 to C6) is modeled with red vinyl tube. (C) Abducens nerve made from yellow rubber fiber is positioned from the venous confluence (corresponding to the Dorello canal) to the superior orbital fissure. The oculomotor nerve, trochlear nerve, and ophthalmic division of the trigeminal nerve are positioned in the superior orbital fissure. The maxillary division and mandibular division of the trigeminal nerve are positioned in the foramen rotundum and foramen ovale, respectively. The trigeminal root is attached to the trigeminal impression of the petrous ridge. The other cranial nerves are positioned in the corresponding foramina. (D) Dura propria of the lateral wall of the cavernous sinus is modeled with brown silicone. ACP, anterior clinoid process; BP, basilar plexus; CS, cavernous sinus; DP, dura propria of the lateral wall of the cavernous sinus; FO, foramen ovale; FS, foramen spinosum; GaG, Gasserian ganglion; IC, internal carotid artery; ICS, intercavernous sinus; IPS, inferior petrosal sinus; MMA, middle meningeal artery; PCP, posterior clinoid process; SP, sphenoparietal sinus; SPS, superior petrosal sinus; SS, sigmoid sinus; TR, trigeminal root; V1, abducens nerve; V2, maxillary division of the trigeminal nerve; V3, mandibular division of the trigeminal nerve; VC, venous confluence; II, optic nerve with chiasm; III, oculomotor nerve; IV, trochlear nerve; V1, ophthalmic division of the trigeminal nerve.

RESULTS

Simulation of the Posterior Transpetrosal Approach and Kawase's Approach using the Modified 3D Temporal Bone Model

During simulation of the posterior transpetrosal approach, the cortical segment of the mastoid bone was removed from the supramastoid crest to the tip of the mastoid, and the mastoid antrum was opened behind Henle's spine (Fig. 5A). The touch of the artificial bone using the high-speed drill was very similar to the crispy touch during real bone drilling. However, the spaces in the mastoid air cells and the mastoid antrum contained artificial bone material powder. The packed material had to be removed using a brush or compressed air. After exposure of the sigmoid sinus, temporal dura mater,

and suboccipital dura mater, the semicircular canals were dissected out (Fig. 5B). The semicircular canals were surrounded by hard cortical bone that was easy to dissect from the mastoid air cells. The thinned bone pieces on the sigmoid sinus were removed by the "eggshell peeling technique" as in real surgery. The presigmoid dura and superior petrosal sinus were exposed (Fig. 5C). Finally, the jugular bulb was dissected out and the fallopian canal opened (Fig. 5D, E).

During simulation of Kawase's approach, the dura mater on Kawase's triangle of the petrous bone apex had to be extirpated because the silicone artificial dura mater lacked elasticity and could not be reflected like the real dura mater (Fig. 6A). The C6 was exposed by drilling the hiatus facialis (Glasscock's triangle). The internal auditory canal was opened, and then the great petrosal nerve, geniculate ganglion, and cochlea were exposed (Fig. 6B). Finally, the Kawase's triangle was drilled away to expose the posterior fossa dura as far as the inferior petrosal sinus (Fig. 6C).

After the simulation surgery, the dissected modified 3D temporal bone was examined by bone density CT, which confirmed that the posterior petrosectomy and anterior petrosectomy were correctly performed (Fig. 7).

Simulation of Dolenc's Approach Using the Modified 3D Whole Skull Model

The frontotemporal craniotomy was performed with a surgical saw, and the sphenoid wing was rongeuired out up to the lateral part of the SOF. However, the silicone model dura mater lacked elasticity and could not be reflected like the real dura mater. Therefore, the frontotemporal dura mater was extirpated. Partial unroofing of the orbit was performed and the periorbita was exposed (Fig. 8A). The optic canal was opened and the optic strut was removed (Fig. 8B). The ACP was removed en bloc (Fig. 8C). After anterior clinoidectomy, the "clinoid space" was opened and the clinoid segment of the ICA (C3) and distal dural

Figure 5 Procedures of the posterior transpetrosal approach. (A) Decortication of the mastoid process and opening of the mastoid antrum behind Henle's spine. (B) Drilling out of the semicircular canals surrounded by compact bone after exposure of the temporal dura, posterior fossa dura, transverse sinus, and sigmoid sinus. (C) Drilling out of the presigmoid dura and superior petrosal sinus. (D) Drilling out of the sigmoid bulb. (E) Final view of mastoidectomy and the opened fallopian canal. AM, external acoustic meatus; DR, digastric ridge; FC, fallopian canal; HS, Henle's spine; JB, jugular bulb; MA, mastoid antrum; MT, mastoid tip; PD, posterior fossa dura; PSD, presigmoid dura; SCC, semicircular canals; SPS, superior petrosal sinus; SS, sigmoid sinus; TD, temporal dura; TS, transverse sinus; VII, facial nerve.

Figure 6 Procedures of Kawase's approach. (A) Exposed Kawase's triangle (anterior surface of petrous bone apex). (B) Opened carotid canal, internal auditory canal, great petrosal nerve, geniculate ganglion, and cochlea. (C) Final appearance of Kawase's approach. The posterior fossa dura between the superior petrosal sinus and inferior petrosal sinus was exposed after drilling away Kawase's triangle. CO, cochlea; C6, intrapetrous portion of the internal carotid artery; FO, foramen ovale; GG, geniculate ganglion; GPN, great petrosal nerve; HF, hiatus facialis; IPS, inferior petrosal sinus; KT, Kawase's triangle; MMA, middle meningeal artery; PD, posterior fossa dura; SPS, superior petrosal sinus; VII, facial nerve; VIII, auditory nerve.

ring were observed (Fig. 8D). The meningo-orbital band and the periosteal bridge in the lateral part of the SOF were identified (Fig. 8D). The dura propria of the lateral wall in the cavernous sinus

was elevated from the oculomotor, trochlear, and trigeminal nerves using the "peeling-off technique" (Fig. 9A). Glasscock's triangle was drilled and the intrapetrous segment of the ICA (C6) was exposed.

Figure 7 Bone density computed tomography scans of the dissected modified three-dimensional temporal bone model after the posterior petrosal approach and Kawase's approach. (A) Opened carotid canal and cochlea. (B) Opened internal auditory canal and mastoid antrum, and exposed lateral semicircular canal. α , area of bone removal after posterior transpetrosal approach; β , area of bone removal after Kawase's approach; CC, carotid canal; CO, cochlea; TC, tympanic cavity; IAC, internal auditory canal; LSC, lateral semicircular canal; MA, mastoid antrum.

Figure 8 Procedures of Dolenc's approach. (A) Exposed periorbita of the orbit and drilling out of the superior orbital fissure. (B) Opened optic canal and exposed optic strut. (C) Removing anterior clinoid process. (D) Opened carotid space. The clinoid segment of the internal carotid artery (C3) can be observed through the carotid space. ACP, anterior clinoid process; C2, supraclinoid portion of the internal carotid artery; C3, clinoid segment of the internal carotid artery; DR, distal dural ring; ES, ethmoid sinus; MOB (SOF), meningo-orbital band (periosteal bridge) in the superior orbital fissure; OC, optic canal; OR, periorbita of the orbit; OS, optic strut; SOF, superior orbital fissure.

Figure 9 Procedures of Dolenc's approach (continued). (A) Peeling off of the dura propria of the lateral wall in the cavernous sinus. (B) Final appearance of Dolenc's approach. The oculomotor, trochlear, and trigeminal nerves and the Gasserian ganglion are exposed. Glasscock's triangle is drilled out and the intrapetrous segment of the internal carotid artery (C6) exposed. C2, supraclinoid segment of the internal carotid artery; C3, clinoid segment of the internal carotid artery; C6, intrapetrous segment of the internal carotid artery; CS, cavernous sinus; GaG, Gasserian ganglion; MMA, middle meningeal artery; V1, ophthalmic division of the trigeminal nerve; V2, maxillary division of the trigeminal nerve; V3, mandibular division of the trigeminal nerve; III, oculomotor nerve; IV, trochlear nerve.

Fig. 9B shows the final appearance of Dolenc's approach. The techniques and procedures of epidural cavernous surgery were accurately experienced except for the frontotemporal dural reflection.

After dissection of the modified 3D whole skull base model, the areas of bone drilling including the opened optic canal and removed ACP were confirmed by bone density CT (Fig. 10).

DISCUSSION

The present study found that the new dissectable temporal bone model (OMeR-KEZLEX-TMB-R-L) and whole skull base model (OMeR-KEZLEX-SKB-L) modified for neurosurgical training have greatly improved artificial bone quality for surgical drilling. In particular, feeling of drilling with the surgical bar and cutting with the surgical saw were almost the same as with the real bone, especially the "crispy" touch during drilling of the mastoid air cells and easy dissection of the semicircular canals and fallopian canal surrounded by compact bone inside the mastoid bone. However, these new models still have some problems. The internal bony spaces such as the mastoid air cells and mastoid antrum are packed with artificial bone material powders, which had to be removed. Another problem was the texture of the artificial dura mater made from silicone. The artificial dura mater could be peeled off the artificial bone surface like the real dura mater, but it lacked elasticity and could not be reflected with the surgical spatula. Epidural approaches in skull base surgery generally include the step of dura mater reflection and exposure of the skull base bone for drilling. In this study, the artificial dura mater was extirpated instead of reflected from the area of epidural bone drilling. To simulate the epidural approach more realistically, we need artificial dura mater made from reflectable material.

The present method of reproduction of the skull base structures using artificial materials offers a good model to develop understanding of the complicated 3D anatomy such as the courses of the cranial nerves and ICA inside the cavernous sinus, and the periosteal bridge in the lateral part of the SOF, which is formed by fused double

Figure 10 Bone density computed tomography scans of the dissected modified three-dimensional whole skull base model after Dolenc's approach. (A) Opened superior orbital fissure and optic canal (arrow). (B) Removed anterior clinoid process (arrowhead). ACP, anterior clinoid process; CS, cavernous sinus; ES, ethmoid sinus; OC, optic canal; PCP, posterior clinoid process.

layers of the periorbital and periosteal layer of the middle fossa. Skull base surgery involves not only drilling the bony structure but also manipulation of the dura mater, venous sinuses, cranial nerves, and major blood vessels. Dissection of these modified models with artificial structures using the surgical drill under the operating microscope can provide a substitute or rehearsal for cadaver dissection. Furthermore, the modified models allow dissection at any time and place. Finally, the dissected models can be observed from different angles and the area of the bony removal can be precisely confirmed by CT. Therefore, these three steps of making the skull base model, dissection of the model, and observation of the dissected model will facilitate better understanding of the complicated 3D anatomy and surgical techniques of the skull base.

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