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## **Understanding anatomy of the petrous pyramid - a new compartmental approach.**

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**Running title:** Petrous compartmental approach

**Background** Surgical anatomy of the petrous pyramid has always been 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 the petrous pyramid anatomy using a new compartmental approach that is simple to understand and remember.

**Methods** The contents of the petrous pyramid of eight temporal bones were exposed through progressive drilling of the superior surface.

**Results** The petrous pyramid is made of a bony container, while its contents were grouped into four 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 two methods of segmentation; the X-method and V-method, were then proposed. This description was then used to describe middle ear relationships, facial nerve anatomy and air cell distribution.

**Conclusion** This new simple compartmental approach allows a comprehensive understanding of the distribution of petrous pyramid contents. Dividing it into anatomical compartments, and then navigating this mental map along specific reference points, lines, spaces, and segments could bring 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, due to the large number of named contents, numerous *foramina*, and specific tridimensional shape. The unique anatomical construction of the temporal bone reflects its particular development process and connections. The temporal bone is composed of five parts: squamous, petrous, mastoid, styloid, and tympanic <sup>1</sup>. It is of note that some authors described it as being composed of three <sup>2</sup> or four parts, by considering the mastoid as an extension from both the petrous and squamous parts <sup>3-5</sup>. All five 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<sup>2,4-6</sup>. The middle and posterior cranial fossae are built on a large pyramid shaped bone, called the petrous pyramid by Pellet et al.<sup>2</sup>, which houses the organs of hearing and equilibrium, and is crossed by cranial nerves and the internal carotid artery (ICA).

Segmentation of the petrous pyramid has been rarely described for surgical purposes<sup>2,7,8</sup>. 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 anatomical architecture of intra-petrous contents.

This way we propose a new anatomical compartmental approach of the petrous pyramid that could ease understanding and navigation along simple landmarks, lines, and spaces. Thanks to different methods of segmentation, we aim to provide an educational tool for surgeons.

## **Materials and methods**

One dry head (two temporal bones) was used to study the walls of the petrous pyramid. In addition, four fresh cadaver heads (eight temporal bones) were harvested in the Anatomy laboratory of University Lyon 1 (Lyon, France), prepared with 10% 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 to XII were carefully left in place as were arteries of the circle of Willis. 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 Motor, Drill, Medtronic, 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 great superficial petrosal nerve (GSPN) was anterior

medial to the *tegmen tympani*. Drilling continued anteriorly, lateral to GSPN, and medial to the *foramen ovale – foramen spinosum* (FO-FS) line, to open the Eustachian tube (ET). The *tensor tympani* muscle, lying above the ET, was sectioned. Drilling then proceeded posteriorly, beyond the incus that marks the *aditus ad antrum*, to enter into the *mastoid antrum* (MA). The external, as well as the internal auditory canals (EAC and IAC, respectively), were exposed. The temporo-mandibular 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 (SCC). Finally, the ICA was freed at the petrous apex, medial to the ET, below the GSPN and trigeminal ganglion, towards its exit through the upper part of the *foramen lacerum* into the cavernous sinus.

## Results

The petrous pyramid can be described as being composed of two 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 antero-medially, pointing to, and opening into the pharynx. The mucosal line is considered as the central piece of this approach since the terms anterior, posterior, medial, and lateral are used relative to this axis, not to the midsagittal plane. All anatomical structures were thus grouped into four compartments and 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, two methods of segmentation were developed. Finally, these blueprints were used to describe 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 three lateral surfaces and a base, all triangular in shape, and is surrounded by cortical bone. The base of the pyramid is facing laterally while 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, while the apical part faces Meckel's cave. It faces antero-superiorly. We adopted the description of Ribas et al. <sup>9</sup>, of its anterior limit. It is composed of a horizontal line starting laterally at a preauricular burr hole, located just anterior to the tragus, facing the dorsum sella medially, and passing through the foramen spinosum. The posterior limit is the petrous ridge, while the lateral limit is the junction with the vertical part of squamous bone.

The posterior surface forms the anterior wall of the cerebellopontine angle and is surrounded by impressions of dural venous sinuses (sigmoid, superior and inferior petrosal sinuses), that form a venous triangle. The inferior surface on other hand faces the neck. The lateral surface (the base) is formed by the lateral surface of the mastoid, and having the external auditory meatus in its antero-superior angle, just posterior to the temporomandibular joint.

### *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 four compartments as detailed below, and as shown in **Figure 3**.

The **mucosal compartment** is defined by the nearly linear alignment of the Eustachian tube anteriorly; the middle ear; and mastoid antrum posteriorly. It is an air-filled mucosa-lined series of cavities extending to the pharynx <sup>3</sup>, in an oblique anterior-medial direction. Extending this line posteriorly into MA divides the mastoid bone into medial and lateral parts. Extending it anteriorly leads to ET bony segment in the junction between petrous and squamous bones <sup>3</sup>; and the more anterior cartilaginous segment of the ET, in the inferior groove of the petro-sphenoid suture, outside the petrous pyramid and opening into the pharynx <sup>3</sup>. The mucosal line was found to be interposed between two parallel lines, the GSPN

line medially and the FO-FS line laterally, as shown in figure 2. All three 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 located lateral to the mucosal line, more specifically to the middle ear. Medially, it meets the middle ear at the tympanic membrane. The cartilaginous EAC is the extension of the bony EAC outside the petrous pyramid.

The **neural compartment** 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 semicircular canals - 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 variable bone density between air cells and the otic capsule made it easily recognizable, unlike the dense cortical bone cover of the pyramid. The *cochlea* has a snail-shell shape, while SCCs are arranged as three flower leafs joined at the center of the flower: the vestibule. The orientation of the SCCs deserves special mention: the three canals are classically described as being perpendicular to each other; the posterior is nearly parallel to the posterior petrous wall<sup>3</sup>; the superior is somewhat related to the prominent *arcuate eminence* at the superior aspect of the petrous pyramid, and is perpendicular to the long axis of the petrous<sup>3</sup>; and the lateral is angled at 30 degrees from the horizontal plane. The facial nerve has a complex course, relations, and branches; and will thus be discussed separately.

The **vascular compartment** is logically composed of the ICA, surrounded by venous and sympathetic plexi. It has 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. 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 towards the *foramen lacerum* before entering the cavernous sinus.

### *Segmentation methods*

After having separated the petrous contents into compartments, we created two segmentation methods that could help understanding and memorizing their distribution: the X-method and the V-methods. 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 two reference lines, which intersected at the middle ear in the form of the letter “X”, thus creating four spaces. The *V-method* (**Figure 4C and F**) described the contents as five segments arranged around the mucosal line, in the form of the “V” letter, having two branches and an angle pointing posteriorly. Two segments lie medial to the mucosal line as the medial branch, two lie lateral to it as the lateral branch, and one 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 two reference lines; mucosal and EAC-IAC lines. We correlated the walls of the middle ear with compartments, lines and spaces. It is shaped like a six-wall box. As part of the mucosal line, it is connected to the ET anteriorly, and to the mastoid antrum posteriorly (by the aditus ad antrum)<sup>3</sup>. 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<sup>3</sup>. It contains the ossicles (malleus, incus and stapes), muscles (tensor tympani and stapedius), as well as mucosal folds. In view of this description, the major relations of the middle ear are listed in **Table 1**<sup>3,4,6,10</sup>.

### *Facial nerve*

It 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 segment on the posterior wall). The segments and branches are detailed in **Tables 2 and 3**<sup>2,3,4,6,10</sup>, 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, while the GSPN runs medial to the ET, supero-laterally to the internal carotid artery (but it lies superiorly to the ET in 15 percent of cases, according to Rhoton<sup>1</sup>).

The facial nerve lies within bony canals throughout its course within the petrous pyramid, first lying within the internal auditory canal (meatal segment), and then the different parts of the facial, or fallopian, canal (including its labyrinthine, tympanic and mastoid segments)<sup>1,3,4,6,10</sup>. 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 superior surface of the petrous pyramid, while 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.

At the division point of the labyrinthine segment, on the medial wall of the middle ear, two angles are formed. The angle between labyrinthine and tympanic segments of facial nerve accommodated vestibule (posterior labyrinth), that can be called the “vestibular angle”, while the angle between labyrinthine segment and the GSPN accommodated the cochlea (anterior labyrinth), thus called the “cochlear angle”.

### *Air cells*

Air cells are described separately in order to complete the description of temporal bone anatomy. They arise through a pneumatization process from the mucosal line. We organized the air cells into seven groups, five 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 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, as a separate group. This group is separated into lateral, medial, superior and inferior cells. The medial cells lie between the ET and the IAC. The seventh and last group, called accessory group, is the extension outside the petrous pyramid, such as extensions into horizontal and vertical squamous parts, zygomatic arch, and into styloid process.

## Discussion

In this article, a new description of petrous pyramid is presented, a region with a complex anatomical architecture, using a compartmental approach. To simplify its anatomy, the petrous pyramid can be modelled as being formed of four compartments (mucosal, cutaneous, neural, and vascular) that are related in space, and later surrounded by the bone. All of these schematic insights could help understanding through progressive buildup of petrous pyramid contents (**Table 4 and Figure 6**). The mucosal line is found between the GSPN line and the FO-FS line. We proposed two methods of segmentation into four spaces (the X-method) and into five segments (the V-method), using two reference lines: the mucosal line, and the EAC-IAC line, that intersect at the middle ear.

### *Anatomy of the petrous pyramid*

The petrous pyramid is built from three out of the five temporal bone parts (petrous, mastoid and squamous), with the middle ear lies obliquely in its center <sup>2</sup>, like a royal chamber. The petrous part lies medial to the middle ear and creates the apical and medial part of the petrous pyramid. Otherwise, the squamous part is lateral; and mastoid posterior to the middle ear;

respectively. The other two parts of the temporal bone, namely the tympanic and styloid parts, are attached to the petrous pyramid on its inferior surface, and are also related superiorly to the middle ear<sup>4</sup>. All five parts of the temporal bone can thus be imagined as gathering around the middle ear, or around the mucosal line as a whole.

As far as anatomical nomenclature is concerned, we chose the line used by Ribas et al.<sup>9</sup> as the anterior limit of the petrous pyramid, contrary to the EAC used by Pellet et al.<sup>2</sup>. It seems a pertinent landmark to guide supra-petrosal craniotomies and our work aims at improving anatomical knowledge for surgeons. Also, we focused on the petrous pyramid as defined by Pellet et al.<sup>2</sup>. In anatomical views, the distinction between the horizontal plate of squamous bone and the petrous pyramid is hard, and perhaps even artificial, as the squamous part extends posteriorly to participate in the formation of the roof of the external auditory canal and middle ear<sup>2,4,6</sup>. Conversely, the petrous pyramid is clearly separated from the sphenoid bone by the petro-sphenoid suture, being medial and parallel to the *FO-FS* line.

**Segmentation:** Pellet et al.<sup>2</sup> used a useful, surgically-based segmentation approach to the petrous pyramid. It included four segments, or sectors: tympanic, mastoid, vestibular, and carotid, for which they used the same names we did herein for the spaces (anterolateral, posterolateral, posteromedial and anteromedial, respectively). These segments do not correlate completely with the spaces proposed here, since we did not include the lines (mucosal, EAC- IAC) in any of the spaces. Roche et al. modified this segmentation, to show four drilling zones<sup>8</sup>, useful in different trans-petrosal approaches. Besides, previous authors proposed the same reference lines with various names as the air axis<sup>4,10</sup> or middle ear cleft<sup>6</sup> for the mucosal line, and the sensorial<sup>4</sup> or auditory line<sup>10</sup> for the EAC-IAC line. An angle of 8 degrees has been described between the two parts of the EAC-IAC line<sup>2</sup>. We hence combine these landmarks to propose an inedited approach, including other parts not occupied by the four compartments, such as the petrous apex, the mastoid, and the roof of the TMJ. Both methods of segmentation help understanding 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<sup>4</sup>. The roof is the tegmen tympani. Detailed description of walls of middle ear is beyond the scope of this work, and is available elsewhere for the interested reader<sup>4,6,10</sup>. The middle ear is classically divided into spaces relative to the position of the tympanic membrane<sup>4,6</sup>. 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 mastoid antrum (through the aditus ad antrum), while the ET is continuous with the protympanum<sup>4,6</sup>.

**Facial nerve:** The facial nerve, as well as its branches, is an important landmark, both on 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 very useful guide to surgical navigation, especially in middle fossa approaches. The GSPN as it runs nearly parallel to the mucosal line and to the petrous ridge can orient surgeon to the axis of the petrous pyramid, and to the location of the Eustachian tube, which lies between it and the more laterally located FO-FS line. The GSPN serves as a limit between two middle fossa triangles, the Kawase and Glascock 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 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 of petrous pyramid around the compartments, such as petrous apex, mastoid and roofs of the EAC and TMJ. It can also extend to other parts of the temporal bone such as 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 hyper-pneumatization, down to the

C2 vertebra <sup>11</sup>. Air cells have been largely studied <sup>6,12-15</sup>; its nomenclature depends mainly on pneumatization tracts, which is very useful for understanding development and connections, but it can be variable and difficult to memorize. In order 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 seven 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 <sup>16</sup>.

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

### ***The compartmental approach***

To the best of our knowledge, this is the first description of petrous pyramid anatomy using the compartmental approach and segmentation methods, ~~based on developmental origin~~. The anatomy of the temporal bone is studied in detail in excellent textbooks, some of which have been used as references <sup>2-6,10,14</sup>. The particularity of this work is drilling the superior surface

and grouping of contents into compartments. We also used the resulting map to re-describe anatomy of major elements, in order 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 classical drilling of the lateral surface of the petrous pyramid. Yet, appreciation of the third dimension, i.e. depth, is not possible. This is why 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.<sup>21</sup> described three parallel lines in the skull base, with an angle of 45 degrees to the midline. The medial line is formed by the ICA and the middle line formed by the Eustachian tube. The lateral line is formed by the medial pterygoid plate, the foramen ovale, the foramen spinosum, and spine of sphenoid, from anterior to posterior, respectively.

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

*The mucosal axis, nearly 45 degrees orientation to the midsagittal plan, has a large number of skull base structures parallel to it, as seen in figure7. As such, this fact forms a solid basis for understanding relationships, inside the petrous pyramid, part of the lateral skull base. This is in contrast to midline skull base, which is more parallel to the mid-sagittal plane.*

*These differences help understand and correlate the different orientations of certain structures, such as medial vs. lateral pterygoid plates, cavernous vs. petrous segments of the ICA, and the different orientation of the vidian n inside the vidian canal vs 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 two 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 re-describe anatomy of the skull base, and even the whole head and neck, on a compartmental basis. This would be of aid to all surgeons working in the head and neck, especially skull base surgeons.*

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 Glascock triangles), as seen in figure 7. Kawase's triangle, or rhomboid, is interposed between the petrous ridge medially and the GSPN laterally. Its anterior limit is the mandibular nerve, while its posterior limit is the arcuate eminence<sup>22</sup>. It can be divided into pre and post-meatal triangles, by the internal auditory canal<sup>23</sup>. Drilling Kawase's rhomboid is used in middle fossa approaches, to access the IAC, and to access the posterior fossa (anterior petrosectomy). Glascock's 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 foramen spinosum and the arcuate eminence<sup>22</sup>.

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, access to the medially located petrous ICA can be done through a superior oblique trajectory, using middle fossa approach, then drilling lateral to the GSPN (Glasscock's triangle), or medial to it (Kawase's rhomboid). Starting drilling in Glasscock's triangle has higher risk of injury to the ET<sup>24</sup>, as can be understood from its location lateral to the GSPN. Anatomical description of the superior petrous surface, for middle fossa approaches, was presented in the amazing dissections by Rhoton<sup>1</sup>.

On the other hand, approaches starting from the lateral surface of the mastoid, behind the EAC, and passing towards the posterior petrous surface, are called posterior petrosectomies. These allow access the posterior cranial fossa. All of them include removal of the mastoid cells (mastoid segment) and can progressively involve more drilling of the petrous pyramid. Approaches can be classified into retrolabyrinthine (mastoid segment only), translabyrinthine (mastoid segment and posterior labyrinth: the whole postero-medial and postero-lateral spaces; exposing the IAC), and transchochlear and transotic approaches (both involve removing the mastoid and the whole otic capsule segments, but the difference is that the first one involves re-routing of the facial nerve, with risk of facial palsy; while the second does not, but with limited work space) <sup>2</sup>. These last two approaches can even be pursued into the petrous apex.

This way, understanding of surgical approaches can be easier, with the possibility to re-describe all microsurgical and endoscopic approaches inside and around the petrous pyramid. As such, the compartmental approach may serve to systematize all approaches used in otology and oto-neurosurgery, according to targets, thus facilitating approach selection. This would be of special help to all surgeons working in the head and neck region.

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

The present study is limited by a lower number of dissections. Further larger studies are required to confirm the reliability and reproducibility of this approach. Drilling from the posterior, lateral and inferior aspect of the petrous pyramid could be of interest to enrich the visualization of contents in three dimensions. Non-orthogonal surgical views have also to be integrated into it, for direct surgical application. Tridimensional constructs and

sagittal/coronal schematic views could also be added to further anatomical studies. This work is mainly qualitative, thus quantitative measures have not been addressed, as the aim was to create the plan, before going into detailed measurements. Future work will be needed to incorporate studies addressing measurements<sup>25</sup> in and around the petrous pyramid, as well as the need to incorporate anatomical variations.

## **Conclusion**

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 simplifies textbook description of the subject, and may thus serve as an introduction to anatomy of the petrous pyramid. It offers the possibility to re-describe anatomy all the way to applications; whether clinical, radiological or surgical; which helps creating a more integrated learning process. Re-interpreting known anatomy is needed to advance and enhance education of the subject, and is also needed in other specialties, as we currently face massive accumulation of medical knowledge beyond our ability to handle; with limited time and resources. Integrating anatomy and radiological and surgical applications may serve as an aid, and example, to create more integrated curricula. As such, we hope that this approach would provide an educational aid for surgical trainees.

## **Acknowledgements**

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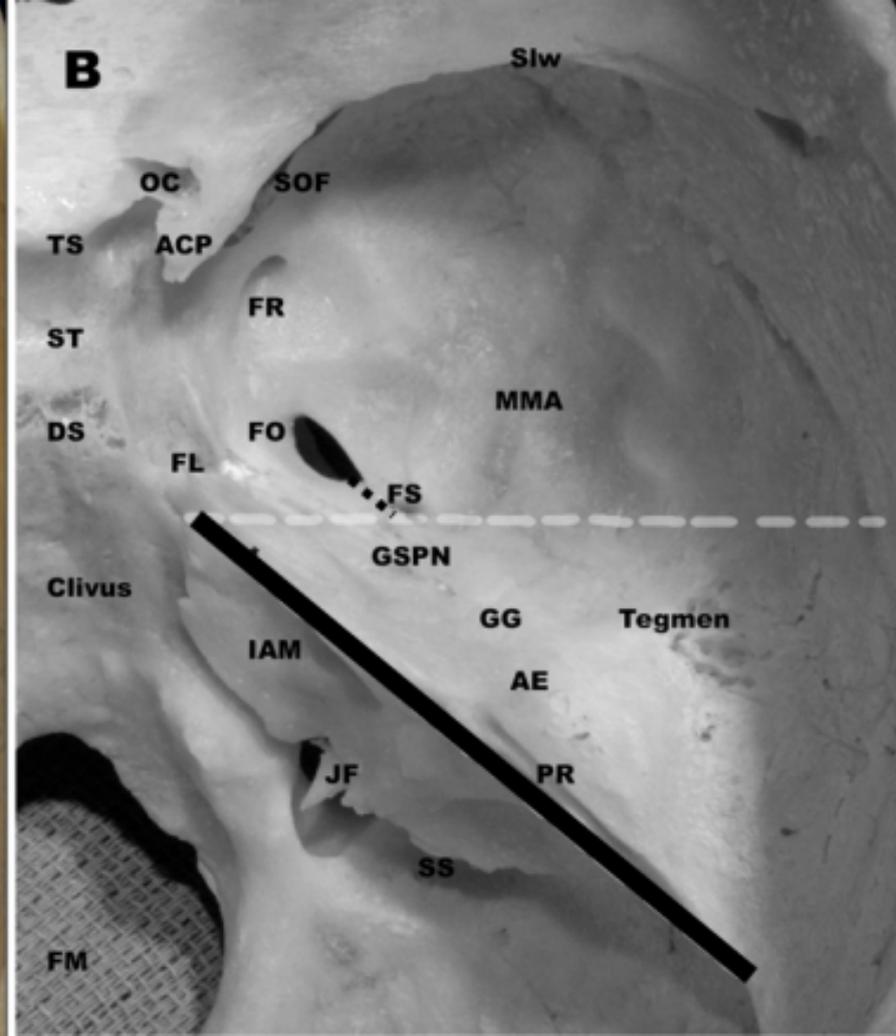
**Figure 1: The right petrous pyramid of a dry skull from a superior view.**

Superior view of the right side of the skull base, showing the middle cranial fossa; and parts of the anterior and posterior cranial fossae. Inset photo shows orientation of the skull base in this anatomical view

**A:** The petrous pyramid is a triangular-shaped partition between the middle and posterior cranial fossae. It makes the posterior part of the floor of the middle cranial fossa.

**B:** A horizontal line is drawn (white discontinuous line) representing the anterior limit of the petrous pyramid as proposed by Ribas et al. This line starts laterally in front of the tragus, i.e. the pre-auricular burr hole, 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) that comes obliquely to form a triangle (thick black line). The lateral limit is where the superior petrous surface meets the vertical plate of squamous bone, i.e. the petro-squamous suture. A line between the foramen ovale and spinosum is shown as black dotted line.

ACP: anterior clinoid process, AE: arcuate eminence, DS: dorsum sellae, FL: foramen lacerum, FM: foramen magnum, FO: foramen ovale, FR: foramen rotundum, GG: geniculate ganglion, GSPN: groove for the greater superficial petrosal nerve, IAM: internal auditory meatus, JF: jugular foramen, MMA: middle meningeal artery groove, OC: optic canal, PR: petrous ridge, Slw: sphenoid lesser wing, SOF: superior orbital fissure, SS: sigmoid sinus groove, ST: sella turcica, TS: tuberculum sellae.

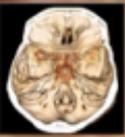
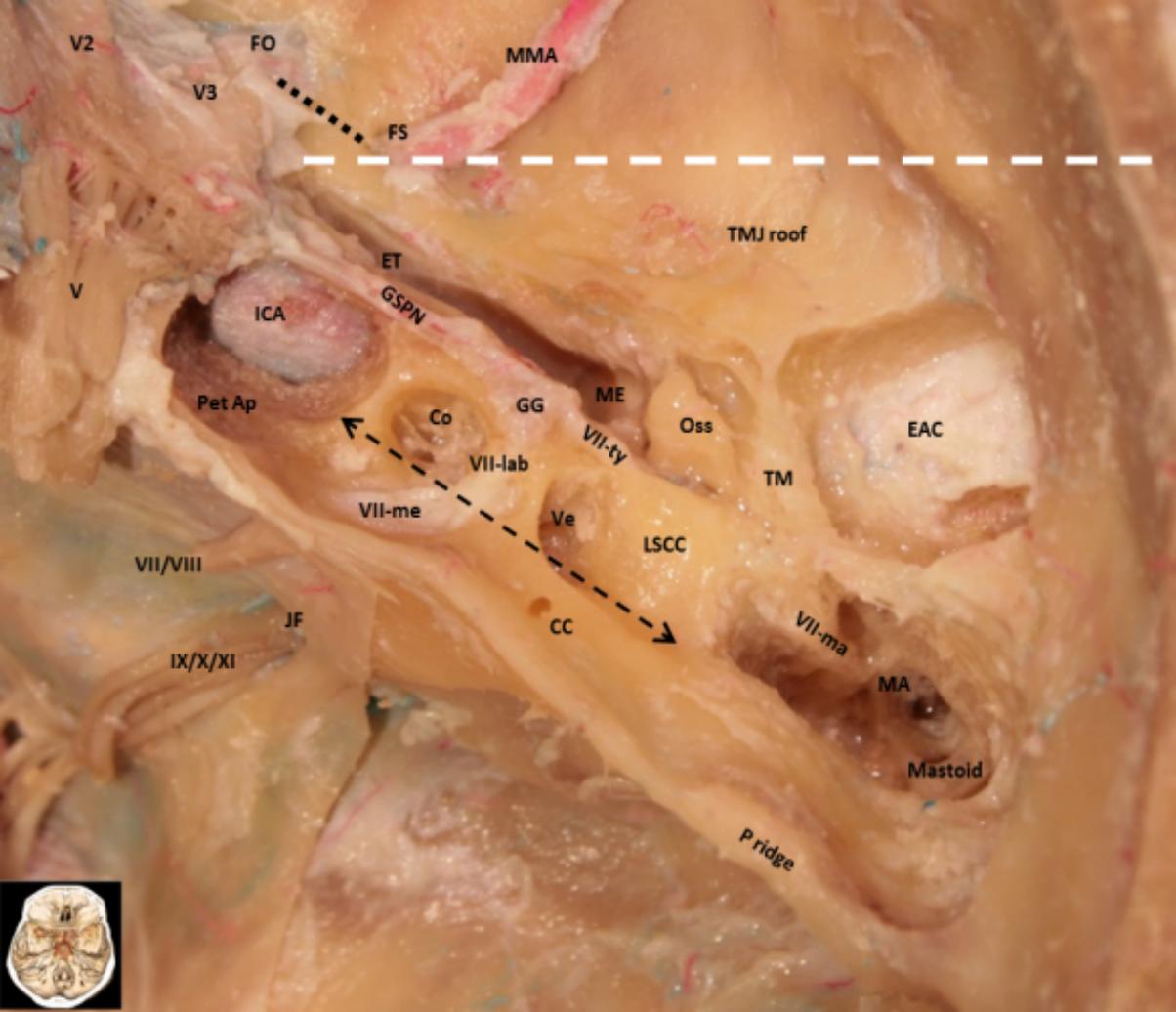


**Figure 2: The contents of the petrous pyramid from a superior view.**

Inset photo shows orientation of the skull base in this anatomical view. Exposed contents of the petrous pyramid after drilling the superior surface are shown in detail. The posterior limit of the petrous pyramid is the petrous ridge (P ridge). 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 foramen spinosum (FS). More medial to the foramen ovale and spinosum are a series of mucosa lined cavities: Eustachian tube (ET) anteriorly, middle ear (ME) and mastoid antrum (MA) more posteriorly, ending within the mastoid bone (mastoid). The mucosal line is used as the axis of the petrous pyramid, not the midsagittal plane. The upper parts of the ossicles (Oss); malleus and incus; are shown. The external auditory canal (EAC) lies laterally to the middle ear and meets it at the tympanic membrane (TM). More anterior to the EAC is the roof of the temporomandibular joint (TMJ). Medial to the middle ear is the glistening hard bone otic capsule (extent shown as black interrupted double arrowed line) containing the cochlea (Co) and the vestibule (Ve), separated by the internal auditory canal containing the meatal segment of the facial nerve (VII-me). Also seen is the common crus (CC) of the posterior and superior semicircular canals; and the lateral semicircular canal (LSCC). The facial nerve continues after exiting the IAC as the labyrinthine segment (VII-lab) to arrive to the middle ear as the geniculate ganglion (GG), and then turns posteriorly (first genu) to continue as the tympanic segment (VII-ty) running below the LSCC. It then 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 GG runs medial to the ET, and even more medial to it is the internal carotid artery (ICA) running inside the petrous apex (Pet ap). A line between the foramen ovale and spinosum (FO-FS line) is shown as black dotted line. The white interrupted line is the location of the line set as the anterior limit of the petrous, passing through the FS. The mixed nerves (IX-XI) are shown entering the jugular foramen (JF) below the petrous pyramid.

CC: common curs, Co: cochlea, EAC: external auditory canal, ET: Eustachian tube, FO: foramen ovale, FS: foramen spinosum, GG: geniculate ganglion, GSPN: groove for the greater superficial petrosal nerve, IAC: internal auditory canal, ICA: internal carotid artery, IX/X/XI: mixed cranial nerves, JF: jugular foramen, LSCC: lateral semicircular canal, MA: mastoid antrum, Mastoid: drilled mastoid cells, ME: middle ear, MMA: middle meningeal

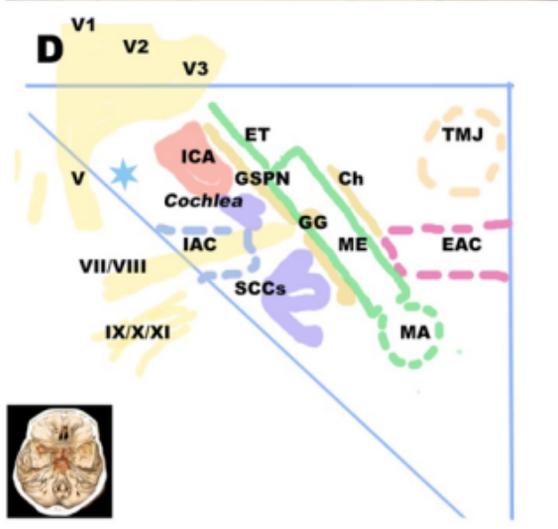
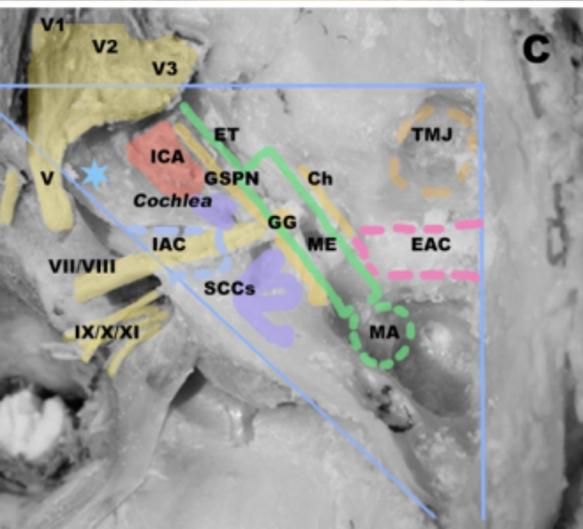
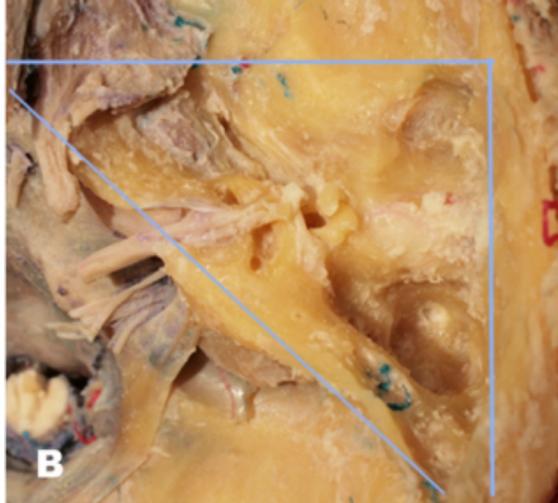
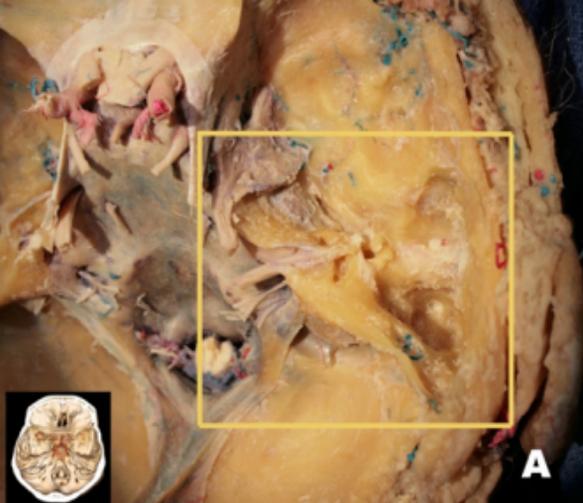
artery, Oss: ossicles, P ridge: petrous ridge, Pet ap: petrous apex, TM: tympanic membrane, TMJ: temporomandibular joint, V: trigeminal nerve, V2: maxillary nerve, V3: mandibular nerve, Ve: vestibule, VII/VIII: facial and vestibulocochlear nerves, VII-lab: labyrinthine segment of facial nerve, VII-ma: mastoid segment of facial nerve, VII-me: meatal segment of facial, VII-ty: tympanic segment of facial nerve.



**Figure 3: Schematic view of petrous pyramid contents superimposed progressively on images of skull base dissections.**

Inset photo shows orientation of the skull base in this anatomical view. The superior aspect of a right petrous pyramid after complete drilling (A), magnification of the petrous pyramid with annotations indicating contents with colors (B and C), and a schematic representation of these (D) are shown. Blue lines show the limits of the superior petrous pyramid. The mucosal compartment (green) courses obliquely from the *mastoid antrum* (MA) posteriorly, towards the pharynx; including the Eustachian tube (ET) and middle ear (ME). The cutaneous compartment (pink) lies laterally to the middle ear and is composed of the external auditory canal (EAC). The neural compartment (blue) lies medial to the middle ear, and is composed of the anterior and posterior labyrinth, respectively; the *cochlea* and semicircular canals (SCCs), on either side of the internal auditory canal. The facial nerve course is shown in yellow running from the internal auditory canal (IAC, surrounded by interrupted blue line) towards the middle ear to end in the geniculate ganglion (GG). It gives origin to the 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 (asterisk). Moreover, some structures that do not belong to the petrous pyramid constitute relevant landmarks: the trigeminal ganglion and its branches lie over the petrous apex and the internal carotid artery, the cranial nerve VI can be seen medially to the trigeminal ganglion, entering its Dorello's' canal at the upper third of the clivus. The lower cranial nerves IX to XI go inferiorly towards the jugular foramen.

Asterix: petrous apex, Ch: chorda tympani, EAC: external auditory canal, ET: Eustachian tube, GG: geniculate ganglion, GSPN: greater superficial petrosal nerve, IAC: internal auditory canal, ICA: internal carotid artery, IX-XI: cranial nerves IX to XI, MA: mastoid antrum, ME: middle ear, SCCs: semicircular canals, TMJ: temporo-mandibular joint, V1-3: branches of the trigeminal nerve, VII-II: the acoustico-facial nerve complex.



#### **Figure 4: Segmentation methods of the 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). Figures A and D show the compartments, while figures B, C, E and F show the two methods of segmentation.

A- Four compartments could be described within the petrous pyramid: mucosal (green), cutaneous (pink), neural (violet), and vascular (red) compartments.

B- The X-method divides the petrous pyramid into **four spaces** through two intersecting lines – the mucosal line (green) and the External-Internal auditory canal (EAC-IAC) line (blue) – forming the letter “X”. The four spaces are located clockwise around the middle ear: (1) antero-medial space containing the cochlea and the petrous apex carrying the ICA, (2) antero-lateral space contained the roof of the TMJ, (3) postero-lateral space contained the smaller lateral part of the mastoid and (4) postero-medial space containing the posterior labyrinth (vestibule and SCC) and the larger medial part of the mastoid. The mastoid thus occupies both the posterior lateral and medial spaces, crossing the endodermal line. On the other hand, the labyrinths occupied both the anterior and posterior medial spaces, on either side of the IAC.

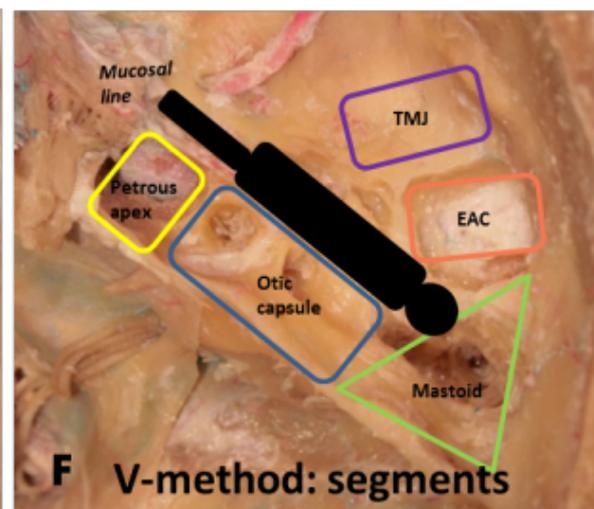
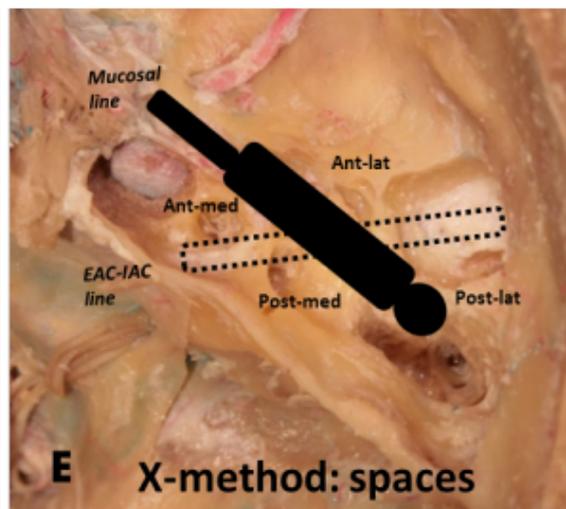
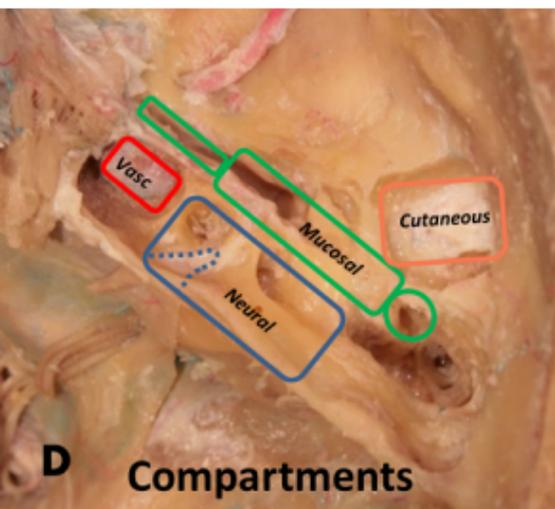
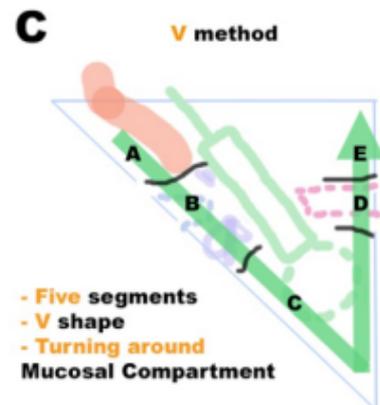
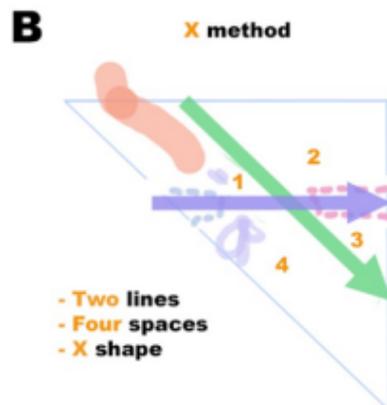
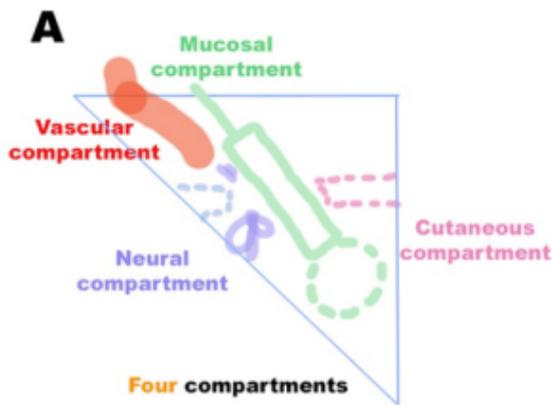
C- The V-method arranges **fives segments** around the mucosal line (green) in a V-shaped form. The five segments are successively called: (A) petrous apex segment medial to the ET and carrying the ICA, (B) otic capsule segment including the IAC, cochlea, vestibule, and SCCs, (C) mastoid segment occupying 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 ET.

D- The four compartments are shown as follows: mucosal (green), cutaneous (orange), neural (blue) and vascular (red). The contour of the internal auditory canal is shown as interrupted blue line.

E- The X-method of segmentation is shown as two 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 five segments around the mucosal line (black). These segments are named accordingly.

EAC: external auditory canal, IAC: internal auditory canal, TMJ: temporomandibular joint



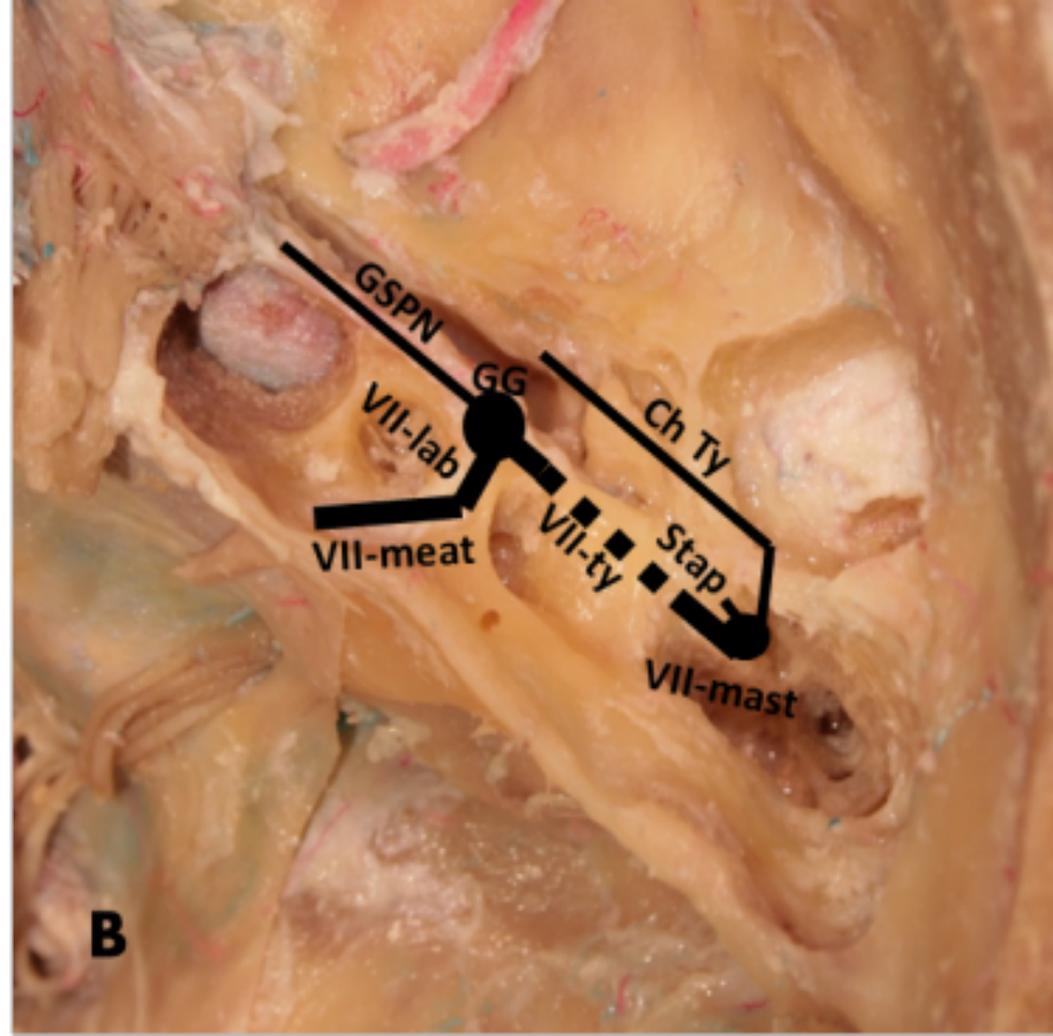
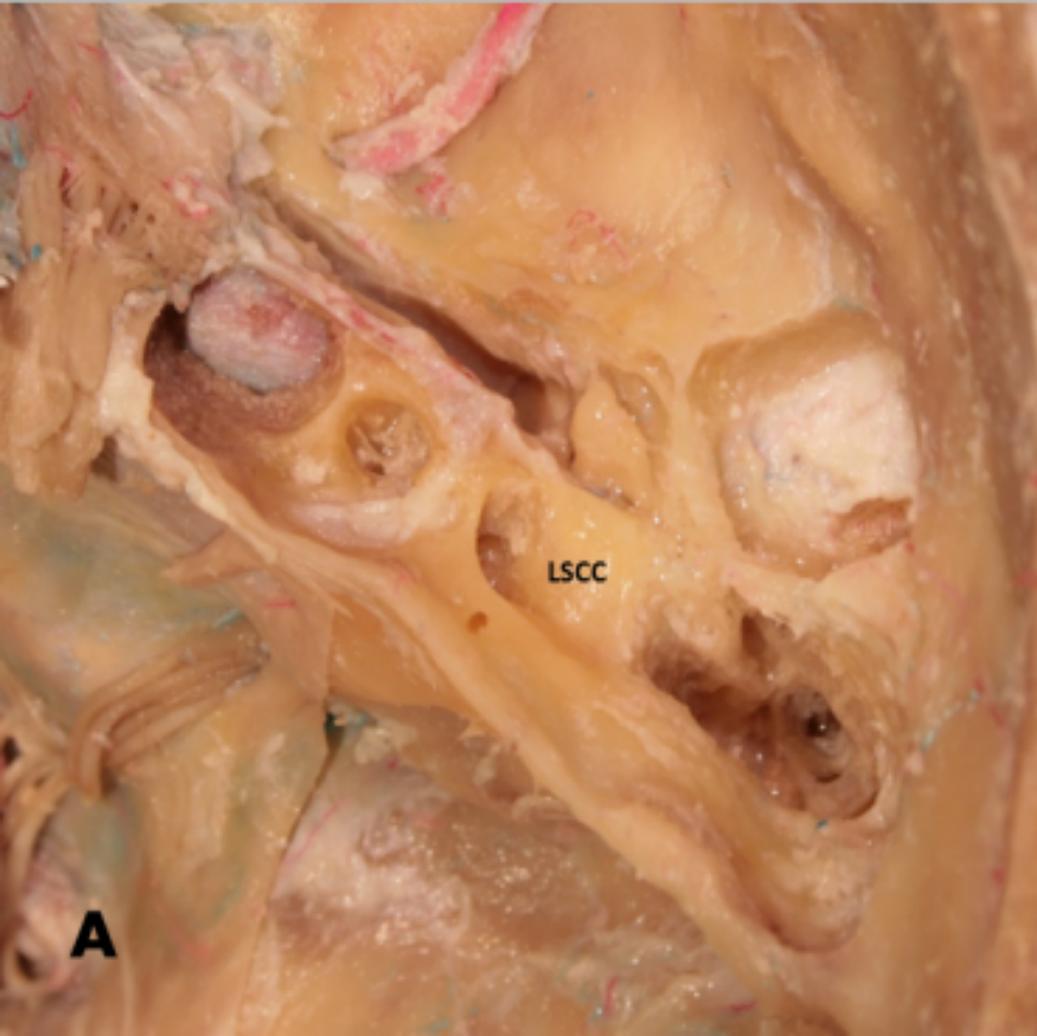
### **Figure 5: Segments and major branches of the petrous part of the facial nerve.**

A: Drilled superior surface of the petrous pyramid. The lateral semicircular canal (LSCC) is shown.

B: Superimposed trajectory of the facial nerve segments and major branches. The facial nerve first passes through the internal auditory canal, as the meatal segment (VII-meat). Then it continues through the otic capsule 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. It then runs on the medial wall of the middle ear as the tympanic segment (VII-t), visible as at first but then becoming hidden beneath the LSCC (interrupted line). It then appears again 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 towards its exit through the stylo-mastoid 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. The tympanic segment reaches the posterior wall of the middle ear, gives rise to two 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).

Ch Ty: chorda tympani, GG: geniculate ganglion, GSPN: greater superficial petrosal nerve, LSCC: lateral semicircular canal, Stap: nerve to stapedius, VII-me: meatal segment of facial, VII-lab: labyrinthine segment of facial nerve, VII-ma: mastoid segment of facial nerve, VII-ty: tympanic segment of facial nerve, VII-Ma: mastoid segment of facial nerve



**Figure 6: Schematic progressive buildup of compartments on a right petrous pyramid.**

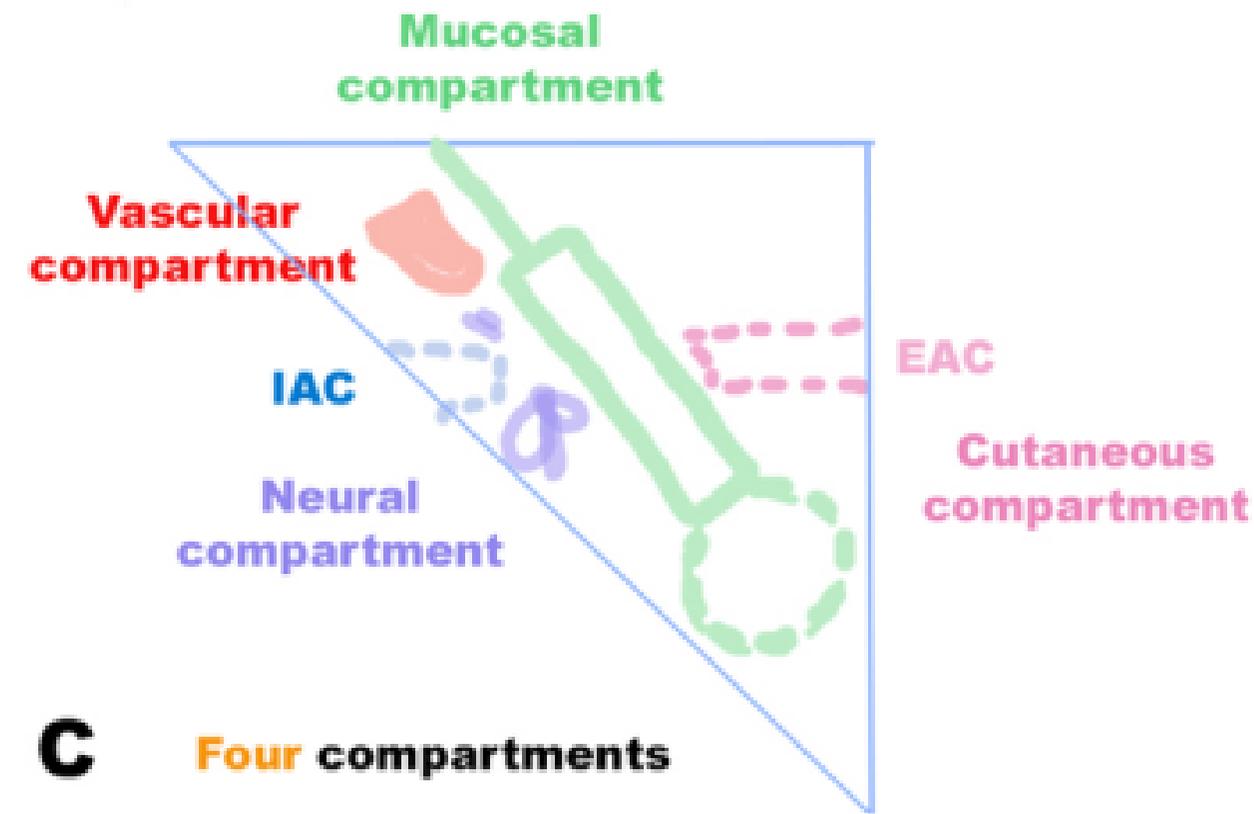
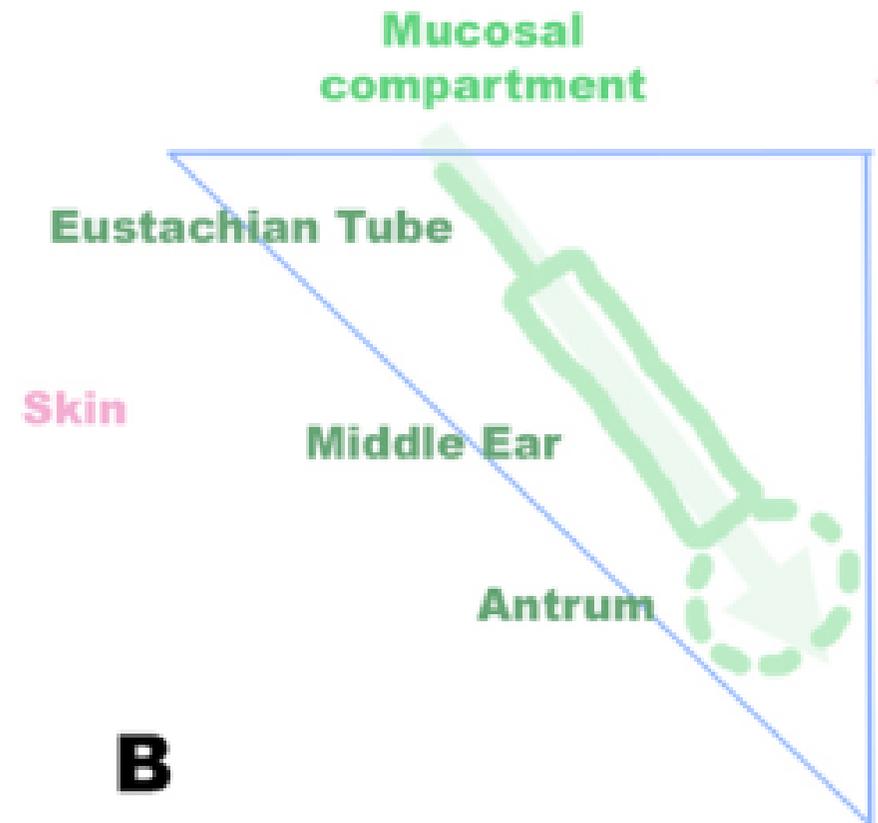
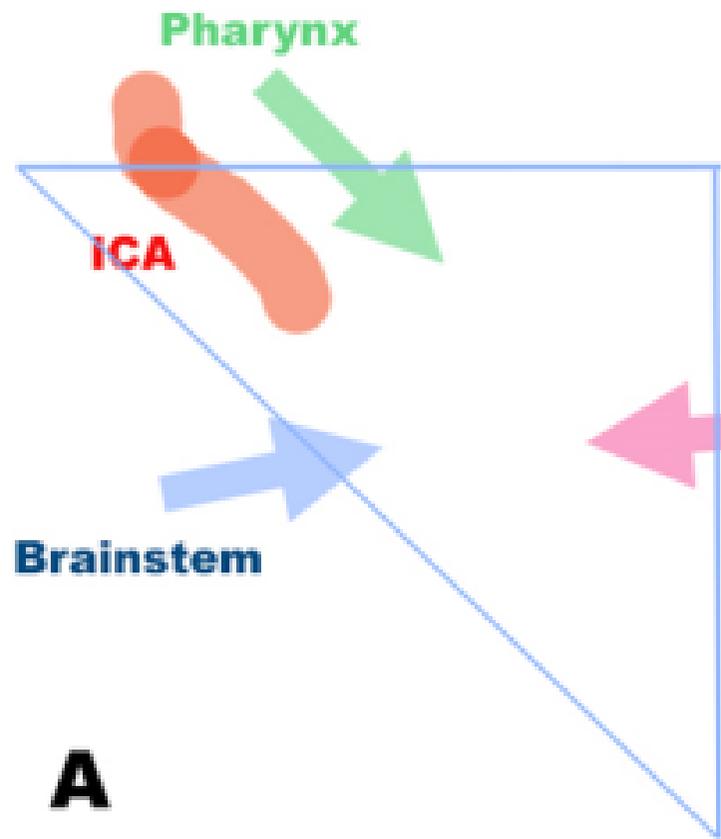
The anatomy of the petrous pyramid can be modelled as four compartments (the contents) developing in proximity, and then surrounded by the bony container. The superior surface of the petrous pyramid is represented by a simple triangle.

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, in red) is coming from the inferior surface of the petrous pyramid and then bends anteriorly, towards 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.

C: The final organization of the petrous pyramid contents.

EAC: external auditory canal, IAC: internal auditory canal, ICA: internal carotid artery.



**Figure 7 : Plan of the petrous pyramid contents from superior perspective, like an X-ray view from above**

A number of linear structures exist within the petrous pyramid. Their orientation and position can be described, relative to the mucosal axis (in green), 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 neural compartment is shown in blue, the cutaneous compartment in pink and the vascular compartment in red. The crossed arrows are for orientation as to the axis of the petrous bone, which corresponds to the mucosal line in our description.

**Longitudinal structures: *Level of the mucosal axis:*** 1- Chorda tympani (Ch Ty): on lateral wall of middle ear, running over the tympanic membrane; and 2- Tympanic segment of facial nerve (VII-t): runs on the medial wall of the middle ear. Three other structures lie here but are not shown for clarity: A- The tensor tympani muscle and canal are above the ET; B-The petro-sphenoid suture is described as being above the cartilaginous ET<sup>3</sup>; and C- The Lesser petrosal nerve is classically described as being parallel and lateral to the GSPN, as it arises from the middle ear, and it thus probably lies above the ET, as it is separated from the GSPN by an average distance of less than three millimeters<sup>15</sup>. ***Lateral to the mucosal axis:*** 1- FO-FS line: in the sphenoid bone, anterior to the petrous pyramid. The foramen spinosum lies on the anterior limit of the petrous, opposite the preauricular burr hole. An extension of this line anteriorly includes the lateral pterygoid plate (LPL)<sup>20</sup>. ***Medial to the mucosal axis*** (*remember that the neural compartment lies medial to the middle ear and that the vascular compartment lies medial to the ET*): 1- GSPN: medial and superior to the ET; 2- ICA: medial to the ET, making part of the lower anterior wall of the middle ear, the GSPN runs above it in 15 percent of cases according to Rhoton<sup>15</sup>; 3- Posterior semicircular canal (PSCC): in the posterior labyrinth, medial to the middle ear, 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 level of the superior petrosal sinus.

**Horizontal structures: *Lateral to the mucosal axis:*** 1- EAC: lateral to middle ear and meeting it at tympanic membrane (not shown). ***Medial to the mucosal axis:*** 1- IAC: medial to ME, does not reach the middle ear, contains meatal segment of facial nerve as well as

cochleo-vestibular nerve; 2- Arcuate eminence: generally overlies the superior semicircular canal (SSCC), and is posterior to the IAC; 3- Labyrinthine segment of facial nerve (VII-t) coming from the end of the IAC to reach the geniculate ganglion (GG) at medial wall of middle ear; and 4- Trigeminal (CN-V) ganglion and its mandibular branch (V3) in yellow: lie on the superior surface of the petrous apex and exits the middle fossa at the foramen oval (FO).

Other structures (drawn as dotted gray lines), not corresponding to the above groups, are shown for completion. These 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<sub>m</sub>, white circle on posterior wall of middle ear and connected to VII<sub>t</sub> and Ch Ty) lying beneath the aditus ad antrum, and descending vertically behind the middle ear. The TMJ lies anterior to the EAC.

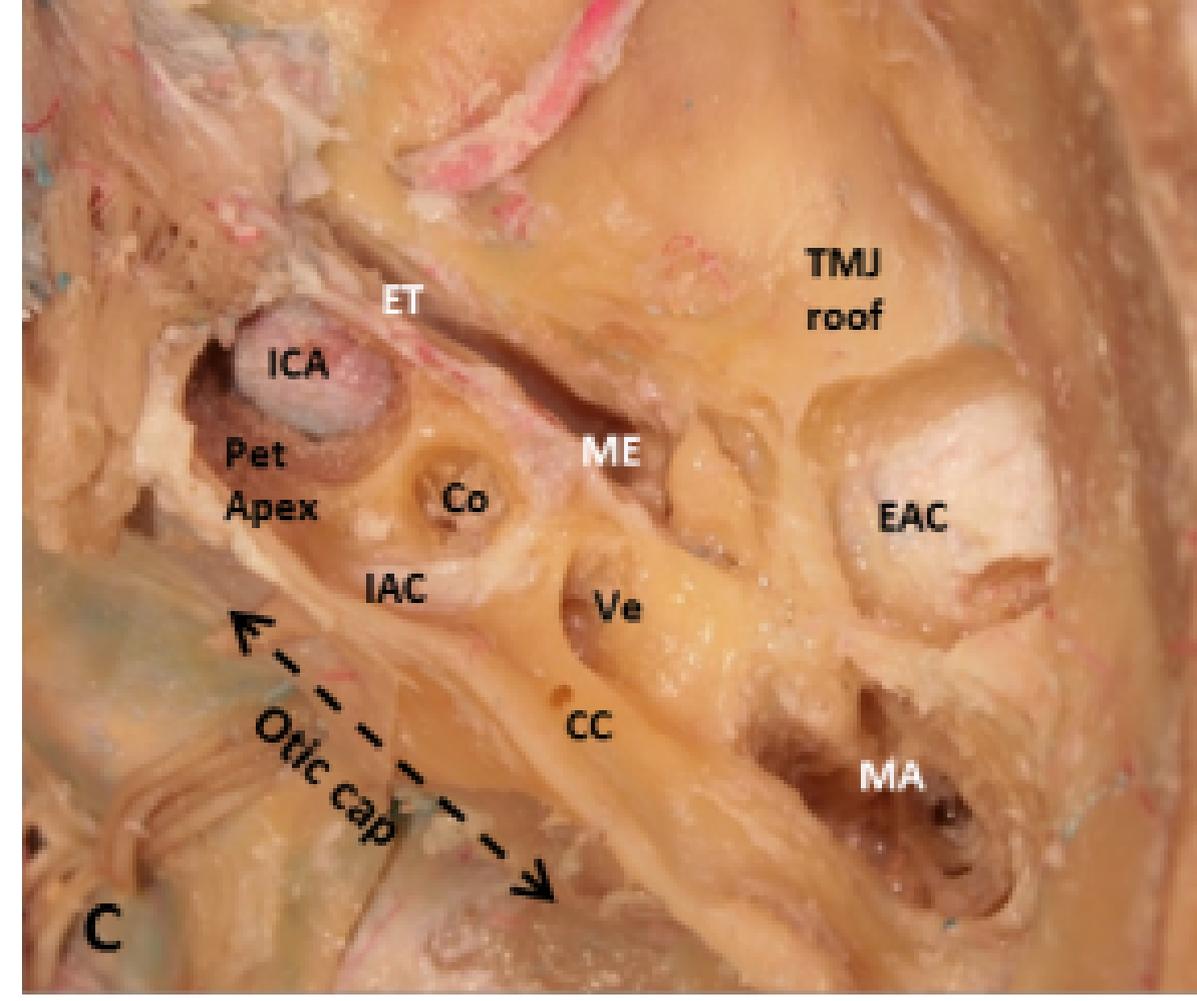
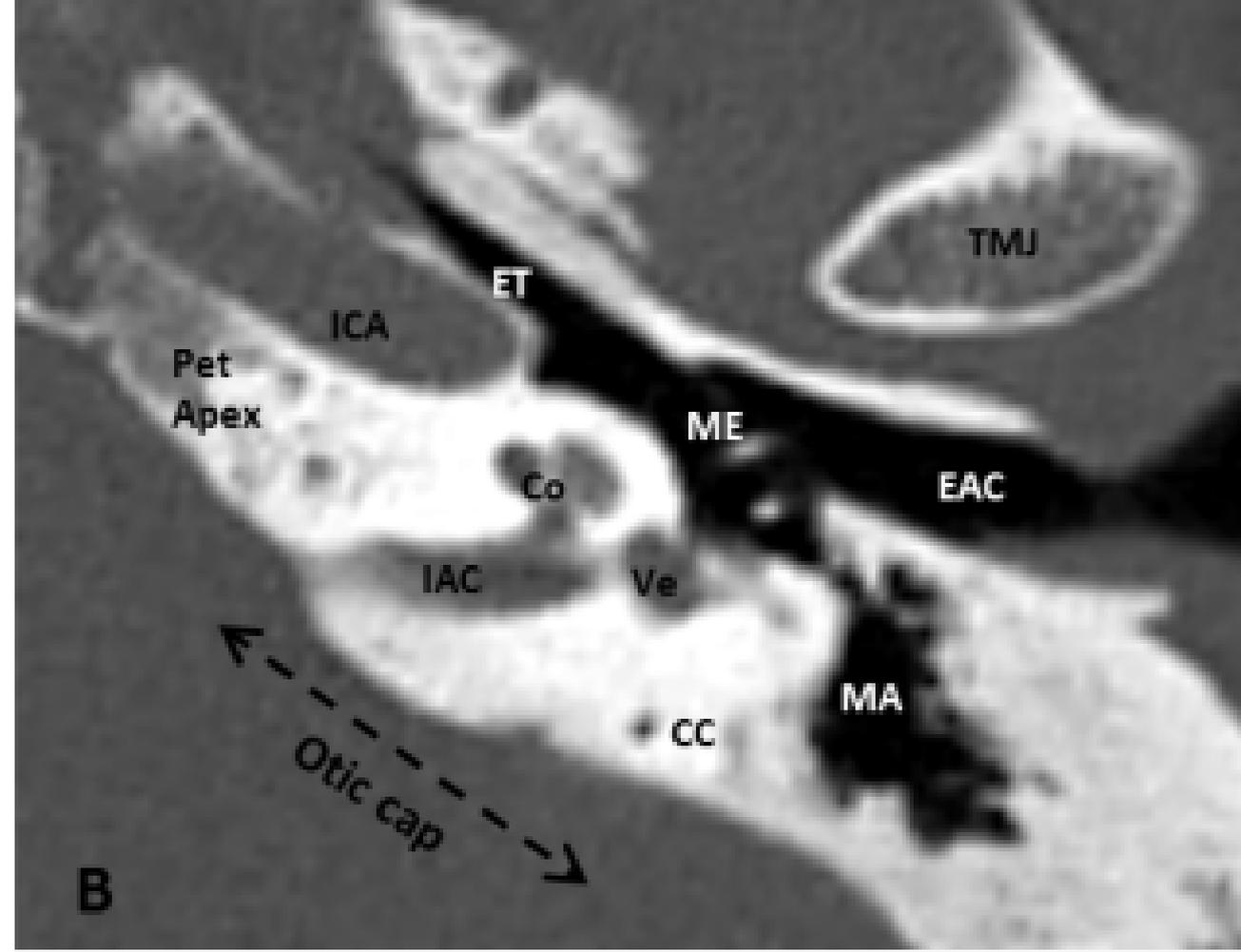
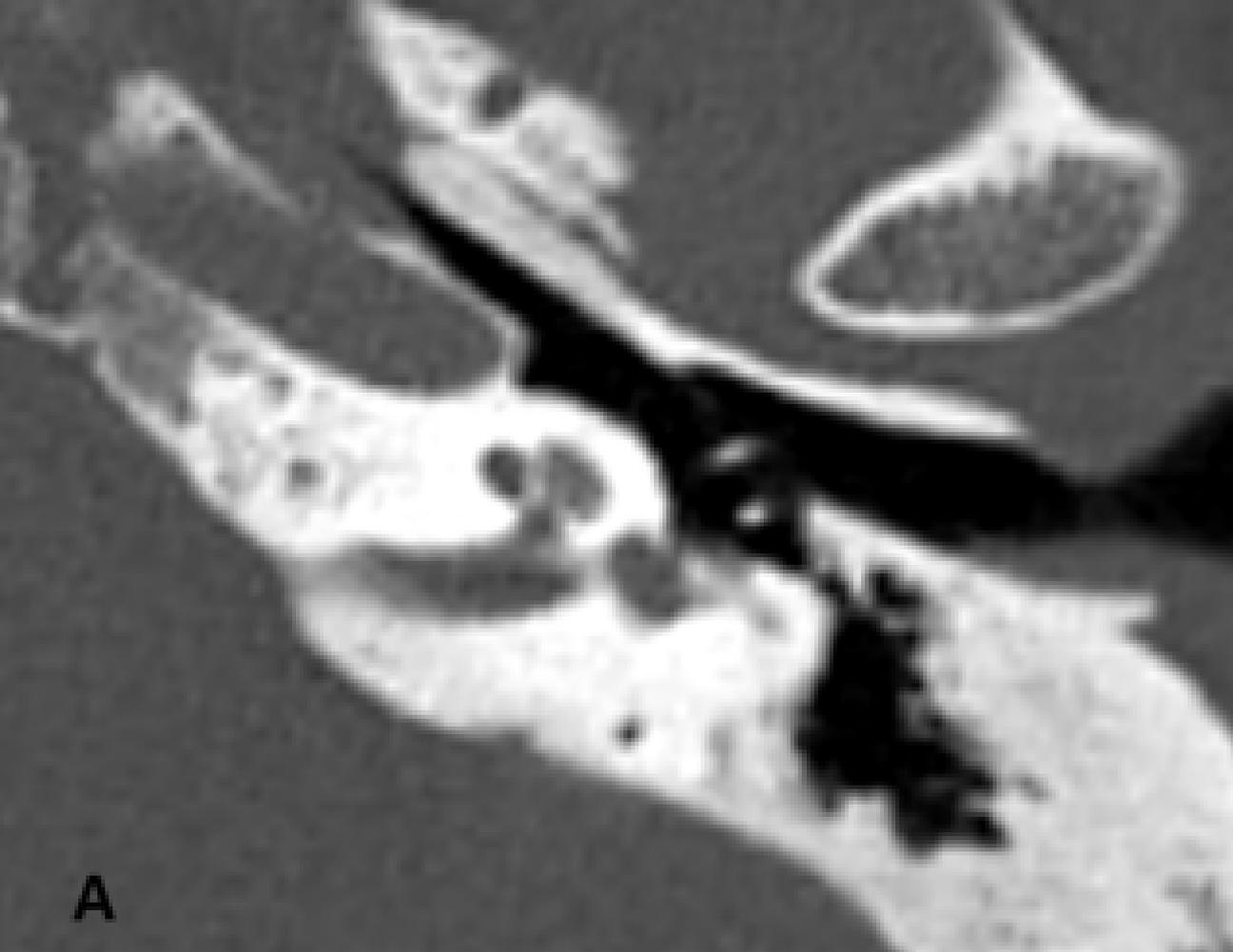
Co: cochlea, EAC: external auditory canal, ET: Eustachian tube, FO-FS: line joining foramen ovale and spinosum, GG: geniculate ganglion, GSPN: greater superficial petrosal nerve, IAC: internal auditory canal, ICA: internal carotid artery, LPL: lateral pterygoid plate, LSCC: lateral semicircular canal, SSCC: superior semicircular canal, MA: mastoid antrum, ME: middle ear, PSCC: posterior semicircular canal, TMJ: temporomandibular joint, CN-V: trigeminal nerve, V: vestibule, V3: mandibular nerve, VII<sub>lab</sub>: labyrinthine segment of facial nerve, VII<sub>m</sub>: mastoid segment of facial nerve, VII<sub>t</sub>: tympanic segment of facial nerve.



### **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: non-labelled axial image, B: labelled axial image and C: corresponding drilled superior surface for comparison). It shows 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 common crus, of the superior and posterior semicircular canals, is also shown. Lateral to the otic capsule is the air density of the endodermal line, with the middle ear (ME) lying directly laterally to the otic capsule, with 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 (Ap). The external auditory canal (EAC), with air density, meets the middle ear laterally, while the temporomandibular joint (TMJ, shown is the mandibular condyle) lies lateral to the ET.

Pet Apex: petrous apex, CC: common crus, Co: cochlea, EAC: external auditory canal, ET: Eustachian tube, ICA: internal carotid artery, IAC: internal auditory canal, MA: mastoid antrum, ME: middle ear, Otic Cap: otic capsule, TMJ: temporomandibular joint (mandibular condyle), Ve: vestibule



**Table 1: The middle ear as related to petrous pyramid compartments, lines and spaces.**

<b>Anterior</b>	<ul style="list-style-type: none"> <li>1- Eustachian tube (ET, anterior part of the mucosal line)</li> <li>2- Tensor tympani muscle above the ET</li> <li>3- Internal carotid artery (ICA) coming from below (coming from inferior surface of temporal bone)</li> </ul>
<b>Posterior</b>	<ul style="list-style-type: none"> <li>1- Mastoid antrum (posterior part of mucosal line, connected by aditus ad antrum in upper part of the posterior wall)</li> <li>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)</li> </ul>
<b>Lateral</b>	<ul style="list-style-type: none"> <li>1- Cutaneous compartment (EAC: separated from the middle ear by the tympanic membrane, zygomatic air cells overlie the EAC)</li> <li>2- Anterolateral space (roof of the temporomandibular joint)</li> <li>3- Posterolateral space (mastoid bone)</li> </ul>
<b>Medial</b>	<p>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): below the facial nerve, 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 SCC: above the facial nerve posteriorly</p>
<b>Superior</b>	<p>Tegmen tympani, separating the middle ear from the middle cranial fossa above (harboring the temporal lobe)</p>
<b>Inferior</b>	<ul style="list-style-type: none"> <li>1- Jugular bulb and ICA (in the upper end of the carotid space of the neck)</li> <li>2- Root of styloid process</li> </ul>

**Table 2: Facial nerve segments and their relations to petrous pyramid contents.**

<b>Petrous CN-VII segments</b>	<b>Description</b>
<b>Meatal segment</b>	<i>Inside the Internal auditory canal (IAC), that separates anterior and posterior labyrinths, lying in the anterosuperior quadrant of the IAC. After its exit from the IAC, the facial nerve will enter the <i>facial canal</i>, which has three segments and two genus, described below.</i>
<b>Labyrinthine segment</b>	<i>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 towards the medial wall of middle ear, ending in the geniculate ganglion. It lies between cochlea and vestibule.</i>
<b>First genu</b>	<i>Where the labyrinthine segments turns posteriorly at the <i>medial wall of middle ear</i>. This is the location of the geniculate ganglion, that is the origin of the greater superficial petrosal nerve (GSPN) running anteriorly, medial to the mucosal line.</i>
<b>Tympanic segment (horizontal)</b>	<i>Running posteriorly on the <i>medial wall of the middle ear (cochlear wall)</i>. It lies laterally to the vestibule anteriorly, but more posteriorly runs below the lateral SCC.</i>
<b>Second genu</b>	<i>Where the tympanic segment turns inferiorly at the <i>posterior wall of the middle ear</i>, below the aditus ad antrum, and lateral semicircular canal (SCC).</i>
<b>Mastoid segment (vertical)</b>	<i>Running vertically inferiorly on the <i>posterior wall of middle ear (mastoid wall)</i>. It exits the petrous pyramid at the stylomastoid foramen, to enter parotid gland.</i>

**Table 3: Branches of the facial nerve within the temporal bone and relations to the mucosal line**

<b>Petrous CN-VII branches</b>	<b>Description</b>
<b>GSPN</b>	Starting at the geniculate ganglion and running anteriorly on the <i>medial wall of the middle ear</i> , for some distance, becoming progressively more superficial. It exits through a hiatus into the superior surface of the petrous pyramid. It runs <i>medial to the mucosal line (specifically: supero-medial to the Eustachian tube), lateral to the cochlea, and superiorly or supero-laterally to the Internal carotid artery (ICA)</i> , towards 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 ICA, called 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 towards the pterygopalatine fossa.
<b>Nerve to stapedius</b>	From the mastoid segment ( <i>on the posterior wall of the middle ear</i> ) running anteriorly to innervate the stapedius muscle, that runs from the posterior wall of the middle ear, to insert into the stapes.
<b>Chorda tympani</b>	From the mastoid segment ( <i>on posterior wall of the middle ear</i> ), running superiorly and anteriorly <i>on the lateral wall of the middle ear (on tympanic membrane)</i> , in a convex upward curve. It exits at petrosquamous fissure, inside canal of Huguier, into the infratemporal fossa (carrying taste and parasympathetic fibers to the tongue and submandibular/sublingual salivary glands, respectively).

**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 three surfaces (superior, posterior and inferior) and a base, also called lateral surface. Its base faces laterally while its apex faces the midline. This pyramid is made by three 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 four groups, or compartments (figure 3). The container is cast around the compartments during development. Certain areas are not occupied by any of the compartments, i.e. mastoid, petrous apex and TMJ roof.
3. The most important is the *mucosal compartment/line*. It comes obliquely from the pharynx towards the mastoid bone, and is formed by three parts: the Eustachian tube anteriorly, the middle ear in the middle, and the mastoid antrum posteriorly (figure 6B). This compartment will give 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 would result in different possible composition of the mastoid and petrous apex segments; as they can be pneumatized, diploic, or sclerotic.
4. The other three 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 external auditory canal (EAC) covered 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 labyrinth – vestibule and semicircular canals - on either side of the internal auditory canal (IAC). This last leads the vestibular, cochlear, and facial nerves from the ponto-medullary junction into the petrous bone. Lastly, the *vascular compartment* lies

inside the petrous apex, medial to the Eustachian tube. It includes the internal carotid artery (ICA) coursing within the carotid canal, towards the *foramen lacerum* (FL).

5. Two reference lines cross at the middle ear, in the center of the pyramid: the mucosal line and the EAC-IAC line. All anatomical structures within the petrous pyramid could be located through two segmentation methods: the X-method creating four spaces thanks to the previous intersecting reference lines; and the V-method delineating five segments around the mucosal line (figure 4).

**Table 5: Proposed nomenclature of air cells based on location within the temporal bone.**

Air cell group	Composition
<p><b>Mastoid (retro-labyrinthine, inside the mastoid segment).</b> Lying at the base of the petrous pyramid, within the triangular mastoid segment. It lies <i>between the otic capsule and the lateral pyramidal surface, i.e., posterior to the otic capsule.</i></p>	<p>This includes the mastoid antrum and surrounding air cells. It is composed of seven groups of air cells that are easier to locate when viewed from the lateral surface according to Allam<sup>12</sup>. From this view the mastoid looks like a triangle with three angles and three walls. The cells include:</p> <ol style="list-style-type: none"> <li>1- Central cells, in the center of the mastoid <i>Three groups on the angles of the triangle</i></li> <li>2- Antral/periantral cells (in the antero-superior angle, including mastoid antrum)</li> <li>3- Sinodural cells (in the postero-superior angle)</li> <li>4- Tip cells (in the inferior angle, having medial and lateral cells, separated by the digastric ridge) <i>Three groups on the walls of the triangle</i></li> <li>5- Peri-facial cells (anteriorly, surrounding mastoid segment of the facial nerve, behind the external auditory canal)</li> <li>6- Tegmental cells (superiorly, beneath the tegmen tympani)</li> <li>7- Peri-sinus cells (posteriorly, around the sigmoid sinus, having medial and lateral cells)</li> </ol>
<p><b>Apical (pre-labyrinthine, inside the petrous apex segment).</b> <i>It lies between the otic capsule and the tip of petrous pyramid, i.e., anterior to the otic capsule.</i></p>	<p>This group can be further classified into:</p> <ol style="list-style-type: none"> <li>1- Supracarotid cells</li> <li>2- Infracarotid cells</li> <li>3- Mediocarotid cells</li> </ol>
<p><b>Peri-labyrinthine</b> (<i>Lying across and also around the otic capsule segment</i>). <i>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.</i></p>	<p>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 :</p> <ol style="list-style-type: none"> <li>1- Trans-labyrinthine cells (passing through the otic capsule, classically called subarcuate cells, passing within the arch of the superior semicircular canal (SCC), along with the petromastoid canal that carries the subarcuate artery).</li> <li>2- Supra-labyrinthine cells (beneath the superior petrous surface). May be classified into anterior and posterior, as related to anterior and posterior labyrinths.</li> <li>3- Infra-labyrinthine cells (beneath the inferior petrous surface). May be classified into anterior and posterior cells (below the anterior and posterior labyrinths, respectively).</li> <li>4- Para-labyrinthine cells (beneath the posterior petrous surface, <i>medial</i> 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.</li> </ol>
<p><b>EAC roof cells</b></p>	<p>Above the EAC.</p>
<p><b>TMJ roof cells</b></p>	<p>In the bony roof of the glenoid fossa.</p>
<p><b>Peritubal</b> (<i>Cells around the Eustachian tube</i>)</p>	<p>This includes:</p> <ol style="list-style-type: none"> <li>1- Medial paratubal (between the Eustachian tube, ET, and the internal carotid artery, ICA)</li> <li>2- Lateral paratubal</li> <li>3- Supratubal</li> <li>4- Infratubal</li> </ol>
<p><b>Accessory (extra-pyramidal)</b></p>	<p><i>Cells extending beyond the petrous pyramid, even outside the boundaries of</i></p>

*the temporal bone.*

1- Zygomatic: within the zygomatic arch and its base

2- Squamous (in the horizontal plate anterior to the roof of the TMJ, and also in the vertical plate)

3- Styloid

4- Occipital (classically considered in the accessory group, but it is an extratemporal extension into the occipital bone)