REVIEW

Morphofunctional Partition of the Middle Ear Cleft

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INTRODUCTION: The classic anatomic description of the middle ear cleft consists of three structural sets : the mastoid, the tympanic cavity and the bony eustachian tube.

AIMS AND OBJECTIVES: The author try to find out observations and arguments demonstrating and defending the original and personal concept of a specific portion (fitting) of the middle ear cleft, which consists in a morphofunctional partition that separates the middle ear cleft in two functional sets; in two different compartments : anteroinferior and posterosuperior.

METHODS: After having reviewed the literature and from the perspective of our combined clinical and research experience, the authors shall critically evaluate the various factors that contribute to the morphofunctional partition of the middle ear cleft.

RESULTS: This partition is an entity, with clinical and surgical implications, and is defined by distinct anatomic, organogenic, mainly histologic, histopathologic and clinic characteristics.

CONCLUSIONS: This original concept of a morphofunctional partition of the middle ear cleft contributes to a better understanding of the physiology of the middle ear cleft, as well as of the pathogenesis of otitis media.

The middle ear cleft and the fibrocartilaginous eustachian tube form an integrated and complex entity. The middle ear cleft consists of the mastoid gas cell system and the tympanic cavity, a tympanum and 4 annexes, the epitympanum and hypotympanum, and the retrotympanum and protympanum. The protympanum corresponds to the bony eustachian tube. In effect, the middle ear cleft is a set of interconnected gas cells that maintain the balance of pressure variations.

Since 1997[1], we have demonstrated and defended the concept of a specific portion of the middle ear cleft: a morphofunctional partition that separates the middle ear cleft into anteroinferior and posterosuperior compartments[2-7]. The anteroinferior compartment can be compared with the nose and the posterosuperior compartment with the lung. We suggest that this partition is an entity with clinical and surgical implications and that it is defined by distinct anatomic, organogenic, histologic, and histopathologic and clinic characteristics.

After having reviewed the literature and from the perspective of our combined clinical and research experience, we shall critically evaluate in this paper the various factors that contribute to the morphofunctional partition of the middle ear cleft. The 2 most important functions of the middle ear cleft mucosa are defined, and the clinical and surgical implications of this entity are presented.

MORPHOFUNCTIONAL PARTITION OF THE MIDDLE EAR CLEFT

Anatomic approach

The tympanic cavity is constricted in its superior third by the interatticotympanic diaphragm, which is a bony membranous barrier perforated by 2 openings. This anatomic barrier divides the middle ear cleft into 2 separate compartments to form diaphragm that is composed of 2 complementary types of structures: mucosal folds and bones with muscular structures (the head and neck of the malleus, the body and short process of the incus, the tensor tympani muscle, the anterior and lateral mallear, and the double posterior

incudal ligaments). This barrier is not impenetrable. There are 2 small permanent openings: the anterior tympanic isthmus, which is situated between the tensor tympani tendon and the stapes; and the posterior tympanic isthmus, which is between the double posterior ligament of the incus and the bony posterior tympanic wall (Figure 1).

Figure 1: The interatticotympanic diaphragm. Superior view of a right tympanic cavity in a fresh human temporal bone specimen. The tegmen tympani has been removed. 1, Malleus head; 2, body of the incus; 3, stapes; 4, anterior tympanic isthmus; 5, posterior tympanic isthmus.

In 1946, Chatellier and Lemoine[8] published a histologic description of the interatticotympanic diaphragm in the newborn. They linked their study to clinically important aspects of treating patients with the complications of acute otitis media. In 1971, Proctor[9] used the term "tympanic diaphragm" and demonstrated that this diaphragm and the aditus play a very important role in determining the degree to which middle ear suppurations may progress. In 1995, Palva and Johnsson[10] used the term "epitympanic diaphragm" and presented a sketch of that diaphragm that was based on serial sections of temporal bones. In 1997, Ars and Ars-Piret used Chatellier's terminology to support the concept of a morphofunctional partition of the middle ear cleft[1] and included the interatticotympanic diaphragm in the description of the partition.

Developmental approach

The development of this diaphragm, which serves as a partition, appears to occur during the first stages of embryonic development. During the first 12 weeks of life, the cartilaginous cells, which are the precursors of

the ossicles, are embedded in loose mesenchyme that limits the expansion of the future tympanic cavity. This mesenchyme is invaded by the epithelium of the future fibrocartilaginous eustachian tube. The progression of the epithelium takes the form of epithelial buds that grow slowly. The buds are hampered by the presence of the future ossicles. They divide into 4 sacci that expand in 4 different directions, lining the tympanic cavity with epithelium and enveloping the ossicles. Those sacci have been described by Proctor[11] (Figure 2). There are the saccus anticus, which extends in a craniofrontal direction and forms the anterior pouch of von Trôltsch; the saccus medius, which forms the attic, extends upward, and usually divides into 3 smaller saccules; the saccus superior, which extends posteriorly and laterally between the malleus handle and the long crus of the incus and forms the posterior pouch of von Trôltsch; and the saccus posterior, which extends along the hypotympanum to form the round window niche, sinus tympani, and oval window niche[12-19]. These structures are very important because they are present at the beginning of the partition of the middle ear cleft and they condition the development and the set up of all the pieces of the puzzle. The development and progression of these sacci in the middle ear cleft form an interatticotympanic diaphragm and its accompanying folds. They also pave the way for the development of 2 epithelia, both of which have specific functions, into the separate anteroinferior and posterosuperior compartments of the middle ear cleft.

Histologic approach

The normal middle ear cleft mucosa is an extension of the mucosa of the rhinopharynx[20-22]. ln the anteroinferior compartment of the middle ear cleft, the epithelial layer is pseudostratified; there are numerous mucous and ciliated cells. The connective tissue is thick and relatively dense. The function of this compartment is devoted primarily to mucociliary clearance. ln the posterosuperior compartment of the middle ear cleft, the epithelial layer is monocellular and contains only flat cells; there are no ciliated or mucous cells. The connective tissue is loose. A gas exchange occurs in this compartment.
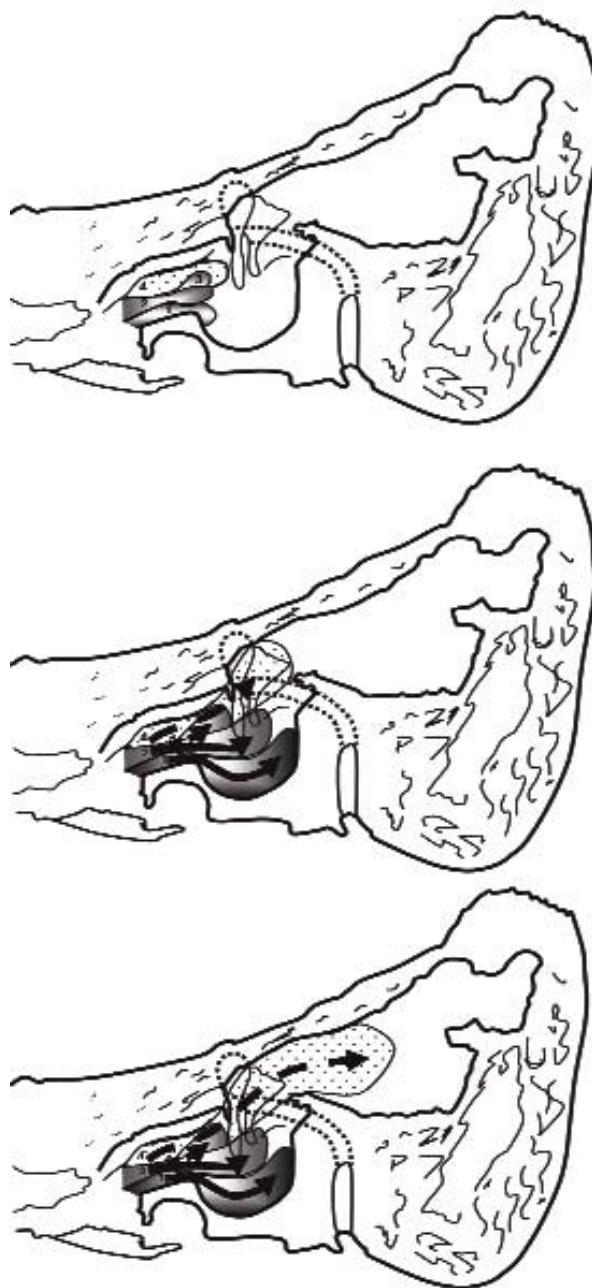

Figure 2: Development of the sacci and gas-containing spaces of the middle ear cleft.[(i)]
1, Saccus anticus; 2, saccus medius; 3, saccus posterior; 4, saccus superior.

[(i)]Proctor B. The development of the middle ear spaces and their surgical significance. J Laryngol Otol 1964;78:631-48.

To investigate that gas exchange, we examined the importance of the tissular barrier that separates the blood compartment containing oxygen-carrying

hemoglobin from the gas-containing spaces of the middle ear cleft. To do so, we measured the distance between the center of gravity of the blood vessels and the basal membrane of the mucosa in the different regions of the middle ear cleft. The mean distance of the anteroinferior part was 70 µm, and that of the posterosuperior part was 40 µm (Figure 3). These measurements imply that there is a significant difference in the diffusion of the gases between the 2 separate compartments of the middle ear cleft[23,24]. We also noted that the connective tissue in the posterosuperior part was looser than that in the anteroinferior part. These facts illustrate the importance of gaseous exchange in the posterosuperior compartment of the middle ear cleft.
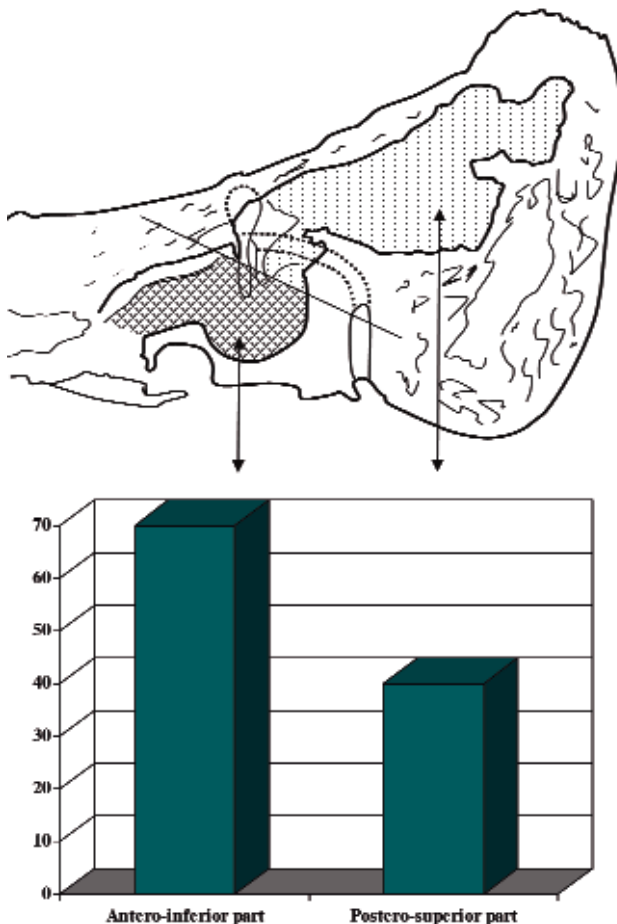
Figure 3: Distance in micrograms between the center of the blood vessels and the basal membrane of the normal mucosa in the anteroinferior and posterosuperior compartments of the middle ear cleft.

Histopathologic approach

Does an inflammatory process modify the behavior of the middle ear cleft mucosa? We conducted similar histomorphometric studies on mucosal samples of the middle ear cleft collected from patients with chronic inflammatory mucosal disease and otorrhea who underwent surgery for chronic suppurative otitis media. That disorder is characterized by the perforation of the tympanic membrane and an intermittent or constant mucopurulent discharge, both of which are associated with irreversible pathologic changes in the mucosa of the middle ear cleft. The mucosa in such diseased middle ear clefts may be thickened by edema, submucosa fibrosis, and infiltration with chronic inflammatory cells.

We next estimated the importance of the tissular barrier that separates, under these inflammatory conditions, the compartment containing red blood cells that transport gases from the gas-containing spaces of the middle ear cleft. To do so, we measured the distance between the center of the blood vessels and the basal membrane of the mucosa in various regions of the middle ear cleft of mucosal pathologic samples (Figure 4, a and b)[25]. We observed that the inflammatory process respects and reinforces the morphofunctional partition of the middle ear cleft. The mean distance between the center of the blood vessels and the basal membrane of the mucosa is 45 µm in the anteroinferior compartment and 22 µm in the posterosuperior compartment (Figure 5). The histologic effect of the inflammatory process appears to be more evident in the posterosuperior compartment of the middle ear cleft.

The inflammatory process reduces by 50% the distance from previously healthy blood vessels to the mucosa. This reduction may be due to an increase in both the number and diameter of the blood vessels (angiogenesis) affected by the inflammatory process. The reduction could also be due to the opening of small superficial submucosal vessels. In any case, that reduction in distance enables increased gas diffusion.

Clinical approach

Tympanosclerosis usually occurs in the anteroinferior part of the eardrum. Tympanic membrane
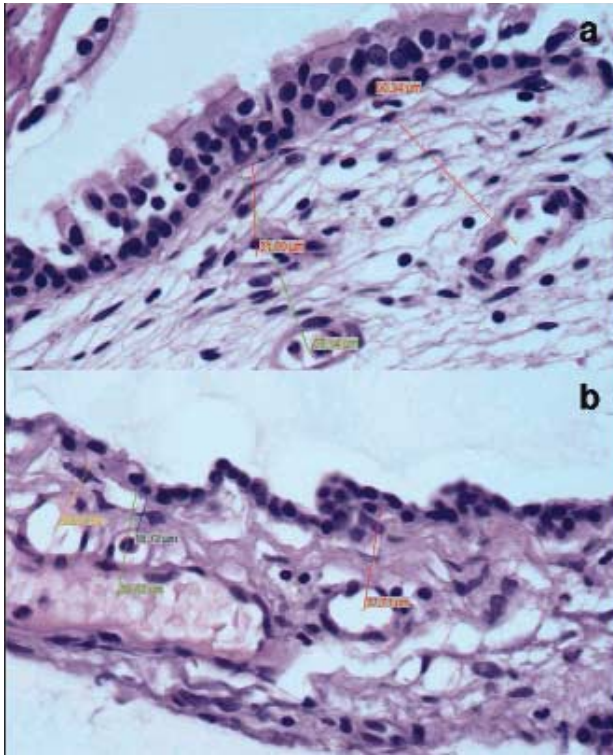
Figure 4, a and b: Epithelium of the mucosa of the middle ear cleft. The 2 types of epithelium vary by site. a) The anteroinferior compartment of the middle ear cleft has a pseudostratified epithelial layer with numerous mucous and ciliated cells. The connective tissue is thick and relatively dense. b) The posterosuperior compartment has a monocellular epithelial layer composed of only flat cells; there are no ciliated or mucous cells. The connective tissue is loose. The blood vessel centers are considered the middle point of the longest axis of the vessels. In this study, the measurements were based on the distance between the blood vessels' center and the basal membrane that is perpendicular to the long axis of the cross-sectioned vessel.
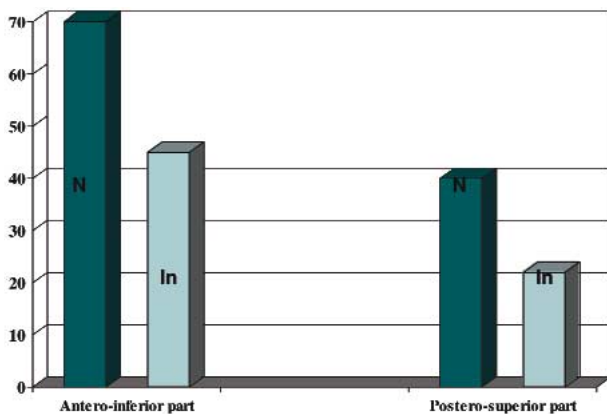
Figure 5: Distance in micrograms between the center of the blood vessels and the basal membrane of the inflamed mucosa in the 2 compartments. A comparison of the healthy and the inflamed mucosa in the anteroinferior and posterosuperior parts of the middle ear cleft.
N, Normal; In, inflamed.

retraction pockets are more often located in the posterosuperior part of the tympanic membrane.

Primary functions of the mucosa according to the partition of the middle ear cleft

Mucociliary clearance

The mucosa of the anteroinferior compartment of the middle ear cleft consists of ciliated and nonciliated cells with a secretory dome. The process of mucociliary clearance propels the mucus towards the eustachian tube, which contains cellular debris, microorganisms, and other exogenous particles. The efficacy of this process depends on the characteristics of the mucus, the effectiveness of the ciliary movements, and the coupling between the cilia and the mucus. The mucous flow consists of 2 layers. The first layer, which is a superficial gel composed of glycoproteins with a high molecular weight, is viscous and elastic. The second (the "sol" or aqueous layer), which is deeply situated and more fluid than the first layer, soaks the cilia, the extremity of which is on the superficial viscid layer. Mucociliary coupling is a dynamic interaction in which ciliary beating propels the viscous upper layer of mucus (the gel layer), while the ciliary bodies, which are bathed in the fluid sol layer, remain immobile. The adequacy of ciliary dynamics depends on the physical properties of the sol layer. The epithelium absorbs sodium, which also carries water. Thus epithelial action controls the fluidity of the sol layer[27].

Mucociliary clearance dysfunction

The mediators of the inflammatory process increase or decrease the transport of sodium to achieve a low or high concentration of that element. Greater degrees of inflammation can interrupt the absorption of sodium (and thus of water) with flood of the middle ear cleft. Sometimes, an acceleration of this sodic absorption reduces the thickness of the sol layer and immobilizes the cilia, which leads to an interruption of the mucociliary clearance and to the formation of a mucous plug[28,29]. The inflammatory process causes deep disturbances in the morphology of (and consequently in the mucociliary clearance of) the mucosa of the anteroinferior compartment of the middle ear cleft. The mucosa becomes thick and edematous and even

polypoid. The height of the ciliated cells increases considerably, and the number of mucous cells increases. In the submucosa, there is an increase in both the number and the size of the microscopic glands. A chronic inflammatory process induces a metaplastic transformation that increases the production of mucus and simultaneously reduces the fluidity of the sol layer. This leads to the formation of a mucous plug that fills the protympanum and obstructs the fibrocartilaginous eustachian tube lumen. Negative pressure in the middle ear cleft then increases progressively; this results in the creation of processes such as tympanic membrane retraction pockets.

Transmucosal gas exchange

The primary purpose of the mucosa of the posterosuperior compartment is to facilitate gas exchange between the middle ear cleft and the blood through a constitutive tissular barrier. To vibrate in an optimal manner, the tympanoossicular system must remain in balance[14]. This means that the intramiddle ear cleft pressure must be equivalent to the atmospheric pressure (760 mm Hg). In ambient air, that value is obtained by calculating the sum of the partial pressures of the 4 main constitutive gases in the air: oxygen, 150 mm Hg; carbon dioxide, 0 mm Hg; nitrogen, 563 mm Hg; and water vapor, 47 mm Hg. However, in the middle ear cleft, the composition of gas varies for 2 main reasons. The middle ear cleft is in a closed cavity that is connected with the external environment by the fibrocartilaginous eustachian tube and the nasal fossae. The gas in the rhinopharynx, which enters the middle ear cleft via the fibrocartilaginous eustachian tube, consists of exhaled gas that contains less oxygen and more carbon dioxide than does ambient air. That gas composition also varies because gas diffusion occurs between the middle ear cleft and the arterial and venous blood via the mucosa. In blood, the partial pressure of these gases differs: There is more oxygen in the arterial blood (93 mm Hg) and more carbon dioxide in the venous blood (44 mm Hg) because the gas exchange occurs at the level of the pulmonary air cells and the tissues throughout body, respectively. Thus the

composition of gas in the middle ear cleft differs from that in ambient air[30-33]. The gradient "out" from middle ear cleft to the capillaries is 57 mm Hg for oxygen, and the gradient "in" from the capillaries to the middle ear cleft is 39 mm Hg for carbon dioxide. This results in a strong negative pressure in the intramiddle ear cleft. However, in spite of the difference in gas composition, the pressure in the middle ear cleft approximates the atmospheric pressure to enable optimal sound transmission. This happens for 3 reasons:

- Because the sum of the partial pressures of oxygen and carbon dioxide is lower in the middle ear cleft (90 mm Hg) than in ambient air (150 mm Hg), nitrogen exerts the higher partial pressure in the middle ear cleft (623 mm Hg) because of its very slow diffusion toward the capillaries.

- The composition of the exhaled gas that enters the middle ear cleft via the tube contains less oxygen and more carbon dioxide than does ambient air. This reduces the passive diffusion of these gases through the mucosa.

- The blood flow through the middle ear cleft mucosa is probably low; this limits the importance of gas diffusion and enables the oxygen and carbon dioxide partial pressures to nearly equalize because each has a high diffusion rate. The same mechanism applies to water vapor, the diffusion rate of which is also very high. Thus transmucosal gas exchange results in gas absorption, which means that negative pressure in the intramiddle ear cleft must be compensated for by tubal dilation.

Transmucosal gas exchange dysfunction

Inflammation increases the both number and diameter of the blood vessels in the mucosa[25,26]. The gas exchange then becomes more intense, and the light physiologic negative pressure that extends into the middle ear cleft increases. The higher the degree of impairment of the transmucosal gas exchange, the greater the decrease in the total pressure of the middle ear cleft. This negative pressure is caused by a gas deficit that constitutes the pathogenic background for the complex otitis media syndrome[33,34].

Clinical and surgical implications

Clinical implications. The anteroinferior compartment of the middle ear cleft, which is situated under the diaphragm, includes the protympanum, mesotympanum, and hypotympanum and is covered by secretory or nonsecretory ciliated cells that enable mucociliary clearance. This middle ear compartment consists of a less rigid chamber because of the presence of the eardrum. Because of the fibrocartilaginous eustachian tube, it opens into an intermittently ventilated gas pocket and communicates with the posterosuperior compartment by both the anterior and posterior tympanic isthmus. It is often the site of secondary bacterial infections from the rhinopharynx.

An inflammatory process involving the mucosa of the anteroinferior middle ear cleft compartment leads to dysfunction in mucociliary clearance and to the accumulation of mucus (factors that can further the development of serous or seromucous otitis). Other types of infection may also develop. Tympanosclerosis could be a rare consequence of inflammation of the mucosa of the anteroinferior middle ear cleft [1,23,25].

The posterosuperior compartment of the middle ear cleft, which is situated above the diaphragm, includes the epitympanum, retrotympanum, aditus ad antrum, antrum, and mastoid gas cell system. It is covered by a richly vascularized cuboidal epithelium that is devoted primarily to gas exchange. It consists of a rigid chamber and an open nonventilated gas pocket that communicates with the anteroinferior compartment via both openings (anterior and posterior isthmi). It may be the site of viral hematogenous infections. Inflammation of the mucosa of the posterosuperior middle ear cleft compartment impairs gas exchange, which in turn leads to the development of a gas deficit in the middle ear cleft and subsequently to the creation of a tympanic membrane retraction pocket that can deteriorate into a cholesteatoma[1,23,25].

The interatticotympanic diaphragm conditions the topography of the retraction pockets. When only 1 opening is blocked, the posterosuperior quadrant of the pars tensa is attracted in the direction of the retrotympanum. When both openings are completely blocked, the pars flaccida is drawn in toward the epitympanum[5]. In the same way, the diaphragm also influences the invasion of the middle ear cleft by a cholesteatoma.

Surgical implications. Simple mastoidectomy is not sufficient to restore the middle ear cleft ventilation. An antroatticomastoidectomy in which the scutum and the posterior bony canal wall are carefully preserved and that is (if necessary) completed with a posterior tympanotomy must be performed with the goal of restoring gas exchange to the posterosuperior part of the middle ear cleft[35]. The posterior wall of the external auditory bony canal must be preserved or reconstructed, because it forms an impenetrable barrier that enables the mastoid gas cell system to function[5,6].

DISCUSSION

Too often, otologic surgeons assume that the operated middle ear cleft is permeated by gaseous flow. However, this cleft is a cavity covered by mucosa through which gas diffusion occurs and both gas and water vapor have a specific diffusion rate that influences the balance of pressure variations in the cleft. When surgical approaches to the middle ear cleft are compared and considered, it is important to remember that after a canal wall up procedure, the mastoid retains its native cuboidal nitrogen-absorbing epithelium. An inflammatory process increases both the number and the diameter of the blood vessels, thereby increasing the diffusion of gas, and the compensated middle ear cleft negative pressure slightly increases[35]. Here too, it is no longer compensated by the buffer role of the mastoid and becomes again pathologic.

In canal wall reconstruction with mastoid obliteration, the removal of the nitrogen-absorbing mastoid epithelium and the obliteration of the mastoid with bone pate decrease the likelihood of negative pressure recurrence. It is important to consider the long-term complications of such a technique, which include intracranial cholesteatoma and/or abscess, even if regular postoperative control is performed by efficient imaging of the obliterated mastoid cavity[36-38]. The canal wall down technique enables the removal of the

nitrogen-absorbing mucosa of the mastoid. The new epithelial lining of the mastoid bowl is a stratified keratinizing epithelium.

By suppressing the pathologic postinflammatory minipartitioning that occurs during the drilling of a diseased mastoid, we achieved a balance of pressure in the various gas cells between the different compartments of the middle ear cleft[5,6]. When we do open the gas cells of the temporal bone, we do not have to perform the largest cavity, searching all the cells. By drilling the middle ear cleft, we intend to restore a steady state among the different anatomofunctional elements, which encourages healing. The opening of a diseased mastoid is essential and permits drainage of the inflammatory secretion, removal of the inflamed granulation mucosa, and the creation of an enlarged gas reservoir. The entire surface area of the mastoid gas cells system is reduced after mastoidectomy, because the fine gas cells walls have been removed. Because the passive-pressure buffer function may be partially governed by the mucosal surface area, it may not be desirable to remove all the gas cells if the mastoid contains healthy cells lined with thin normal mucosa[5,6].

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