ORIGINAL ARTICLE

Understanding Anatomy of the Petrous Pyramid—A New Compartmental Approach

Mamdouh Tawfik-Helika[1], Patrick Mertens[2], Guilherme Ribas[3], Michael D. Cusimano[4], Martin Catala[5], Ramez Kirollos[6], Timothée Jacquesson[2,7]

■ BACKGROUND: **Learning surgical anatomy of the petrous pyramid can be a challenge, especially in the beginning of the training process. Providing an easier, holistic approach can be of help to everyone with interest in learning and teaching skull base anatomy. We present the complex organization of petrous pyramid anatomy using a new compartmental approach that is simple to understand and remember.**

■ METHODS: **The surfaces of the petrous pyramid of two temporal bones were examined; and the contents of the petrous pyramid of 8 temporal bones were exposed through progressive drilling of the superior surface.**

■ RESULTS: **The petrous pyramid is made up of a bony container, and its contents were grouped into 4 compartments (mucosal, cutaneous, neural, and vascular). Two reference lines were identified (mucosal and external-internal auditory canal lines) intersecting at the level of the middle ear. The localization of contents relative to these reference lines was then described, and 2 methods of segmentation (the X method and the V method) were then proposed. This description was then used to describe middle ear relationships, facial nerve anatomy, and air cell distribution.**

■ CONCLUSIONS: **This new compartmental approach allows a comprehensive understanding of the distribution of petrous pyramid contents. Dividing it into anatomic compartments, and then navigating this mental map along specific reference points, lines, spaces, and segments, could create a useful tool to teach or learn its complex tridimensional anatomy.**

INTRODUCTION

The temporal bone belongs to the skull base and is known to be a complex bone, because of the large number of named contents, and its particular tridimensional shape. The unique anatomic construction of the temporal bone reflects its particular development process and connections. The temporal bone is composed of 5 parts: squamous, petrous, mastoid, styloid, and tympanic.[1] Some researchers have described it as being composed of 3[2] or 4 parts, by considering the mastoid as an extension from both the petrous and squamous parts.[3-5] All 5 parts contribute to the middle ear walls, with the petrous part medially, the squamous part laterally, the mastoid part posteriorly, and both styloid and tympanic parts inferiorly.[2,4-6] The middle and posterior cranial fossae are built on a large pyramid-shaped bone, called the petrous pyramid by Pellet et al.,[2] which houses the

Key words
- Anatomy
- Middle ear
- Petrous
- Pyramid
- Segmentation
- Space
- Temporal bone

Abbreviations and Acronyms
CSF: Cerebrospinal fluid
EAC: External auditory canal
ET: Eustachian tube
FO: Foramen ovale
FS: Foramen spinosum
GSPN: Greater superficial petrosal nerve
IAC: Internal auditory canal
ICA: Internal carotid artery
MA: Mastoid antrum
SCC: Semicircular canal
TMJ: Temporomandibular joint

From the [1]Department of Neurosurgery, Beaujon University Hospital, Assistance publique hopitaux de Paris, Clichy, France; [2]Department of Anatomy, University of Lyon 1, Lyon, France; [3]Department of Surgery, University of São Paulo Medical School, São Paulo, Brazil; [4]Division of Neurosurgery, St. Michael's Hospital, University of Toronto, Toronto, Ontario, Canada; [5]Sorbonne Université, CNRS UMR 7622, INSERM ERL 1156, IBPS, Paris, France; [6]Senior Consultant, National Neuroscience Institute, Singapore; and [7]Skull Base Multi-disciplinary Unit, Department of Neurosurgery B, Neurological Hospital Pierre Wertheimer, Hospices Civils de Lyon, Lyon Cedex, France

To whom correspondence should be addressed: Mamdouh Tawfik-Helika, M.D. [E-mail: drmamdoh@hotmail.com]

Citation: World Neurosurg. (2019) 124:e65-e80.
https://doi.org/10.1016/j.wneu.2018.11.234

Journal homepage: ***www.journals.elsevier.com/world-neurosurgery***

Available online: ***www.sciencedirect.com***

organs of hearing and equilibrium and is crossed by cranial nerves and the internal carotid artery (ICA). The petrous pyramid is the area of interest in this work.

Segmentation of the petrous pyramid has rarely been described for surgical purposes.[2,7,8] However, better understanding of its tridimensional architecture could further help teaching, imaging, and surgical planning. Despite seeming complexity, the petrous pyramid structure shows certain patterns that can be better appreciated from a superior view. These patterns can simplify understanding the anatomic architecture of intrapetrous contents. Traditional description of temporal bone anatomy starts with its parts and goes directly into details; such as middle ear contents and the facial nerve. Yet, having a clear understanding of the general plan, while facing a large number of details, may be difficult in the beginning of the training process, which is already time limited. This may even make it harder to step up into use for clinical applications, especially for young surgical trainees. Having a holistic plan may provide an easier way to start learning. Breaking down a complex map into smaller parts and understanding their relative positions, before analyzing each of them, might provide a useful way to conceptualize, learn, and navigate. Like any map, it needs to have reference points and directions for orientation purposes; as well as landmarks; for proper use.

We propose a new anatomic compartmental approach to the petrous pyramid that could ease understanding and navigation along simple landmarks, lines, and spaces. As a result of different methods of segmentation, we aim to provide an educational tool for surgeons; as one advances progressively from creating the map, to its use and applications.

METHODS

One dry head (2 temporal bones) was used to study the walls of the petrous pyramid. In addition, 4 fresh cadaver heads (8 temporal bones) were harvested in the anatomy laboratory of University Lyon 1 (Lyon, France), prepared with 3% formaldehyde, and then injected with colored latex (Aérographe Colorex Technics, Magenta and Cyan [Phocéenne de chimie, Marseille, France]). The vertex and the whole brain were removed, including the brainstem. Cranial nerves II—XII were carefully left in place, as well as the ICA. The dura was gently removed at each side and the skull base was then exposed with cisternal segments of all cranial nerves of the middle and posterior cranial fossa.

Drilling (Midas Rex [Medtronic, Fort Worth, Texas, USA]) started at the center of the superior aspect of the petrous pyramid, to unroof the middle ear, removing the tegmen tympani, and exposing the malleus and incus. The hiatus of the greater superficial petrosal nerve (GSPN) was anterior and medial to the tegmen tympani. Drilling continued anteriorly, lateral to GSPN, and medial to the foramen ovale (FO)—foramen spinosum (FS) line, to open the eustachian tube (ET). The tensor tympani muscle, lying above the ET, was sectioned. Drilling then proceeded posteriorly, beyond the short process of the incus that marks the aditus ad antrum, to enter into the mastoid antrum (MA). The external auditory canal (EAC) and the internal auditory canal (IAC) were exposed. The temporomandibular joint (TMJ) was just anterior to the EAC. Drilling achieved on both sides of the IAC to find the anterior labyrinth (the cochlea) and the posterior labyrinth (the vestibule and semicircular canals [SCCs]). The ICA was freed at the petrous apex, medial to the ET, below the GSPN and trigeminal ganglion, toward its exit through the upper part of the foramen lacerum into the cavernous sinus. The major space-occupying contents of the petrous pyramid were then grouped into four groups, or compartments, having different composition, lining, and connections. These are the mucosal, cutaneous, neural and vascular compartments; respectively. The other parts of the petrous pyramid, not occupied by any of the four compartments, have also been adressed.

RESULTS

The petrous pyramid can be described as being composed of 2 parts: the bony container and the contents, which are described in terms of compartments. Four compartments are thus described based on their nature and connections: mucosal, cutaneous, neural, and vascular. The mucosal compartment or line consists of the ET, middle ear, and MA and is used as the axis of reference. It is drawn obliquely anteromedially, pointing to, and opening into the pharynx. The mucosal line is considered as the central piece of this approach because the terms anterior, posterior, medial, and lateral are used relative to this axis, also called the mucosal axis; not to the midsagittal plane. All major anatomic structures were thus located relative to the mucosal axis: the mucosal compartment lies along the axis, the cutaneous compartment (EAC) lateral to the middle ear, the neural compartment (IAC + anterior labyrinth or cochlea + posterior labyrinth made up of vestibule and SCCs) medial to the middle ear, and the vascular compartment (ICA) medial to the ET. Then, 2 methods of segmentation were developed. These blueprints were used to describe the anatomy of the middle ear, facial nerve, and air cells.

The Container: General Form and Location of the Petrous Pyramid

The petrous pyramid is the partition separating the middle and posterior cranial fossae, as shown in Figure 1. It is pyramid shaped with 3 lateral surfaces and a base, all triangular; and is surrounded by cortical bone. The base of the pyramid faces laterally whereas the apex faces the midline. The superior/anterior surface forms the posterior part of the floor of the middle cranial fossa and faces the temporal lobe, whereas the apical part faces Meckel's cave. We adopted the description of its anterior limit as was proposed by Ribas et al.[9] It is composed of a horizontal line starting laterally at a preauricular burrhole, located just anterior to the tragus, facing the dorsum sella medially, and passing through the FS. The posterior limit is the petrous ridge, whereas the lateral limit is the junction with the vertical part of the squamous bone.

The posterior surface of the petrous pyramid on each side, along with the clivus, form the anterior wall of the posterior cranial fossa. The posterior petrous surface is surrounded by impressions of dural venous sinuses (sigmoid; and superior and inferior petrosal sinuses), that form a venous triangle. The superior margin has an impression for the superior petrosal sinus; and the lateral margin has the groove for the vertical segment of the sigmoid sinus. The inferior margin has a groove for the inferior petrosal sinus anteriorly; the horizontal segment of the sigmoid sinus posteriorly; while the middle part is occupied by the jugular

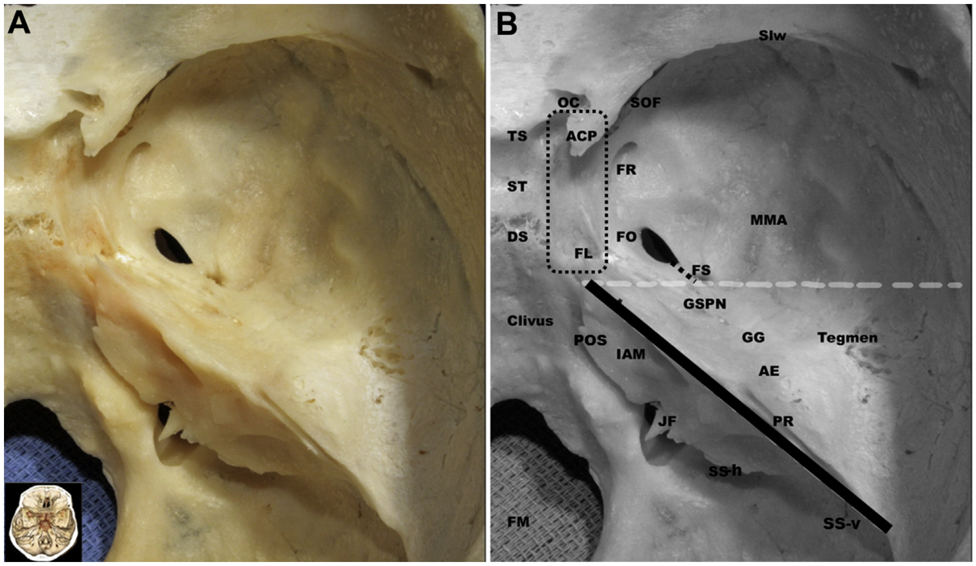

Figure 1. The right petrous pyramid of a dry skull from a superior view. Superior view of the right side of the skull base, showing the floor of the middle cranial fossa; as well as parts of the anterior and posterior cranial fossa floors. Inset shows orientation of the skull base in this anatomic view. (**A**) The petrous pyramid is the partition between the middle and posterior cranial fossae. It makes up the posterior part of the floor of the middle cranial fossa. (**B**) The limits of the superior and posterior petrous surfaces are shown. A horizontal line is drawn (*white discontinuous line*) representing the anterior limit of the superior surface. This line starts laterally in front of the tragus (i.e., the preauricular burrhole; not a point) and extends medially passing through the foramen spinosum (FS) to meet the petrous ridge behind the foramen lacerum (FL). The posterior limit is the petrous ridge (PR, *thick black line*). The lateral limit is where the superior petrous surface meets the vertical plate of the squamous bone. A line between the foramen ovale (FO) and FS is shown as a black dotted line. The posterior petrous surface is triangular, limited superiorly by the PR; its lateral limit is the groove for the vertical segment of the sigmoid sinus (SS-v). Its inferior limit is composed of three parts: the groove for the horizontal segment of the sigmoid sinus (SS-h) posteriorly; the petro-occipital suture (POS, level of the inferior petrosal sinus) anteriorly; and the jugular foramen (JF) in the middle. The relative position of the superimposed cavernous sinus is shown as dotted rectangle, and inlcudes the posteriorly located FL. The anterior and middle cranial fossae are separted by the sphenoid ridge (sphenoid lesser wing, Slw), while the petrous ridge separates the middle and posterior cranial fossae. ACP, anterior clinoid process; AE, arcuate eminence; DS, dorsum sellae; FM, foramen magnum; FR, foramen rotundum; GG, geniculate ganglion; GSPN, groove for the greater superficial petrosal nerve; IAM, internal auditory meatus; MMA, middle meningeal artery groove; OC, optic canal; SOF, superior orbital fissure; ST, sella turcica; TS, tuberculum sellae.

foramen, as seen in Figure 1. The sigmoid sinus exits the jugular foramen to become the internal jugular vein; and the foramen also carries the exiting cranial nerves IX to XI. These relations are shown in Figure 1; and also shown is the location of the superimposed cavernous sinus on the middle fossa floor. On the other hand, the inferior petrous surface; faces the neck; while the lateral surface (the base) is formed by the lateral surface of the mastoid, with the external auditory meatus in its anterosuperior angle, just posterior to the TMJ.

The Contents: Compartments

The final aspect of the petrous contents after drilling of the superior surface is shown in Figure 2. The contents were organized into 4 compartments as detailed in the following paragraphs and as shown in Figure 3. These compartments were shown to have specific and consistent relationships, in terms of location, within the petrous pyramid.

The mucosal compartment is defined by the nearly linear alignment of the ET anteriorly; the middle ear; and MA posteriorly, as shown in Figure 2 and colored green in Figure 3. It is an air-filled mucosa-lined series of cavities extending to the pharynx,[3] in an oblique anteromedial direction. Extending this line posteriorly into the MA divides the mastoid into medial and lateral parts. Extending it anteriorly leads to the ET bony segment in the junction between the petrous and squamous bones[3] and the more anterior cartilaginous segment of the ET outside the petrous pyramid and opening into the pharynx. The mucosal line was found to be interposed between 2 parallel lines, the GSPN line medially and the FO-FS line laterally, as shown in Figure 2. All 3 are nearly parallel to the petrous ridge.

The cutaneous compartment is formed by the skin-lined and air-filled bony EAC (walled inferiorly by the tympanic bone). It is shown in pink in Figure 3 and is located lateral to the mucosal line, more specifically to the middle ear. Medially, it meets the

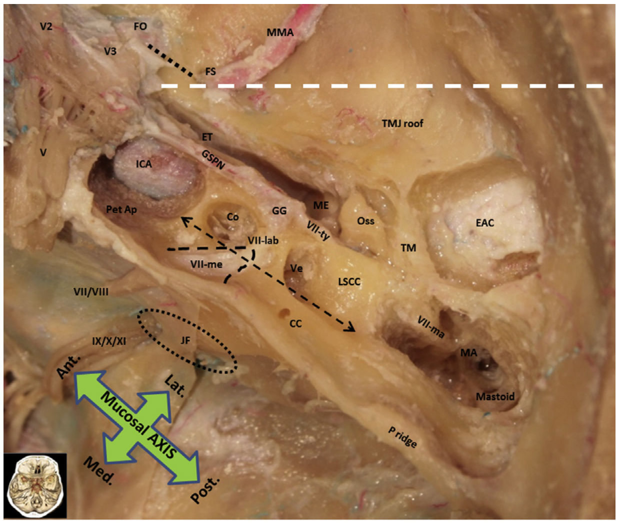

Figure 2. Superior view of contents of the right petrous pyramid after drilling of its superior surface. Inset shows orientation of the skull base in this anatomic view. The *crossed green arrows* indicate the mucosal axis, parallel to the mucosal line, which is used as the reference for directions in this work, not the mid-sagittal plane. The posterior limit of the petrous pyramid is the petrous ridge (P ridge). The *white interrupted line* is the location of the line set as the anterior limit of the petrous pyramid, passing through the foramen spinosum (FS).The trigeminal nerve (V); and its mandibular branch (V3) exiting through the foramen ovale (FO), are seen on the upper left part. More posterior are the middle meningeal artery (MMA) entering through the FS. A line between the FO and FS is shown as *black dotted line.* More medial to the FO and FS are a series of mucosa-lined cavities, i.e., the mucosal line: eustachian tube (ET) anteriorly, middle ear (ME) and mastoid antrum (MA) more posteriorly, ending within the mastoid. The upper parts of the ossicles (Oss), i.e., malleus and incus, are exposed inside the middle ear. The external auditory canal (EAC) lies laterally to the ME and meets it at the tympanic membrane (TM) level; the figure showing a bony ridge above it . More anterior to the EAC is the roof of the temporomandibular joint (TMJ). Medial to the ME is the glistening hard bone of the otic capsule (extent shown as black interrupted double arrowed line, which also shows the extent of the more laterally located middle ear). The otic capsule contains the cochlea (Co) anteriorly, and the vestibule (Ve) posteriorly, separated by the internal auditory canal (IAC, cone shaped, contoured by interrupted line) containing the meatal segment of the facial nerve (VII-me). The vestibule is nearly on a line connecting the EAC and IAC. Cranial nerves VII and VIII enter through the internal auditory meatus, which has a relatively anterior position to the otic capsule, then running inside the IAC which has an oblique trajectory. Also seen is the common crus (CC) of the posterior and superior semicircular canals; and the circular aspect of the lateral semicircular canal (LSCC). The facial nerve continues after the ending of the IAC, as the labyrinthine segment (VII-lab) to arrive at the ME as the geniculate ganglion (GG); and then turns posteriorly (first genu) to continue as the tympanic segment (VII-ty), running on the medial wall of the middle ear. The anterior part of VII-ty is lateral to the vestibule, and the posterior part runs below the LSCC. It reappears behind the LSCC as it turns down (second genu) below the aditus ad antrum and descends vertically as the mastoid segment (VII-ma). The greater superficial petrosal nerve (GSPN) coming from the geniculate ganglion runs medial and parallel to the ET, and even more medial to it is the internal carotid artery (ICA) running inside the petrous apex (Pet ap). The mixed cranial nerves (IX/X/XI) are shown entering the jugular foramen (JF, dotted ovoid) below the petrous pyramid, which also allows exit of the more laterally located sigmoid sinus (not shown). The JF is a defect between the middle part of the inferior margin of the petrous pyramid, and the occipital bone, and lies at the same level as the otic capusle, being below and behind it. CC, common curs; GSPN, groove for the greater superficial petrosal nerve; Mastoid, drilled mastoid cells; V2, maxillary nerve; V3, mandibular nerve; VII/VIII, facial and vestibulocochlear nerves.

middle ear at the tympanic membrane. The cartilaginous EAC is the extension of the bony EAC outside the petrous pyramid.

The neural compartment (colored blue in **Figure 3**) is composed of the dense bone of the otic capsule, medial to the mucosal line, or more specifically, medial to the middle ear. The otic capsule contains the inner ear sensory organs separated by the IAC into anterior (cochlea) and posterior (vestibule and SCCs) labyrinths. The cochlea and vestibule lie anterior and posterior to the fundus of the IAC, and they receive the cochlear and vestibular nerves, respectively. The vestibule nearly lies on a line connecting the EAC and IAC. The variable bone density between air cells and the otic capsule make it easily recognizable, unlike the dense cortical bone cover of the pyramid. The cochlea has a snail-shell shape, whereas SCCs are arranged like 3 flower leafs joined at the center of the flower (the vestibule). The orientation of the SCCs deserves special mention: the 3 canals are classically described as being perpendicular to each other; the posterior is nearly parallel to the posterior petrous wall[3]; the superior is related to the prominent arcuate eminence at the superior aspect of the petrous pyramid, and is perpendicular to the long axis of the petrous[3]; and the lateral is angled at 30° from the horizontal plane. The posterior and superior SCCs share a common crus, as shown in **Figure 2**. The facial nerve has a complex course, relations, and branches and is thus discussed separately.

The vascular compartment is logically composed of the ICA, surrounded by venous and sympathetic plexi. It is shown in red in **Figure 3**. It has an anterior and posterior genus but the most prominent part is the horizontal segment, which was located medial and parallel to the mucosal line, or more specifically to the ET; and generally separated by a septum. It runs within the carotid canal, inside the petrous apex, which is part of the petrous bone proper, and is located anterior to the otic capsule. The ICA enters the carotid canal at the inferior aspect of the petrous pyramid, and it then angles to a horizontal segment, just anterior to the cochlea. It crosses below the trigeminal ganglion going toward the foramen lacerum before turning up and entering the cavernous sinus.

Segmentation Methods

After separating the petrous contents into compartments, 2 segmentation methods were created that could help understanding and memorization of their distribution: the X method and the V method. Two reference lines were used: the mucosal line and the EAC-IAC line (**Figure 4**). Both these lines have a nearly straight course.

The X method (**Figure 4B** and **E**) described the pyramid organization as being divided by the 2 reference lines, which intersected at the middle ear in the form of the letter X, thus creating 4 spaces. The V method (**Figure 4C** and **F**) described the contents as 5 segments arranged around the mucosal line, in the form of the letter V, with 2 branches and an angle pointing posteriorly. Two segments lie medial to the mucosal line as the medial branch, 2 lie lateral to it as the lateral branch, and 1 lies behind it as the angle of the V.

Middle Ear

The middle ear lies in the center of the petrous pyramid and is the point of intersection of the 2 reference lines: mucosal and

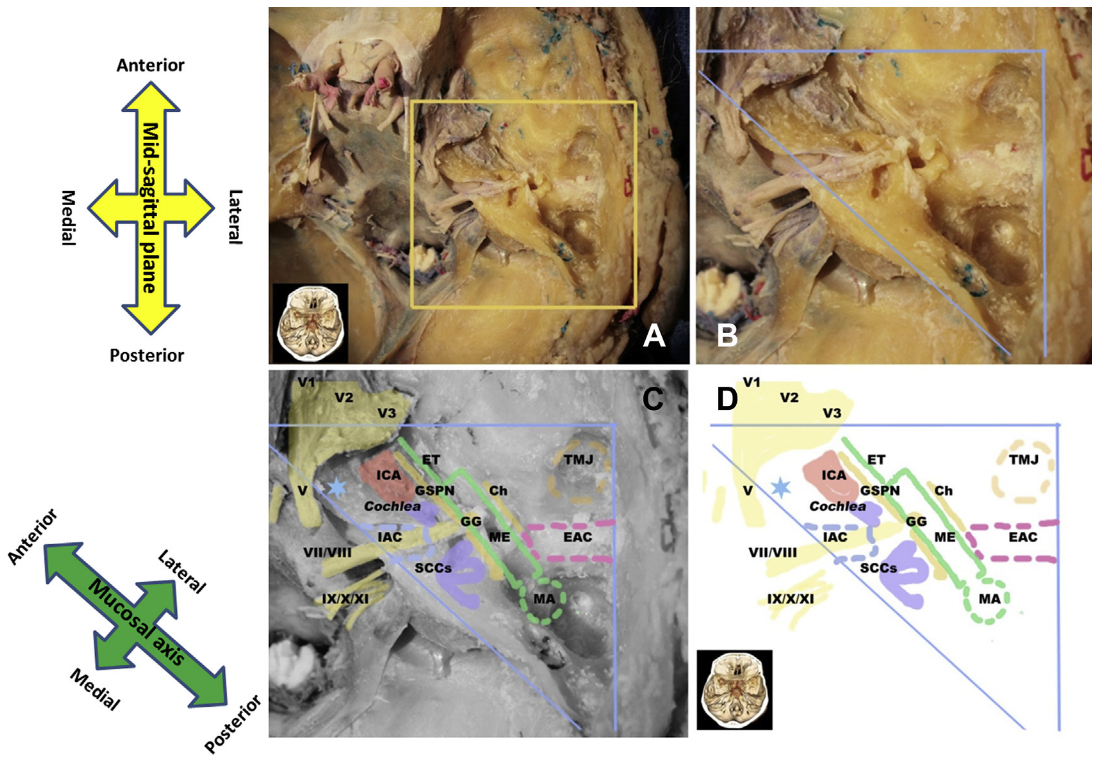

Figure 3. Schematic view of petrous pyramid contents superimposed progressively on images of skull base dissections. Inset in **D** shows orientation of the skull base in this anatomic view. On the left are two crossed arrows; the upper vertical yellow one shows the mid-sagittal plane; and the lower green oblique one shows the mucosal axis, with orthogonal directions relative to it. Shown here are the superior aspect of a right petrous pyramid after complete drilling (**A**), magnification of the petrous pyramid (**B**), with annotations indicating contents with colors (**C**), and their schematic representation (**D**). The triangle of blue lines shows the limits of the superior surface of the petrous pyramid. The mucosal compartment (*green*) courses obliquely from the mastoid antrum (MA) posteriorly, towards the pharynx in the anterior midline (not shown); including the eustachian tube (ET) and middle ear (ME). The cutaneous compartment (*pink*) lies laterally to the ME and is composed of the external auditory canal (EAC). The neural compartment (*blue*) lies medial to the ME and is composed of the anterior and posterior labyrinths, respectively; the cochlea and semicircular canals (SCCs). These lie anterior and posterior to the internal auditory canal (IAC, surrounded by interrupted blue line); respectively. The facial nerve course is shown in yellow running inside the IAC towards the ME, and continues beyond the IAC to end in the geniculate ganglion (GG), and then runs posteriorly as the tympanic segment. It gives origin to two major branches; the greater superficial petrosal nerve (GSPN) and the chorda tympani (Ch), but facial nerve anatomy will be addressed separately in another figure for clarity. The vascular compartment (*red*) is medial to the ET and is composed of the internal carotid artery (ICA) inside the petrous apex (*). Moreover, some structures that do not belong to the petrous pyramid constitute relevant landmarks: the trigeminal ganglion (V) lies over the petrous apex and the internal carotid artery; and also seen is cranial nerve VI medially to the trigeminal ganglion, entering Dorello's canal lateral to the upper third of the clivus, and is colored yellow. The lower cranial nerves IX–XI go inferiorly toward the jugular foramen. The temporomandibular joint (TMJ) lies anterior to the EAC. V1–3, branches of the trigeminal nerve; VII–VIII, the acousticofacial nerve complex.

EAC-IAC lines. We correlated the walls of the middle ear with compartments, lines, and spaces. It is shaped like a 6-walled box. As part of the mucosal line, it is connected to the ET anteriorly, and to the MA posteriorly (by the aditus ad antrum).[3] Just above the ET, in a separate canal, is the tensor tympani muscle, originating from the wall of the cartilaginous ET and adjacent bone, going into the middle ear to attach to the incus.[3] It contains the ossicles (malleus, incus, and stapes) and muscles (tensor tympani and stapedius), as well as mucosal folds that can be used to divide the middle ear into subcompartments.[4] In view of this description, the major relations of the middle ear are listed in **Table 1**.[3,4,6,10]

Facial Nerve

The facial nerve is considered as a part of the neural compartment. Its segments and branches are closely related to the neural compartment (meatal segment inside the IAC, and labyrinthine segment extending between the IAC and the medial wall of the middle ear) and to the mucosal line, especially to the walls of the middle ear (tympanic segment on its medial wall and mastoid

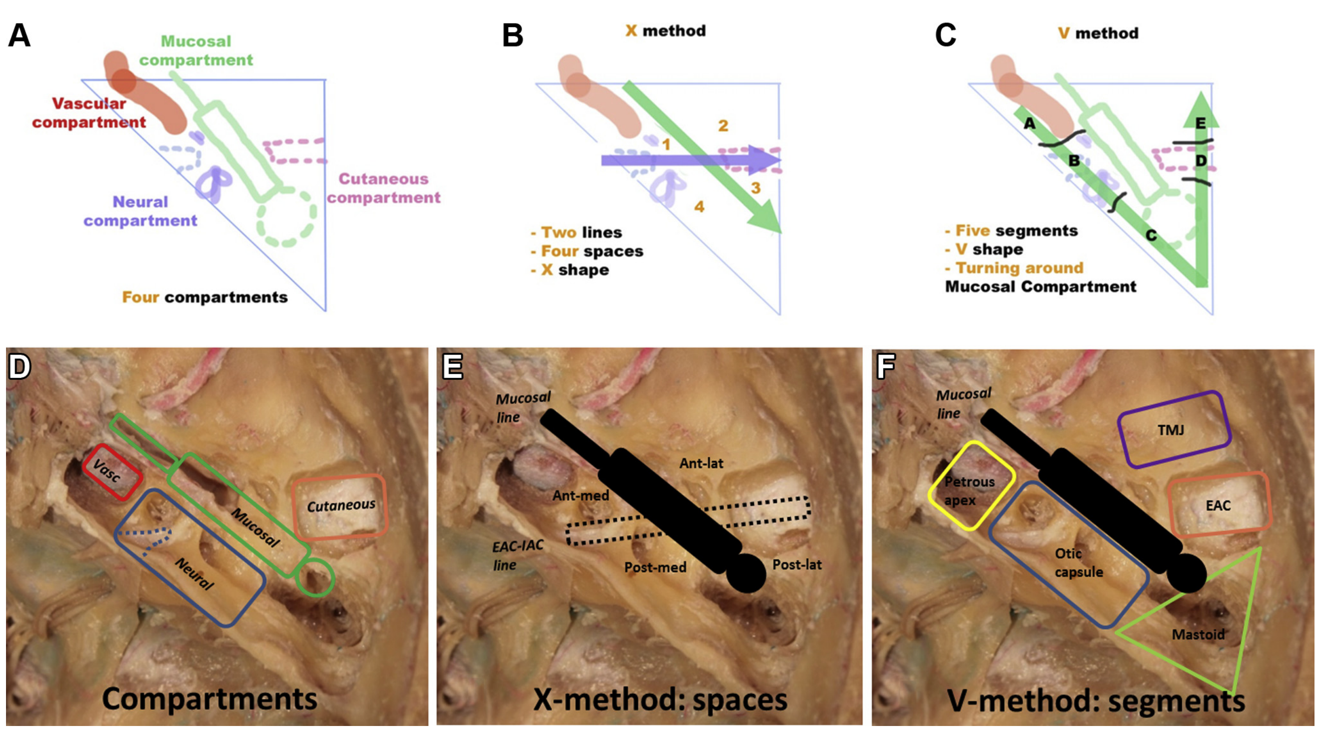

Figure 4. Segmentation methods of the right petrous pyramid contents as seen from above. Organization and segmentation methods are shown as diagrammatic figures (**A**—**C**) and superimposed on dissection photos (**D**—**F**). (**A**) and (**D**) show the compartments, whereas (**B**), (**C**), (**E**), and (**F**) show the 2 methods of segmentation. (**A**) Four compartments could be described within the petrous pyramid: mucosal (*green, with its different segments*), cutaneous (*pink*), neural (*violet*), and vascular (*red*) compartments. (**B**) The X method divides the petrous pyramid into 4 spaces through 2 intersecting lines (the mucosal line [*green*] and the external-internal auditory canal (EAC-IAC) line [*blue*]), forming the letter X. The 4 spaces are located clockwise around the middle ear: (1) anteromedial space containing the cochlea and the petrous apex carrying the internal carotid artery, (2) anterolateral space containing the roof of the temporomandibular joint (TMJ), (3) posterolateral space contained the smaller lateral part of the mastoid, and (4) posteromedial space containing the posterior labyrinth (vestibule and semicircular canal) and the larger medial part of the mastoid. The mastoid thus occupies both the posterolateral and parts of the posteromedial spaces, crossing the mucosal line. On the other hand, the labyrinths occupy both the anterior and posterior medial spaces, on either side of the IAC. (**C**) The V method arranges 5 segments around the mucosal line (*green*) in a V-shaped form. The 5 segments are successively called: (*A*) petrous apex segment medial to the eustachian tube and carrying the internal carotid artery, (*B*) otic capsule segment including the IAC, cochlea, vestibule, and semicircular canals, (*C*) mastoid segment occupying the angle around the mastoid antrum, (*D*) EAC segment lateral to the middle ear; and (*E*) TMJ segment which is the roof of the TMJ, lateral to the eustachian tube. (**D**) The 4 compartments are shown as follows: mucosal (*green*), cutaneous (*orange*), neural (*blue*), and vascular (*red*). The contour of the internal auditory canal is shown as an interrupted blue line. (**E**) The X method of segmentation is shown as 2 lines: mucosal (*black*) and EAC-IAC (*dotted black*), intersecting at the middle ear creating anteromedial (ant-med), anterolateral (ant-lat), posteromedial (post-med), and posterolateral (post-lat) spaces. (**F**) The V method of segmentation is based on 5 segments around the mucosal line (*black*). These segments are named accordingly.

segment on the posterior wall). The segments and branches are detailed in **Tables 2** and **3**,[2-4,6,10] respectively, and are shown diagrammatically in **Figure 5**. All segments and branches of the facial nerve did not pass lateral to the mucosal line. Branches of the intrapetrous facial nerve also show direct relation to the mucosal line. One branch (chorda tympani) lies on the lateral wall of the middle ear; the stapedius branch lies inside the posterior wall of the middle ear, whereas the GSPN runs medial to the ET, superolaterally to the ICA (but it lies superiorly to the ET in 15% of cases, according to Rhoton[1]).

The facial nerve lies within the bony canals throughout its course within the petrous pyramid, first lying within the IAC (meatal segment), and then the different parts of the facial, or fallopian, canal (including its labyrinthine, tympanic, and mastoid segments).[1,3,4,6,10] The facial nerve enters the posterior surface of the pyramidal bone complex at the internal auditory meatus. Its meatal and labyrinthine segments take a progressively ascending course, becoming progressively more superficial as it approaches the medial wall of the middle ear. At this point is the geniculate ganglion, also the division point into the tympanic segment and the GSPN, and turning point of the facial nerve as the first genu. The geniculate ganglion may be exposed in case of dehiscence. The GSPN becomes progressively more superficial, to exit its canal, to lie on the superior surface of the apical part of the petrous pyramid, whereas the tympanic segment becomes progressively deeper as it runs posteriorly, below the lateral SCC, to meet the posterior wall of the middle ear below the aditus ad antrum. One variation we found was the trajectory of the labyrinthine segment of the facial nerve which generally takes a curving course antero-laterally while advancing towards the middle ear as shown

Table 1. The Middle Ear Relations to Petrous Pyramid Contents

Anterior	1) Eustachian tube (anterior part of the mucosal line) 2) Tensor tympani muscle above the eustachian tube 3) Internal carotid artery coming from below (coming from inferior surface of temporal bone)
Posterior	1) Mastoid antrum (posterior part of mucosal line, connected by aditus ad antrum in upper part of the posterior wall) 2) Mastoid segment of cranial nerve VII (vertically descending on this wall, below the aditus ad antrum, to exit at stylomastoid foramen into the parotid space and gland)
Lateral	1) Cutaneous compartment (external auditory canal: separated from the middle ear by the tympanic membrane, with air cells overlying the external auditory canal) 2) Anterolateral space (roof of the temporomandibular joint) 3) Posterolateral space (mastoid)
Medial	Neural compartment, both anterior and posterior labyrinths, as well as facial nerve tympanic segment, are related to the medial wall. Tympanic segment of facial nerve: lying as a somewhat horizontal line, dividing the medial wall into upper third (attic), and lower two thirds. Yet, the neural compartment creates some impressions on the medial wall: 1) cochlear promontory (anterior labyrinth): located anteriorly; 2) oval and round windows: with the oval window above the round window, connecting the middle ear to the vestibule (not cochlea), located below the facial nerve and behind the promontory; and 3) lateral semicircular canal: above the posterior part of facial nerve tympanic segment posteriorly
Superior	Tegmen tympani, separating the middle ear from the middle cranial fossa above (harboring the temporal lobe)
Inferior	1) Jugular bulb (in the upper end of the carotid space of the neck) 2) Root of styloid process

in **Figure 2**; but in one specimen it was in line with the meatal segment, as shown in **Figure 3.**

At the division point of the labyrinthine segment, on the medial wall of the middle ear, 2 angles are formed. The angle between the labyrinthine and tympanic segments of the facial nerve accommodates the vestibule (posterior labyrinth), which can be called the vestibular angle, whereas the angle between the labyrinthine segment and the GSPN accommodates the cochlea (anterior labyrinth) and is thus called the cochlear angle. In summary; the facial nerve segments and branches can be correlated to petrous spaces and segments. The meatal and labyrinthine segments pass within the otic capsule segment, between the anteromedial and anterolateral spaces. The other two segments, as well as the major branches, are more related to mucosal line parts. The tympanic segment lies on the posterior part of the medial wall of the middle ear (lateral to posterior labyrinths); while the mastoid segment lies on its posterior wall. The GSPN initially lies on the anterior part of the medial wall of the middle ear (lateral to the anterior labyrinth), then exits through a hiatus to lie on the superior petrous surface, more specifically on the petrous apex segment, being superomedial to the ET. The other major branch, i.e., the chorda tympani, lies on the lateral wall of the middle ear.

Table 2. Facial Nerve Segments and their Relations to Petrous Pyramid Contents

Petrous Cranial Nerve VII Segments	Description
Meatal segment	Inside the IAC, which separates anterior and posterior labyrinths, lying in the anterosuperior quadrant of the IAC. After its exit from the IAC, the facial nerve enters the facial canal, which has 3 segments and 2 genus, described below
Labyrinthine segment	Continuation of the IAC line to the middle ear, but more often making a curve concave anteriorly. It is the first part of the facial canal, running toward the medial wall of middle ear, ending in the geniculate ganglion. It lies between the cochlea and vestibule
First genu	Where the labyrinthine segments turns posteriorly at the medial wall of the middle ear. This is the location of the geniculate ganglion, which is the origin of the greater superficial petrosal nerve running anteriorly, medial to the mucosal line
Tympanic segment (horizontal)	Running posteriorly on the medial wall of the middle ear (cochlear wall) separating its upper third and lower two thirds. Its anterior part lies laterally to the vestibule, while its posterior part runs below the lateral semicircular canal
Second genu	Where the tympanic segment turns inferiorly at the posterior wall of the middle ear, below the aditus ad antrum, and lateral semicircular canal
Mastoid segment (vertical)	Running vertically inferiorly on the posterior wall of middle ear (mastoid wall). It exits the petrous pyramid at the stylomastoid foramen, to enter the parotid gland

IAC, internal auditory canal.

Table 3. Branches of the Facial Nerve within the Petrous Pyramid and Relations to the Mucosal Line

Petrous Cranial Nerve VII Branches	Description
GSPN	Starting at the geniculate ganglion and running anteriorly on the medial wall of the middle ear, for some distance, becoming progressively more superficial. It exits through a hiatus into the superior surface of the petrous pyramid. It runs medial to the mucosal line (specifically, superomedial to the eustachian tube), lateral to the cochlea, and superiorly or superolaterally to the internal carotid artery, toward the foramen lacerum. It continues below the trigeminal ganglion on its way to the foramen lacerum. It then joins sympathetic fibers from the plexus around the internal carotid artery, called the deep petrosal nerve, to become the vidian nerve. At this point, the newly formed vidian nerve has a direction parallel to the midsagittal plane and runs inside the vidian canal toward the pterygopalatine fossa
Nerve to stapedius	From the mastoid segment (on the posterior wall of the middle ear) running anteriorly to innervate the stapedius muscle, which runs from the posterior wall of the middle ear, to insert into the stapes
Chorda tympani	From the mastoid segment (on the posterior wall of the middle ear), running superiorly and anteriorly on the lateral wall of the middle ear (on the tympanic membrane), in a convex upward curve. It exits at the petrosquamous fissure, inside the canal of Huguier, into the infratemporal fossa to join the lingual nerve (carrying taste and parasympathetic fibers to the tongue and submandibular/sublingual salivary glands, respectively)

Air Cells

Air cells are described separately to complete the description of temporal bone anatomy. They arise through a pneumatization process from the mucosal line. We organized the air cells into 7 groups, 5 of them correlate to the segments described in the V method. Air cells are thus grouped into prelabyrinthine (apical), perilabyrinthine (around and inside the otic capsule), retrolabyrinthine (mastoid), EAC roof cells (above the EAC) and TMJ

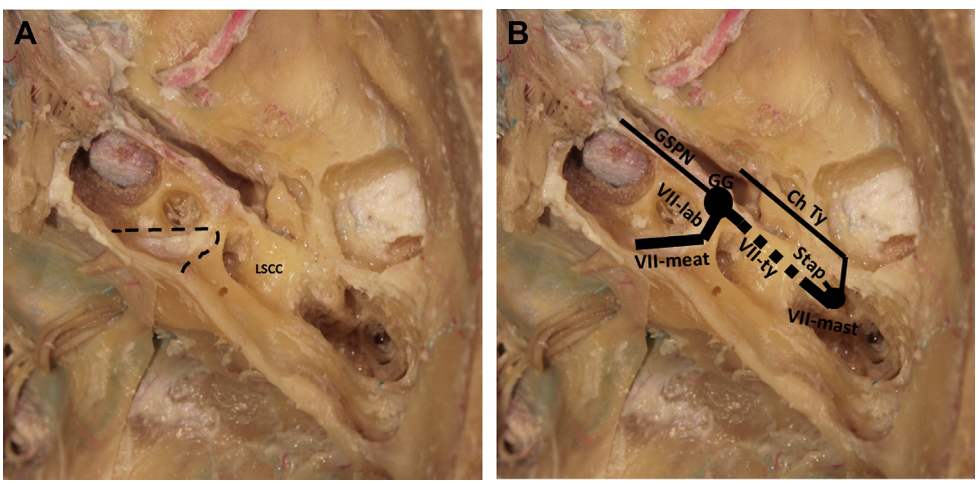

Figure 5. Segments and major branches of the right intra-petrous facial nerve. (**A**) Drilled superior surface of the petrous pyramid. The contour of the internal auditory canal is marked by interrupted line. The lateral semicircular canal (LSCC) is also shown. (**B**) Superimposed trajectory of facial nerve segments (*thick black lines*) and major branches (*thin black lines*). The facial nerve first passes through the internal auditory canal, as the meatal segment (VII-meat). Then, it continues through the otic capsule, mostly in an angled fashion, towards the middle ear as the labyrinthine segment (VII-lab). It meets the middle ear at the geniculate ganglion (GG, *black oval shape*), where it turns posteriorly as the first genu. Then it runs on the medial wall of the middle ear as the tympanic segment (VII-ty), with its anterior part being visible lateral to the vestibule, but the posterior part becomes hidden beneath the LSCC (*interrupted line*). It then reappears as it turns down vertically at the second genu to become the mastoid segment (VII-mast, *black round shape*), running on the posterior wall of the middle ear, and this segment continues toward its exit through the stylomastoid foramen into the parotid gland. Branches: At the level of the GG it gives rise to the greater superficial petrosal nerve (GSPN) running anteriorly; medial and parallel to the eustachian tube, and superolaterally to the internal carotid artery. The mastoid segment runs on the posterior wall of the middle ear, and gives rise to 2 branches: the chorda tympani (Ch Ty) running on the lateral wall of the middle ear and tympanic membrane, having an upward convex curve, and exits the middle ear through the canal of Huguier to enter the infratemporal fossa to meet the lingual nerve. The other branch is the nerve to stapedius muscle (Stap).

Table 4. Stepwise Approach to Understanding the Petrous Pyramid Contents

1) The temporal bone is composed of 5 parts: petrous, squamous, mastoid, tympanic, and styloid. The petrous pyramid separates the middle and posterior cranial fossae. It has 3 surfaces (superior, posterior, and inferior) and a base, also called the lateral surface. Its base faces laterally, whereas its apex faces the midline. This pyramid is made up of 3 temporal bone parts: petrous, mastoid, and parts of the squamous
2) The petrous pyramid can be described as a primitive bony container, surrounded by cortical bone; and contents, grouped into 4 groups, or compartments (Figure 3). The container is cast around the compartments during development, and forms canals around certain structures such as EAC, ICA and facial nerve. Certain areas are not occupied by any of the compartments (i.e.,the mastoid, parts of the petrous apex, and the temporomandibular joint roof)
3) The most important is the mucosal compartment/line. It comes obliquely from the pharynx toward the mastoid bone, and is formed by 3 parts: the eustachian tube anteriorly, the middle ear in the middle, the mastoid antrum posteriorly (Figure 6B). This compartment gives rise to air cells to a variable extent, through the process of pneumatization, in areas of pyramid not occupied by any of the compartments, as listed above. This factor results in different possible composition of the mastoid and petrous apex segments, which can be pneumatized, diploic, or sclerotic
4) The other 3 compartments coming into contact with the mucosal line are the cutaneous, neural, and vascular compartments (Figure 6C). The cutaneous compartment is lateral to the middle ear and is composed of the bony external auditory canal lined by skin and transmits air vibrations to the middle ear. The neural compartment lies medial to the middle ear and connects the middle ear to the brainstem, and contains anterior (cochlea) and posterior labyrinths (vestibule and semicircular canals) on either side of the internal auditory canal. The internal auditory canal leads the vestibular, cochlear, and facial nerves from the pontomedullary junction into the petrous pyramid. The vascular compartment lies inside the petrous apex, medial to the eustachian tube. It includes the internal carotid artery coursing within the carotid canal, toward the foramen lacerum
5) Two reference lines cross at the middle ear, in the center of the pyramid: the mucosal line and the EAC-IAC line. All anatomic structures within the petrous pyramid could be located through 2 segmentation methods: the X method, creating 4 spaces as a result of the previous intersecting reference lines, and the V method, delineating 5 segments around the mucosal line (Figure 4)

roof cells, in the roof of the glenoid fossa. The sixth group is classically described as peritubal cells lying around the ET, and we find it useful to maintain it as a separate group. This group is separated into lateral, medial, superior, and inferior cells. The medial cells, when present, lie between the ET and the ICA. The seventh and last group, called the accessory group, is the extension outside the petrous pyramid, such as extensions into the horizontal and vertical squamous parts, the zygomatic arch, and into the styloid process.

DISCUSSION

In this article, a new description of the petrous pyramid is presented, a region with a complex anatomic architecture, using a compartmental approach. To simplify its anatomy, the petrous pyramid contents can be modeled as being formed of 4 compartments (mucosal, cutaneous, neural, and vascular) that are related in space and surrounded by the bone. All these schematic insights could help understanding through progressive buildup of petrous pyramid contents (Table 4 and Figure 6). The

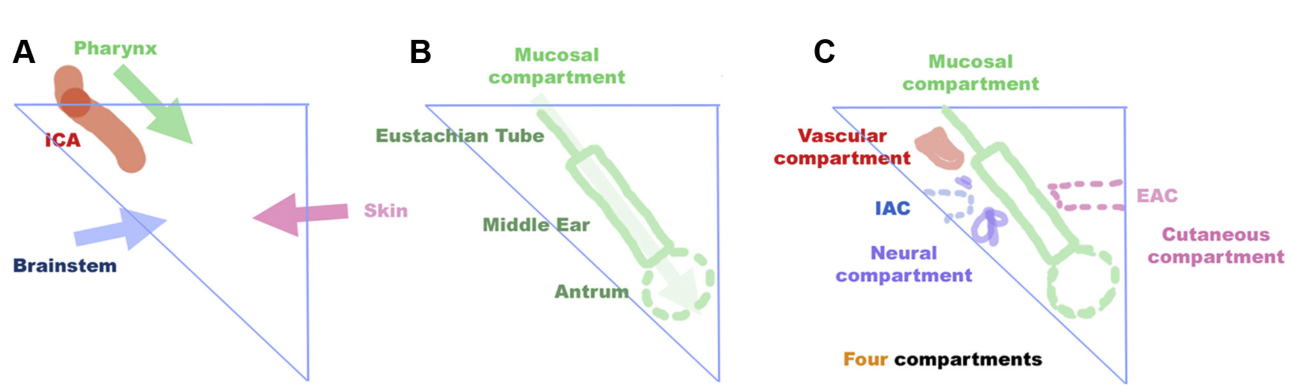

Figure 6. Schematic progressive buildup of compartments on a right petrous pyramid. The anatomy of the petrous pyramid can be modeled as 4 compartments (the contents) developing in proximity, and then surrounded by the bony container. The superior surface of the petrous pyramid is represented by a simple triangle. (**A**) The mucosal compartment (*green arrow*) is an extension of the pharynx, the cutaneous compartment (*pink arrow*) is an invagination of skin on the lateral surface of the head, the neural compartment (*blue arrow*) is in connection to the brainstem, while the vascular compartment (internal carotid artery, ICA, *red*) comes from the inferior surface of the petrous pyramid and then bends anteriorly, toward the apex of the pyramid. (**B**) The mucosal compartment, or line/axis, is the most important compartment; it is linear arrangement of the eustachian tube, middle ear, and mastoid antrum, from anterior to posterior; respectively. (**C**) The final organization of the petrous pyramid contents. EAC, external auditory canal; IAC, internal auditory canal.

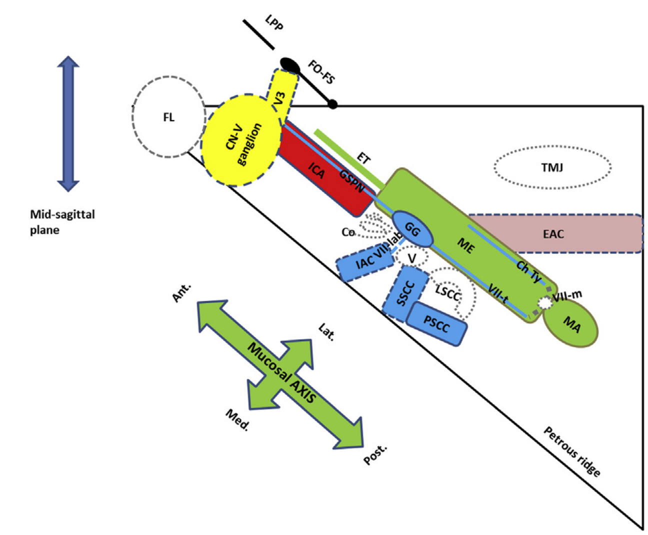

Figure 7. Plan of the petrous pyramid contents from superior perspective, like a radiographic view from above. Several linear structures exist within the petrous pyramid. Their orientation and position can be described, relative to the mucosal axis (*green, double crossed arrows*), as seen from the superior perspective. They can be classified into longitudinal structures (*continuous lines*), being relatively parallel to the mucosal axis, and horizontal ones (*dashed lines*), being relatively perpendicular to it. The *vertical double arrowed line* represents the mid-sagittal plane for reference. The neural compartment is shown in blue, the cutaneous compartment in pink, and the vascular compartment in red. The foramen lacerum (FL) is a defect in the apical part of the pyramid, between the petrous pyramid, and the sphenoid and occipital bones.
Longitudinal structures: *level of the mucosal axis*: 1) chorda tympani (Ch Ty): on the lateral wall of the middle ear (ME), running over the tympanic membrane; and 2) tympanic segment of facial nerve (VII-t): runs on the medial wall of the ME. Three other structures lie here but are not shown for clarity: 1) the tensor tympani muscle and canal are above the eustachian tube (ET); 2) the petrosphenoid suture probably lies above the lateral part of the groove for the cartilaginous ET[3] but this needs further study; and 3) the lesser petrosal nerve which is classically described as being parallel and lateral to the greater superficial petrosal nerve (GSPN), as it arises from the ME, and it thus probably lies above the ET, because it is separated from the GSPN by an average distance of <3 mm according to Lang. *Lateral to the mucosal axis:* 1) foramen ovale and foramen spinosum line: in the sphenoid bone, anterior to the petrous pyramid. The foramen spinosum lies on the anterior limit of the petrous, opposite the preauricular burrhole. An extension of this line anteriorly includes the lateral pterygoid plate (LPP), and posteriorly the spine of sphenoid (not shown). *Medial to the mucosal axis* (remember that the neural compartment lies medial to the ME and that the vascular compartment lies medial to the ET): 1) GSPN: medial and superior to the ET; 2) internal carotid artery (ICA): medial to the ET, making part of the lower anterior wall of the ME, the GSPN runs above it in 15% of cases according to Rhoton[1]; 3) posterior semicircular canal (PSCC): in the posterior labyrinth, medial to the ME, lying near the posterior petrous surface and the petrous ridge; and 4) petrous ridge: the most medial, constant, and most easily accessible of these lines. It provides attachment to the tentorium, and lies at the level of the superior petrosal sinus. **Horizontal structures**: *Lateral to the mucosal axis*: 1) EAC: lateral to ME and meeting it at tympanic membrane (*not shown*). *Medial to the mucosal axis*: 1) IAC: medial to ME, it does not reach the ME, and it contains the meatal segment of facial nerve as well as cochleovestibular nerve; 2) arcuate eminence: generally overlies the superior semicircular canal (SSCC), and is posterior to the IAC; 3) labyrinthine segment of facial nerve (VII-l) coming from the end of the IAC to reach the geniculate ganglion (GG) at medial wall of ME; and 4) trigeminal (CN-V) ganglion and its mandibular branch (V3) in yellow: lie on the superior surface of the petrous apex; and V3 exits the middle fossa at the foramen ovale. **Other structures** (*dotted gray lines*), not corresponding to the above groups, are shown for completion. These structures include the lateral SCC (LSCC) running above the tympanic segment of the facial nerve, the cochlea (Co, snail shape in front of IAC), the vestibule (V, oval shape behind the IAC), the mastoid segment of facial nerve (VII-m, white circle on posterior wall of ME and connected to VII-t and Ch Ty) lying beneath the aditus ad antrum, and descending vertically behind the ME. The TMJ lies anterior to the EAC. FO-FS, line joining foramen ovale and spinosum; MA, mastoid antrum; TMJ, temporomandibular joint; CN-V, trigeminal nerve; V3, mandibular nerve.

Table 5. Proposed Nomenclature of Air Cells Based on Location within the Temporal Bone

Air Cell Group	Composition
Mastoid (retrolabyrinthine, inside the mastoid segment). Lying at the base of the petrous pyramid, within the triangular mastoid segment. It lies between the otic capsule and the lateral pyramidal surface (i.e., posterior to the otic capsule)	This includes the mastoid antrum and surrounding air cells. It is composed of 7 groups of air cells that are easier to locate when viewed from the lateral surface, according to Allam.[12] From this view, the mastoid looks like a triangle with 3 angles and 3 walls. The cells include: 1) Central cells, in the center of the mastoid; 3 groups on the angles of the triangle 2) Antral/periantral cells (in the anterosuperior angle, including mastoid antrum) 3) Sinodural cells (in the posterosuperior angle) 4) Tip cells (in the inferior angle, having medial and lateral cells, separated by the digastric ridge); 3 groups on the walls of the triangle 5) Perifacial cells (anteriorly, surrounding mastoid segment of the facial nerve, behind the external auditory canal) 6) Tegmental cells (superiorly, beneath the tegmen tympani) 7) Perisinus cells (posteriorly, around the sigmoid sinus, having medial and lateral cells)
Apical (prelabyrinthine, inside the petrous apex segment). It lies between the otic capsule and the tip of petrous pyramid (i.e., anterior to the otic capsule)	This group can be further classified into: 1) Supracarotid cells 2) Infracarotid cells 3) Mediocarotid cells
Perilabyrinthine (lying across and also around the otic capsule segment). Cells interposed between the otic capsule and cortical bone of the superior, inferior, and posterior surfaces, respectively. They thus provide connection between the apical and mastoid cells around the otic capsule	It lies medial to the middle ear and does not include cells pertaining to the mastoid groups posteriorly or to the apical group anteriorly. This includes: 1) Translabyrinthine cells (passing through the otic capsule, classically called subarcuate cells, passing within the arch of the superior semicircular canal, along with the petromastoid canal, which carries the subarcuate artery) 2) Supralabyrinthine cells (beneath the superior petrous surface). May be classified into anterior and posterior, as related to anterior and posterior labyrinths 3) Infralabyrinthine cells (beneath the inferior petrous surface). May be classified into anterior and posterior cells (below the anterior and posterior labyrinths, respectively) 4) Paralabyrinthine cells (beneath the posterior petrous surface, medial to otic capsule, as contrasted to the middle ear situated lateral to it). They surround the end of the internal auditory canal at the opening of the internal auditory meatus, being superior, inferior, anterior, and posterior to it; thus called suprameatal, inframeatal, premeatal, and postmeatal, respectively
External auditory canal roof cells	Above the external auditory canal
Temporomandibular joint roof cells	In the bony roof of the glenoid fossa
Peritubal (cells around the eustachian tube)	This includes: 1) Medial paratubal (between the eustachian tube and the internal carotid artery) 2) Lateral paratubal 3) Supratubal 4) Infratubal
Accessory (extrapyramidal)	Cells extending beyond the petrous pyramid, even outside the boundaries of the temporal bone. 1) Zygomatic: within the zygomatic arch and its base 2) Squamous: divided into horizontal plate cells (bone lying anterior to the roof of the TMJ making part of the roof of the infratemporal fossa); and vertical plate cells (bone making the medial wall of the temporal fossa) 3) Styloid 4) Occipital (classically considered in the accessory group, but it is an extratemporal extension into the occipital bone)

mucosal line is found between the GSPN line and the FO-FS line. We proposed 2 methods of segmentation into 4 spaces (the X method) and into 5 segments (the V method), using 2 reference lines (the mucosal line and the EAC-IAC line) that intersect at the middle ear. As the discussion proceeds, we will provide more anatomical description to complete the overall view, and will try to provide clinical correlations. This would demonstrate how to use this approach to facilitate anatomical learning, and how to integrate it directly into clinical applications.

From a superior perspective, and in relation to the mucosal axis, petrous bone contents can be grouped into longitudinal and horizontal structures. This grouping simplifies understanding and memorization of interrelationships of different components, integrated into a single map. Longitudinal structures are relatively parallel to the mucosal line, whereas horizontal structures have a relatively perpendicular orientation (**Figure 7**). This classification is similar to that of petrous pyramid fractures into longitudinal and horizontal types. The anatomy of single parts and interrelationships can vary significantly, and, thus, anatomy must be studied on an individual basis, on preoperative images.

Anatomy of the Petrous Pyramid

The petrous pyramid is built from 3 of the 5 temporal bone parts (petrous, mastoid, and parts of the squamous), with the middle ear lying obliquely in its center,[2] like a royal chamber. The petrous part lies medial to the mucosal line and creates the apical and medial part of the petrous pyramid, including both the otic capsule and petrous apex segments. Relations of all three parts of the temporal bone to the middle ear was described above. All 5 parts of the temporal bone can be imagined as gathering around the middle ear or around the mucosal line as a whole.

As far as nomenclature is concerned, we focused on the petrous pyramid as defined be Pellet et al., as the parition between the middle and posterior cranial fossae.[2] Yet, we chose the line used by Ribas et al.[9] as the anterior limit of the petrous pyramid, contrary to the EAC used by Pellet et al.[2] It seems a pertinent landmark to guide suprapetrosal craniotomies and our work aims at improving anatomic knowledge and orientation for surgeons. In anatomic views, the distinction between the horizontal plate of squamous bone and the petrous pyramid is hard, and perhaps even artificial, because the squamous part extends posteriorly to participate in the formation of the roof of the EAC and middle ear.[2,4,6] Conversely, the petrous pyramid is clearly separated from the sphenoid bone by the petrosphenoid suture, being medial and parallel to the FO-FS line.

Segmentation. Pellet et al.[2,7] acknowledged the composite nature of the petrous pyramid, and used a useful surgically based segmentation approach to the petrous pyramid. The importance of this work cannot be overstated. They used as limits the posterior wall of the EAC, the anterior wall of the IAC, the medial wall of the middle ear, and the outer surface of the labyrinthine mass. It thus created 4 segments or sectors: tympanic (EAC and middle ear), retrolabyrinthine (mastoid), labyrinthine (or posterior labyrinthine), and carotid (cochlea and petrous apex containing ICA), for which they used the same names as we do for the spaces (anterolateral, posterolateral, posteromedial, and anteromedial, respectively). Roche et al.[8] modified this segmentation, to show 4 drilling zones, useful in different transpetrosal approaches.

The segments described by Pellet et al. do not correspond completely with our proposed segments and spaces, since we did not include the lines (mucosal and EAC-IAC) into any of the spaces, and we also included the TMJ roof as part of the definition of the petrous pyramid. We proposed two different methods of segmentation (X- and V-methods) describing four spaces and five segments around the mucosal line; respectively. We think they provide a relatively simple and clear description, while being concordant with the holistic view of petrous pyramid contents that we tried to provide. Besides, previous investigators proposed the same reference lines with various names, such as the air axis[4,10] or middle ear cleft[6] for the mucosal line and the sensorial[4] or auditory[10] line for the EAC-IAC line. An angle of 8° has been described between the 2 parts of the EAC-IAC line.[2] We hence combine these landmarks to propose an inedited approach, including other parts not occupied by the 4 compartments, such as the petrous apex, the mastoid, and the roof of the TMJ. Both methods of segmentation can help understand the various approaches in otology and otoneurosurgery.

Middle Ear. In the middle ear, mechanical information is transmitted by the ossicular chain (malleus, incus, and stapes), from the cutaneous compartment (via the tympanic membrane) to the neural compartment (via the oval window). The walls of the middle ear are designated by major relations, so the anterior wall is called the carotid wall, inferior wall the jugular, medial wall the cochlear, and posterior wall the mastoid.[4] The roof is the tegmen tympani. Detailed description of the walls of the middle ear is beyond the scope of this work and is available elsewhere for the interested reader.[4,6,10] The middle ear is classically divided into spaces relative to the position of the tympanic membrane.[4,6] The mesotympanum is the central part, lying opposite the tympanic membrane. The epitympanum (or attic), the protympanum, the hypotympanum, and the retrotympanum lie superior, anterior, inferior, and posterior to the tympanic membrane; respectively. It is through the attic that the middle ear communicates with the MA (through the aditus ad antrum), whereas the ET is continuous with the protympanum.[4,6]

Facial Nerve. The facial nerve, as well as its branches, is an important landmark, both on the superior petrous surface as well as during lateral approaches to the middle ear. The importance of preserving its function cannot be overemphasized. Understanding its course and branches, and relating it to other structures within the petrous pyramid, offers a useful guide to surgical navigation, especially in middle fossa approaches. The GSPN, because it runs nearly parallel to the mucosal line and to the petrous ridge, can orient surgeons to the axis of the petrous pyramid and to the location of the ET, which lies between it and the more laterally located FO-FS line. The GSPN serves as a limit between 2 middle fossa triangles: the Kawase and Glasscock triangles. Exposing a segment or a branch of the facial nerve can serve as a landmark to be followed to other parts, such as following the GSPN to the

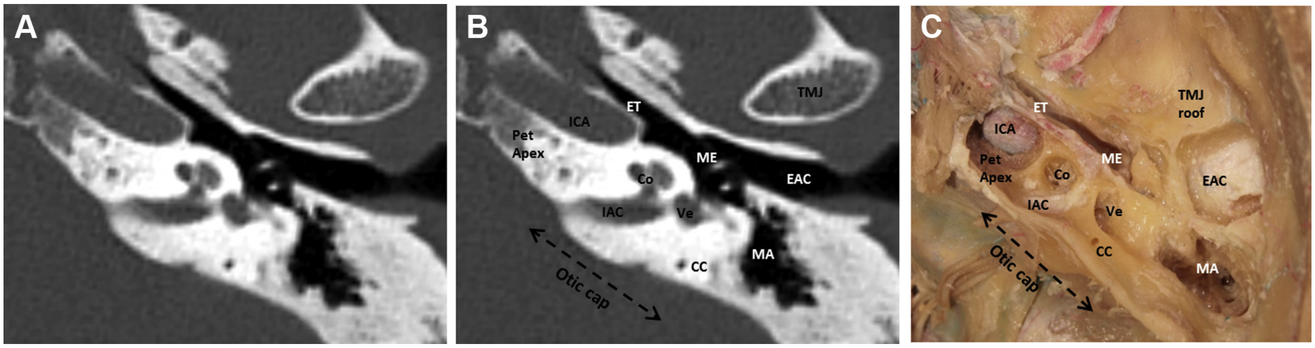

Figure 8. Localization of contents of the petrous pyramid on cross-sectional images. Computed tomography of the skull base, showing contents of the left temporal bone: (**A**) nonlabeled axial image, (**B**) labeled axial image, and (**C**) corresponding labelled drilled superior surface of the right petrous pyramid for comparison. These images show the communication of the middle ear with the eustachian tube and mastoid antrum. Identification of petrous pyramid contents starts with the hyperdense bone of the otic capsule (otic cap, limits shown as *double arrowed line*), with fluid-filled labyrinths inside it (i.e., the cochlea [Co] anteriorly and of the vestibule [Ve] posteriorly, separated by the internal auditory canal [IAC, the meatal segment of the facial nerve is seen in C]). The common crus (CC), common segment between the superior and posterior semicircular canals, is also shown. Lateral to the otic capsule is the air density of the mucosal line, with the middle ear (ME) lying directly laterally to the otic capsule; the eustachian tube (ET) anterior to it, and the mastoid antrum (MA) posterior to it, opening into mastoid air cells. The middle ear shows parts of the malleus and incus. Medial to the ET, and anterior to the otic capsule is the linear soft tissue density of the internal carotid artery (ICA), lying within the petrous apex (Pet Apex). The external auditory canal (EAC), with air density, meets the middle ear laterally. More anteriorly is the temporomandibular joint (TMJ, shown here is the mandibular condyle in **A** and **B**; while its roof is shown in **C**) which lies lateral to the ET.

geniculate ganglion, and then to the tympanic or labyrinthine segments of the facial nerve.

Air Cells. The pneumatization process starts from the mucosal line and can replace any part ofthe petrous pyramid, in areas not occupied by the compartments, such as the petrous apex, mastoid, and roofs of the EAC and TMJ, and it also includes cells passing through the otic capsule. It can also extend to other parts of the temporal bone such as the zygomatic process, and vertical and horizontal plates of the squamous part, to a variable degree. It may even extend into the occipital bone, and in rare cases of hyperpneumatization, down to the C2 vertebra.[11] Air cells have been widely studied[6,12-15]; their nomenclature depends mainly on pneumatization tracts, which is useful for understanding development and connections, but their distribution can be variable and difficult to localize and name. To be concordant with our description of the petrous pyramid, and to help precise localization and identification, we propose a classification of temporal bone air cells, according to location, dividing them into 7 groups, as detailed in **Table 5**. Air cells provide pathways of disease extension, and also surgical corridors during surgery, if studied and identified precisely. An example is using a transmastoid approach, and then working below the otic capsule, through infralabyrinthine cells, to access the petrous apex to drain petrous apex cholesterol granuloma.[16]

Air cell presence can cause cerebrospinal fluid (CSF) leakage in the postoperative period if not dealt with carefully during surgery[17] and, thus, the need for precise identification in terms of location, during both surgical planning and execution. Pneumatization of the petrous apex is present in one third of cases, and certain diseases depend on its presence, such as cholesterol granuloma, whereas the presence of vascular bone marrow would provide more risk for hematogenous metastasis to the petrous apex.[18] The presence of fatty bone marrow inside the petrous apex can be seen as hyperintense T1 signal on magnetic resonance images.[18] After a translabyrinthine approach to the posterior cranial fossa, CSF leak through the ET can be problematic. CSF can reach the ET from the middle ear, but it can also take a side route through the peritubal cells, from other connected cell groups.[19] For this reason, plugging of the ET is needed,[2,4] and the plug should be advanced as far as possible, to avoid leakage using this bypass circuit.[4] Bone density of the mastoid has been classified into pneumatized, diploic (partially pneumatized), and sclerotic (nonpneumatized).[20] This classification can be applied to the petrous apex as well.

The Compartmental Approach: Applications, Limitations and Future Perspectives

To the best of our knowledge, this is the first description of petrous pyramid anatomy using the compartmental approach and segmentation methods. The anatomy of the temporal bone is described in detail in several textbooks, some of which have been used as references.[2-6,10,14] The particularity of this work is drilling the superior surface and grouping of contents into compartments. We also used the resulting map to redescribe the anatomy of major elements, to maintain concordance throughout the text. Superior surface dissection offers a two-dimensional x-ray type of view of petrous contents, which gives a global view of the whole contents and thus shows certain patterns that cannot be appreciated from classic drilling of the lateral surface of the petrous pyramid. Yet, appreciation of the third dimension, (i.e., depth) is not possible. For this reason, we used descriptions of anatomy reported in the literature, especially of the lateral views, to offer the reader correlations to the third dimension. Lacking the third dimension means that depth, vertical obliquity, kinks, or curves cannot be appreciated. Examples include the relative depth of the ICA as related to the ET; the relative depths of different segments and branches of the facial nerve; the ascending course of the horizontal ICA; and the superiorly convex curve of the chorda tympani.

Rayappa et al.[21] described 3 parallel lines in the skull base, with an angle of 45° to the midline. The medial line is formed by the ICA and the middle line formed by the ET. The lateral line is formed by the lateral pterygoid plate, the FO, the FS, and spine of sphenoid, from anterior to posterior; respectively.

The mucosal axis, with nearly 45° orientation to the midsagittal plane, has many skull base structures parallel to it, as seen in **Figure 7**. This fact forms a solid basis for understanding relationships, inside the petrous pyramid, which is part of the lateral skull base. This situation is in contrast to the midline skull base, which is more parallel to the midsagittal plane. These differences help understand and correlate the different orientations of certain structures, such as medial versus lateral pterygoid plates, cavernous versus petrous segments of the ICA, and the different orientation of the vidian nerve inside the vidian canal versus the GSPN. In the first example, both medial and lateral pterygoid plates meet at the pterygoid process, just posterior to the pterygopalatine fossa, which is a central station in understanding the central skull base. On the other hand, the last 2 examples (ICA and GSPN) change axis at the level of the foramen lacerum. These insights provide some keys to deciphering the complex anatomy of this region and perhaps can help redescribe the anatomy of the skull base, and even the whole head and neck, on a compartmental basis. This factor would be of aid to all surgeons working in the head and neck, especially skull base surgeons. Details on relationships of the petrous pyramid to surrounding intracranial and neck contents, along with their clinical applications, will not be discussed in this manuscript for simplicity.

SURGICAL APPLICATIONS

The view from above is helpful for surgical navigation during middle fossa approaches; for surgical orientation and localization; and for understanding middle fossa triangles (Kawase and Glasscock triangles), as seen in **Figure 7**. The Kawase triangle, or rhomboid, is interposed between the petrous ridge medially and the GSPN laterally. Its anterior limit is the mandibular nerve, whereas its posterior limit is the arcuate eminence.[22] It can be divided into premeatal and postmeatal triangles, by the IAC.[23] Drilling the Kawase rhomboid is used in middle fossa approaches, to expose the contents of the IAC, and to access the posterior fossa (anterior petrosectomy). The Glasscock triangle is also located posterior to the mandibular nerve, but it lies laterally to the GSPN, and its lateral limit is a line between the FS and the arcuate eminence.[22]

In surgical practice, different approaches dictate different angles of view that are far from standard orthogonal projections. Spatial information depends on angle of view and also on position relative to chosen reference points, lines, and planes. For example, the medially located petrous ICA can be accessed through a superior oblique trajectory, using a middle fossa approach, passing above the superior petrous surface, and then drilling lateral to the GSPN (the Glasscock triangle), or medial to it (the Kawase rhomboid). Starting drilling in the Glasscock triangle has higher risk of injury to the ET,[24] as can be understood from its location lateral to the GSPN. Drilling the superior petrous surface can be used as a drilling exercise, or a training model, for neurosurgical trainees, in contrast to drilling of the lateral petrous surface used in otology. An anatomical description of the superior petrous surface, for middle fossa approaches, was presented in the dissections by Rhoton.[1]

On the other hand, approaches starting from the lateral surface of the mastoid, behind the EAC, and allowing access to the posterior petrous surface, and posterior cranial fossa, are called posterior petrosectomies. Understanding the basic differences between different types of posterior petrosectomies can be eluding for the novice. The view from above may ease understanding the drilling zones, or modules; even though the approaches are done starting from the lateral, not superior, petrous surface. They involve progressively more bone removal in order to increase posterior cranial fossa exposure, as needed. All include removal of the mastoid cells (mastoid segment). Approaches can be classified into retrolabyrinthine (mastoid segment only), translabyrinthine (mastoid segment and posterior labyrinth: the whole posteromedial and posterolateral spaces; exposing the IAC), and transcochlear and transotic approaches (both involve removing the mastoid and the whole otic capsule segments, but the difference is that the first approach involves rerouting of the facial nerve, with risk of facial palsy; whereas the second does not, but with limited work space).[2] These last 2 approaches can even be pursued into the petrous apex.

Thus, understanding of surgical approaches can be made easier, with the possibility of redescribing all microsurgical and endoscopic approaches inside and around the petrous pyramid. The compartmental approach may serve to systematize all approaches used in otology and otoneurosurgery, according to targets, thus facilitating approach selection. This understanding would be of special help to surgeons working in the head and neck region.

RADIOLOGICAL APPLICATIONS

The compartmental approach can be extrapolated directly into radiological applications as well. It facilitates anatomical localization on cross-sectional imaging studies for the young trainee (**Figure 8**) and may be used to redescribe the radiologic anatomy, to be used as an educational tool. This factor can also help radiologic diagnosis through creation of differential diagnostic lists based on the anatomic location of disease (i.e., compartmental pathology). It may thus be of aid to radiologists as well.

LIMITATIONS AND FUTURE PERSPECTIVES

The present study is limited by a lower number of dissections, which limits the study of anatomical variations, such as angles.

Further larger studies are required to confirm the reliability and reproducibility of this approach. More studies are needed to correlate anatomy of structures outside and inside the petrous pyramid, through drilling of the inferior and posterior petrous surfaces, to connect them to neck spaces and intracranial compartments (such as cisterns); respectively. They could be of interest to enrich the visualization of contents in 3 dimensions. Nonorthogonal surgical views have also to be integrated, for direct surgical application. Tridimensional constructs and sagittal/coronal schematic views could also be added to further anatomic studies. This work is mainly qualitative, and thus, quantitative measures have not been addressed, because the aim was to create a plan, before going into detailed measurements. Future work is needed to incorporate studies addressing measurements[25] in and around the petrous pyramid, as well as the need to incorporate anatomical variations, such as angles, and external and internal dehiscences, that would modifiy the map for each individual patient. With this map in place, more anatomical details can be added such as middle ear subcompartments, and vascularization and innervation pathways. This map can then be used to systematize surgical approaches to compartments, segments, and to disease processes involving multiple compartments and even extending outside the pyramid. Pathology can then be added, with study according to site of origin, extension pathways (such as air cells) and different behaviours (eg, destruction, displacement and infiltration across boundaries, both within and between compartments) which has both diagnostic and surgical applications, similar to the use of fascial spaces in the neck. Perhaps this type of study would be pursued into viewing the bigger picture; to redescribe the entire skull base and the whole head and neck, for a more integrated learning experience, destined to all head and neck specialists.

CONCLUSIONS

Surgical navigation is an exercise that requires deep anatomical knowledge. Identifying a structure may depend on its aspect, shape, or connections, but one of the most important parameters for identification is location. Localizing a structure in a complex territory requires a map, which may be easier to learn if its patterns or rules are well understood and memorized. The other requirements for navigation are the presence of reference points, lines, and planes, for orientation purposes; as well as the presence of landmarks, to help jumping from one point to the next. The compartmental approach can serve such a purpose, especially for middle fossa approaches. It may provide a holistic view of structures inside and around the petrous pyramid, as well as a simplified version of textbook description of the subject, and may thus serve as an introduction to the anatomy of the petrous pyramid. It offers the possibility of redescribing anatomy, including applications, whether clinical, radiological, or surgical, which may help create a more integrated learning process. Reinterpreting known anatomy is needed to advance and enhance education of the subject and is also needed in other specialties, as a result of the massive accumulation of medical knowledge, which is beyond our ability to handle, because of limited time and resources. We think that this type of approach may serve as an aid, and example, to create more integrated curricula in the future. It would likely help communication; through a common language; between skull base surgeons in different specialties, and to radiologists as well. As such, we wish that this approach will provide an educational aid for surgical trainees.

ACKNOWLEDGMENTS

We thank the technical staff of the Department of Anatomy of the University of Lyon for their preparation of the specimens. We warmly thank Dr P. Robinson for English editing.

REFERENCES

1. Rhoton AL. The temporal bone and transtemporal approaches. *Neurosurgery*. 2000;47(3 suppl): S211-S265.

2. Pellet W, Cannoni M, Pech A, eds. *Otoneurosurgery*. Berlin: Springer; 2012.

3. Standring S. *Gray's Anatomy: The Anatomical Basis of Clinical Practice*. Philadelphia: Elsevier; 2016.

4. Mansour S, Magnan J, Haidar H, Louryan S, Nicolas K, eds. *Comprehensive and Clinical Anatomy of the Middle Ear*. Heidelberg: Springer-Verlag; 2013.

5. Santini JJ. *Atlas d'ostéologie du crâne*. Paris: Masson; 1980.

6. Proctor B. *Surgical Anatomy of the Ear and Temporal Bone*. New York: Thieme; 1989.

7. Fournier HD, Mercier P, Roche PH. Surgical anatomy of the petrous apex and petroclival region. *Adv Tech Stand Neurosurg*. 2007;32:91-146.

8. Roche P-H, Lubrano V, Noudel R, Melot A, Régis J. Decision making for the surgical approach of posterior petrous bone meningiomas. *Neurosurg Focus*. 2011;30:E14.

9. Ribas GC, Rodrigues AJJ. The suprapetrosal craniotomy. *J Neurosurg*. 2007;106:449-454.

10. Ladril J-P. *Atlas raisonné d'anatomie: Caisse du tympan, oreille interne*. Paris: Louis Pariente; 2008.

11. Quigley A, Shannon H. Craniocervical pneumatization. *J Radiol Case Rep*. 2013;7:27-33.

12. Allam AF. Pneumatization of the temporal bone. *Ann Otol Rhinol Laryngol*. 1969;78:49-64.

13. Jadhav AB, Fellows D, Hand AR, Tadinada A, Lurie AG. Classification and volumetric analysis of temporal bone pneumatization using cone beam computed tomography. *Oral Surg Oral Med Oral Pathol Oral Radiol*. 2014;117:376-384.

14. Gulya AJ. *Anatomy of the Temporal Bone with Surgical Implications*. Boca Raton, FL: CRC Press; 2007.

15. Lang J. *Skull Base and Related Structures*. Stuttgart: Schattauer; 1999.

16. Wilson D, Hodgson R. Transmastoid infralabyrinthine approach to petrous temporal bone. *Skull Base Surg*. 1991;1:188-190.

17. Yamakami I, Uchino Y, Kobayashi E, Yamaura A. Computed tomography evaluation of air cells in the petrous bone—relationship with postoperative cerebrospinal fluid rhinorrhea. *Neurol Medicochir*. 2003;43:334-338.

18. Harnsberger H. *PocketRadiologist, Temporal Bone: Top 100 Diagnoses*. Salt Lake: Amirsys; 2003.

19. Jen A, Sanelli PC, Banthia V, Selesnick SH. Relationship of petrous temporal bone pneumatization to the eustachian tube lumen. *Laryngoscope*. 2004; 114:656-660.

20. Hindi K, Alazzawi S, Raman R, Prepageran N, Rahmat K. Pneumatization of mastoid air cells, temporal bone, ethmoid and sphenoid sinuses. Any correlation? *Indian J Otolaryngol Head Neck Surg*. 2014;66:429-436.

21. Rayappa C, Kumaresh K. Cancer of the skull base. In: Staffieri A, Sebastian P, Kapre M, Varghese BT, Kazi R, eds. *Essentials of Head and Neck Cancer*. Delhi: Byword Books; 2012.

22. Kiris T, Sankhla S, Lawton M, Zabramski J, Spetzler R. Microsurgical anatomy of the cavernous sinus. *Barrow Quarterly*. 1996;12. Available at: https://www.barrowneuro.org. Accessed November 2018.

23. Altieri R, Sameshima T, Pacca P, et al. Detailed anatomy knowledge: first step to approach petroclival meningiomas through the petrous apex. Anatomy lab experience and surgical series. *Neurosurg Rev*. 2017;40:231-239.

24. Banerjee A, Thakur J, Ezer H, Chittiboina P, Guthikonda B, Nanda A. Petrous carotid exposure with eustachian tube preservation: a morphometric elucidation. *Skull Base*. 2011;21:329-334.

25. Sennaroglu L, Slattery WH. Petrous anatomy for middle fossa approach. *Laryngoscope*. 2003;113:332-342.

Conflict of interest statement: The authors declare that the article content was composed in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Received 4 July 2018; accepted 26 November 2018

Citation: World Neurosurg. (2019) 124:e65-e80.
https://doi.org/10.1016/j.wneu.2018.11.234

*Journal homepage: **www.journals.elsevier.com/world-neurosurgery***

*Available online: **www.sciencedirect.com***