



Skull Anatomy

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Operative Anatomy of the Human Skull: A Virtual Reality Expedition

An understanding of skull anatomy is important for neurosurgical efficiency. The advent of virtual reality and advances in computer graphics technology has enabled the development of simulated experiences and illustrative representations of intricate anatomical relationships. Maintaining a working mental representation of this environment to augment one's capabilities during operative intervention can be particularly cumbersome.

Prior efforts to educate surgical trainees on the intricacies of neuroanatomy have involved meticulous dissection of cadaveric specimens and a review of two-dimensional (2D) representations of anatomical dissections and illustrations. Based on these resources, surgeons have to reconstruct the anatomy in the three-dimensional (3D) space to appreciate the full anatomical relationships. Therefore, there is a need for models that can assist with 3D mental reconstruction of neuroanatomical principles for understanding both normal and pathological cerebral structures.

Computer graphics and 3D digital designs have an established presence in the neurosurgical literature, particularly within the past decade, to augment education. The Visible Human Project was an endeavour by the National Library of Medicine to create a complete 3D representation of a male and female human body for the purpose of education.^{1,2} This endeavour introduced 3D modelling as a novel means of referencing anatomical data.

Digital modelling technology is particularly useful for the field of neurosurgery given the intricate 3D anatomy within the cranial contents and spine. Cranial digital surgical simulation was first initiated in the late 1980's and early 1990's.^{1,3} More recent developments in 3D computerized models have been used to assist with the visuo-spatial challenges of temporal lobectomy,⁴ cerebral aneurysm clipping,^{5,6} transpetrous surgical approach model,⁷ temporal bone dissection,^{8,9} and posterior fossa surgical planning.¹⁰ Advancement in the realism of this technology will also lead to more robust simulation models.

Importantly, these digital models can produce patient-specific 3D print models that provide an opportunity to create physical models to emulate intricate surgical anatomy. This concept was demonstrated for basic otolaryngologic surgical planning in the 1990's^{3,11} and has since expanded to include calvarial vault reconstruction during craniostomy surgery, the vertebral column during posterior screw fixation, and aneurysm configuration during microsurgery.¹²⁻¹⁴

Educational digital models of segments of cranial contents have been created and demonstrated the potential of this technology as a reference. Kockro and Hwang in 2009 created an interactive 3D virtual model of the temporal bone and its intricate microsurgical anatomy to assist with understanding the anatomical relationships.¹⁵ Multiple prior attempts to create temporal bone virtualizations have been reported and are claimed to positively impact the understanding of the body's most intricate bony anatomy.^{14,16-19} Nowinski et al. in 2011 created a digital 3D cerebrovascular atlas through computer software referencing multiple 3T and 7T magnetic resonance imaging (MRI) scans to create a continuous cerebrovascular tree that serves as an educational, research, and clinical reference.²⁰ The literature is devoid of a repository of 3D virtual models for all cranial bones and important neurovascular structures, which is necessary to provide a comprehensive reference.

Through detailed analysis of cadaveric osteologic specimens, software modelling of radiographic reconstructions, and critical examination by an

anatomist, the authors have developed an anatomically accurate and comprehensive 3D digital model of the human cranium. The virtual human skull model has been divided into 6 different anatomical zones to facilitate illustration of the intricate anatomical relationships. We believe these models and accompanying text will provide a useful reference for neurosurgical applications.

Anatomy



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Model 1: An overview of the exterior skull osteological anatomy is demonstrated (**The instructions for use of this and the other following models are as follows:** Please use the full screen function for optimal visualization (by clicking on the arrows on the right lower corner of the model). To move the model in 3D space, use your mouse's left click and drag; to enlarge the object, use the mouse's wheel. The right click and drag function moves the model across the plane.) Please click on the "Select an annotation" link at the bottom of the window and then choose "Show annotations" to expose the annotations on the model.



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Model 2: An overview of the interior skull osteological anatomy is demonstrated.

Frontal Bone

The frontal bone is a large, unpaired bone that starts out developmentally as two halves that fuse together, along the metopic suture. The frontal bone articulates with the right and left parietal bones, the zygomatic bones, the sphenoid bone, the ethmoid bones, lacrimal bones, maxillary bones, and the nasal bones.^{21,22} The frontal bone is made up of three parts: the squamous, orbital and nasal parts. The squamous portion is the largest and smoothest. On either side of the midline are two rounded

elevations, called the frontal eminences.^{21,22} Beneath these are two superciliary arches joined in the middle by the glabella. Laterally, the supraorbital margins form the orbital rim and contain the supraorbital notch which transmits the supraorbital vessels and nerves.²³

Inferior to the glabella lie the nasal notch and spine, which articulate with the nasal bones and the perpendicular plate of the ethmoid. The cranial surface of the squamous portion of the frontal bone contains the sagittal sulcus, in which the sagittal venous sinus resides. The edges of the sulcus extend inferiorly to form the frontal crest, to which the falx cerebri attaches. The orbital portion of the frontal bone is formed by two orbital plates joined by the ethmoidal notch, which is filled by the cribriform plate of the ethmoid.^{22,23} The inferior surface of each orbital plate contains a small depression under the zygomatic process called the lacrimal fossa.²³ The orbital portion of the frontal bone contains the frontal sinuses and the frontonasal ducts.



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Model 3: Frontal Bone

Ethmoid Bone

The ethmoid bone is an unpaired bone shaped like a cube that articulates with 13 cranial and facial bones. The cranial bones it articulates with, include the frontal and sphenoid bones. The ethmoid has three parts: the cribriform plate, the ethmoidal labyrinth, and perpendicular plate.²² The cribriform plate integrates into the ethmoidal notch of the frontal bone. Anteriorly, this articulation forms the foramen cecum. The crista galli is a midline upward projection to which the falx cerebri attaches. On either side of the crista galli, the cribriform plate has grooves that hold an olfactory bulb. Tiny foramina in the cribriform plate allow for the transmission of the olfactory nerves.

Extending inferiorly from the cribriform plate at the midline is the

perpendicular plate.²² The perpendicular plate is almost entirely smooth except for a number of grooves on either side that lodge the olfactory nerves. Below the cribriform plate laterally lies the ethmoidal labyrinth which contains a network of thin-walled cavities, the ethmoidal cells.

The lateral surfaces of the labyrinth are covered by very thin, smooth plates called the lamina papyracea.²² The posterior parts of the medial surfaces of the labyrinth contain thin, curved bones that form the superior nasal conchae and have an associated superior meatus. Another curved projection forms the middle nasal conchae, which also have an associated meatus. Just inferior to the middle concha is a small, bony projection called the uncinat process, which forms a part of the medial wall of the maxillary sinus.



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Model 4: Ethmoid Bone

Sphenoid Bone

The sphenoid bone is an unpaired bone situated in the middle of the cranial base. It articulates with the adjacent temporal, parietal, frontal, occipital, ethmoid, zygomatic, palatine, and vomer bones and its intricate microanatomy includes numerous foramina.^{22,24} This bone is the center of attention in endonasal skull base surgery.

The sphenoid bone is made up of several parts: a central body that contains the sella turcica, and two greater wings and two lesser wings laterally.²⁵ The greater wings make up the anterior portions of both middle fossae and the lesser wings make up the posterior portion of the anterior cranial fossa. The clinoid processes are important features of the sphenoid bone in skull base surgery.

The anterior clinoid processes are very prominent ends of the lesser wing of the sphenoid bone and extend toward the Sylvian fissure.^{22,25} The

middle clinoid processes are eminences forming the anterior border of the sella turcica.²² The posterior clinoid processes form the ends of the dorsum sellae, and their size and form vary greatly in individuals. The tentorium cerebelli attaches to the posterior clinoids. The optic canals, which transmit the optic nerves and the ophthalmic arteries, are located at the junction of the body and the lesser wings.^{21-23,25} A groove in the midline of the sphenoid body creates the optic groove, posterior to which is the tuberculum sellae.

The cleft created between a greater and lesser wing forms the superior orbital fissure, which transmits the oculomotor nerve (III), trochlear nerve (IV), the lacrimal, nasociliary, and frontal divisions of the ophthalmic nerve (V1), abducens nerve (VI), superior and inferior divisions of the ophthalmic vein, and the sympathetic fibers from the cavernous sinus.²⁵ Each greater wing contains the foramen rotundum, which transmits the maxillary nerve (V2); foramen ovale, which transmits the mandibular nerve (V3), accessory meningeal artery and often times the lesser petrosal nerve; and foramen spinosum, which transmits the middle meningeal vessels and the recurrent branch of the mandibular nerve.

Inferiorly, the sphenoid bone contains two pterygoid processes, made up of a medial and lateral plate, to which the medial and lateral pterygoid muscles attach, allowing for jaw movement.²² When looking at the sphenoid bone from the anterior direction, the pterygoid or Vidian's canal can be noted inferomedial to the foramen rotundum. The Vidian's nerve, artery, and vein are transmitted through this canal. Vidian's nerve is formed by the union of the greater petrosal nerve and the deep petrosal nerve within the canal.²²



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Model 5: Sphenoid Bone

Temporal Bone

The temporal bones are divided into the squamosal, mastoid, tympanic, styloid, and petrous segments. Each articulates with the zygomatic bone (zygomaticotemporal suture), sphenoid bone (sphenosquamosal suture), parietal bone (parietosquamous suture), and occipital bone (occipitomastoid suture).²²⁻²⁴ Understanding the anatomy of the temporal bone is critical to a number of open skull base approaches.²⁶ A number of critical neurovascular structures, namely, the lower seven cranial nerves and the major vessels to and from the brain, traverse the temporal bone.

Externally, the squamous portion of the temporal bone is smooth and provides attachment for the temporalis fascia and muscle at the superior and inferior temporal lines, respectively.²² The zygomatic process, which has an anterior and posterior root, extends anteriorly and articulates with the zygomatic bone. Near the anterior root of the zygomatic process is the articular tubercle, just posterior to which is the glenoid fossa, where the temporomandibular joint resides.²² Posteromedial to the glenoid fossa is the petrotympanic fissure which transmits the chorda tympani and the tympanic branch of the maxillary artery.²⁶ The tympanic portion of the temporal bone includes the external auditory meatus.²² When looking into the external auditory meatus in a bony preparation, normally covered by the tympanic membrane, features of the medial wall of the tympanic cavity can be visualized; the fenestra vestibuli (oval window), which is covered by the footplate of the stapes bone, and the fenestra cochleae (round window), which is covered by the secondary tympanic membrane.

Inferiorly, there are two processes, the vaginal process laterally and the styloid process medially. The stylomastoid foramen is just posterior to the styloid process and transmits the facial nerve and the stylomastoid branch of the posterior auricular artery.^{22,26} Posteriorly, near the mastoid bone is the tympanomastoid fissure which transmits the auricular nerve of CN X.²⁶

The mastoid process is a large protuberance in the posterior part of the temporal bone that provides attachment to the occipitalis, posterior auricular, sternocleidomastoid, posterior belly of the digastric, splenius

capitis, and longissimus capitis muscles. It is filled with air cells.²² Also, on the inferior surface is the carotid canal which transmits the internal carotid artery and the accompanying sympathetic plexus of nerves. Adjacent to the carotid canal are the tympanic and cochlear canaliculi. The tympanic canaliculus transmits the tympanic branch of CN IX and the inferior tympanic artery. The cochlear canaliculus transmits the perilymphatic duct and vein.^{22,26}

On the cranial surface, the mastoid bone has an impression for the sigmoid sinus and a small foramen that usually transmits an emissary vein to the sinus. The petrous portion has an impression for the superior petrosal sinus, which drains blood from the cavernous sinus to the transverse sinus. The arcuate eminence, which marks the location of the superior semicircular canal, is an important landmark. Anterior and lateral to the arcuate eminence is an extremely thin segment of bone called the tegmen tympani, which separates the tympanic cavity from the cranial cavity.

Within the petrous portion of the temporal bone are all of the structures of the inner ear, including the ossicles, cochlea and semicircular canals.²⁶ The internal acoustic meatus is an obvious foramen that transmits the facial nerve (CN VII), vestibulocochlear nerve (CN VIII), and the internal auditory branch of the basilar artery.²⁶ Just superior and lateral to this is the aqueduct of the vestibule, which transmits the endolymphatic duct and a small artery and vein. Inferior and slightly lateral to the internal acoustic meatus is the cochlear aqueduct which transmits the perilymphatic duct.^{22,26}

At the anteromedial part of the temporal bone is the anterior portion of the carotid canal.²¹ Just lateral to that is the bony portion of the Eustachian tube.^{22,24} Superior to the Eustachian tube is a shallow groove extending laterally and posteriorly to an opening, called the hiatus of the facial canal, which transmits the greater petrosal nerve.

The temporal bone has relevance to many surgical approaches utilized in neurosurgery. The middle fossa, subtemporal anterior transpetrosal

(otherwise referred to as the Kawase approach), translabyrinthine, transcochlear, subtemporal preauricular infratemporal, postauricular transtemporal approach, and presigmoid (supra- and infra-tentorial) approach to the middle and posterior fossae.



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Model 6: Temporal Bone (Please note: Due to heavy annotation in this model, you have to zoom in to see the inner ear structures. Alternatively, click on "Select an annotation link at the bottom of the window and hide annotations so that the deep anatomy is visible.)

Parietal Bone

The paired parietal bones join at the sagittal suture to form the sides and roof of the cranium. Aside from articulating with each other, the parietal bones articulate with the frontal (coronal suture), occipital (lambdoid suture), temporal (squamosal suture), and sphenoid bones.²⁴ The external surface is marked by a point near the center called the parietal eminence. Inferior to this are two curving lines, the superior and inferior temporal lines.²²

The superior temporal line is the site of attachment of the temporalis muscle fascia and the inferior temporal line is the upper attachment of the temporalis muscle.²² The inner surface of the parietal bone has a sulcus for the superior sagittal sinus and accompanying foveolae granulares, depressions for the arachnoid granulations. Inferiorly, there is a groove for the middle meningeal artery.



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Model 7: Parietal Bone

Occipital Bone

The occipital bone makes up the posterior portion of the cranium and the skull base and contains three parts: the squamous part, basilar part, and lateral parts. The occipital bone articulates with the parietal (lambdoid suture), temporal (occipitomastoid suture), and sphenoid bones.^{22,24} Externally, the most prominent part of the squamous portion of the occipital bone is the external occipital protuberance, specifically the inion, to which the nuchal ligament and trapezius muscles attach.²² The planum occipitale is the smooth portion of the bone superiorly.

Inferior to the planum occipitale are a series of nuchal lines, the superior and inferior nuchal lines oriented transversely. The superior nuchal lines join medially to the external occipital protuberance. The median nuchal line extends from the external occipital protuberance to the foramen magnum. The interior surface of the squamous part contains the internal occipital protuberance, occupied by the torcular Herophili, which is the junction of the sagittal sulcus, grooves of the transverse sinuses, and the occipital sulcus.²² The vermian fossa lies in the posterior portion of the foramen magnum.

The basilar part of the occipital bone extends upward from the foramen magnum forming the clivus, which articulates with the dorsum sellae of the sphenoid bone.^{27,28} The exterior surface of the basilar part contains the pharyngeal tubercle.

The lateral parts of the occipital bone make up the sides of the foramen magnum. On their undersurface lie the occipital condyles. Behind the occipital condyle is the condyloid fossa and condyloid canal, which transmits an emissary vein. The hypoglossal canal is a tunnel within the condyle which transmits the hypoglossal nerve (XII) and the meningeal branch of the ascending pharyngeal artery.

The hypoglossal canal is an important landmark for far lateral approaches to the ventral brainstem. On the external surface, extending laterally from the condyle, is the jugular process with the jugular notch anterior to it. The jugular notch makes the posterior part of the jugular foramen.²⁹ The upper surface of the lateral part forms the jugular tubercle which overlies

the hypoglossal canal.^{22,28,29} The largest foramen in the occipital bone, the foramen magnum, transmits the medulla, the spinal accessory nerve (XI), vertebral arteries, anterior spinal arteries, posterior spinal arteries, and alar ligaments.^{22,28}



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Model 8: Occipital Bone

Conclusions

Computer graphic technology has a rich history in the field of neurosurgery and has an increasingly popular presence within the literature as its utility has grown. The skull models that were presented have the potential to serve as a novel method of understanding cranial anatomy with an emphasis on accuracy, completeness, and visual appeal. It has utility in educational, illustrative, and surgical training purposes. The models provide critical insight into the close associations between neurovascular structures and the adjacent bones that compose the skull. These models also highlight the impact that advances in computer graphic technology has and will continue to have in the field of neurosurgery.

The above materials have also been included in the following article in the [Operative Neurosurgery](#).

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