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Pre- and postnatal changes in the human tympanic cavity

Ph.D. Thesis

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INTRODUCTION

Since dawn of the nineteenth century anatomy of temporal bone was strongly related to ear therapy. The versatile symptoms and often lethal complications urged the morphological description of normal and pathological temporal bone. Sections were carried out more frequently and anatomical background of ear diseases got in focus. At that time ear therapy and anatomy of the ear were closely related, the discipline of the anatomy failed to put emphasis onto this rather tiny part of skull. Nobles of ear therapy recognized the relation tympanic cavity and mastoid process (*Wilde, Toynbee, Stacke, Jansen, E. Cheatle,* etc.) and implied mastoidectomy as a treatment for purulent otitis. In the fifties of the nineteenth century the introduction of 'head-mirror' (Tröltsch) revolutionized ear therapy and anatomy. Using 'head-mirror' the floor of the outer ear with the tympanic membrane could be routinely investigated and paracentesis were carried out more frequently to heal purulent otitis.

It was at the end of the nineteenth century when *Schwalbe* and *Siebenmann* published their work on anatomy of the temporal bone. Their monographies study temporal bone anatomy in detail including thorough descriptions of even the smallest items. These works substantiated the classical descriptive anatomy of temporal bone and were regarded as the essentials of ear anatomy. No breakthrough was published regarding the anatomy of bony ear until the midst of the twentieth century when *Anson* and *Bast* published the development of the inner ear in 1949 based on the analysis of several hundreds of fetal, juvenile and adult temporal bones. Using three dimensional models development of tympanic cavity and its spaces and the ossification of the labyrinth were patterned.

In contrast to the considerable expansion of ear symptoms the exploration of anatomical relations were rather neglected. Numerous puzzles in ear pathology or pathophysiology remained unanswered and everyday ear surgery practice poorly contributed to our anatomical knowledge of field. Whereas ear pathology and morphological and molecular studies of inner ear have been accelerated, middle ear and temporal bone surgery have been based on the classical general anatomical descriptions. Although some anatomical works focus on surgical anatomy of the temporal bone (*Anson*, *Donaldson*, *Gulya*, *Proctor*, *Schuknecht*), they fail to offer a firm developmental or histological-morphological background for the optimal utilization of modern techniques. *Béla Bollobás* was first to present the microsurgery of the tympanic cavity. Individual chapters discuss the main items of the tympanic cavity in this book which is completed by the presentation of both fetal and adult anatomical variances.

AIMS

Since the surgical anatomy of temporal bone is rather poorly explored, the main point of my work was to answer questions that arise in everyday clinical ear therapy by investigating the development of middle ear.

1. The only natural opening of middle ear is the auditory tube that assures the ventilation of the tympanic cavity. Functional disturbance of the canal is typically observed in early childhood that leads to recidive inflammation of the middle ear. Whereas the cartilaginous part of the auditory tube has been intensively studied, the detailed anatomical description of the bony part called protympanum has been practically missing. Therefore, the embryonic anlages of the bony tissue of the protympanum and its consequent attributes were first explored that was completed by the description of the development of the carotid canal. This canal forms a considerable part of the medial wall of the protympanum, abnormal anatomy of the canal supposedly leads to disturbance of ventilation as well as to surgical problems.
2. The promontory is a large and significant item on the medial wall of the tympanic cavity. During cochlear implantation applied in severe hearinglos or deafness an electrode is lead into the cochlea through a hole on the promontory. Although cochlear implantation has become everyday surgical practice during the last forty years, no descriptions have exactly localized the turns of the cochlea behind the promontory. In order to place the hole precisely the topography and relation of bony items of the medial wall of the tympanic cavity in the three main anatomical planes, i.e. horizontal, frontal and sagittal planes and from the directions of typical surgical approaches was demonstrated in detail.
3. Among others, chorda tympani has been implicated in idiopathic temporal pains also referred to as Costen-syndrom. Patients may have similar complaints after temporomandibular joint sugery. These phenomena can be accounted for by the

topographical relation of the chorda tympani that is described to exit middle ear thorough the Glaserian fissure. Based upon few descriptions of an individual bony canal around the anterior portion of the chorda tympani referred to as anterior chordal canal I focused on the development of the chorda tympani to reveal the relation between the nerve and its surrounding and to assess the risk of mechanical injuries of chorda tympani ventral to the tympanic cavity.

4. The round window niche is a relatively small but significant field of the tympanic cavity. In previous early decades the active electrode was introduced into the cochlea through the round window niche during cochlear implantation. The importance of the niche is gained nowadays by perilymphatic leakage and subsequent deafness or by local drug therapy of severe hearinglos. Shape and structure of the round window niche have been contradictively presented in the past years. For that reason analysis of several hundreds of temporal bones aimed to reveal the understand of the bony round window niche and to demonstrate most typical forms and variances of the niche.

5. The tegmen tympani is a separating wall between tympanic cavity and middle cranial fossa. It forms a continuous surface that borders middle ear from intracranial space. In some individuals, however, dehiscences are present in the tegmen that may lead to severe, even lethal clinical symptoms. In most cases dehiscences are caused by skull trauma or surgical interventions but it is regarded non-traumatic only in 10% of the cases that includes congenital dehiscences. Since latter cases are commented by theories only, the last aim was to clarify the establishment and differential diagnosis of congenital defect of the tegmen with the analysis of the development of tympanic cavity.

MATERIALS AND METHODS

For developmental studies of temporal bone 948 temporal bones were used. Most of these bones were macerated skulls or isolated temporal bones of the Department of Anatomy, Histology and Embryology, of the Department of Human Morphology and Developmental Biology and of the Department of Forensic Medicine of Semmelweis University. Histological investigations were completed by the histological temporal bone collections of Harvard University and of Pittsburgh University. All investigations were carried out according to the guidelines of Regional Scientific and Ethical Committee for Reseach (TUKEB 83/1999).

Maceration

Juvenile and adult temporal bones that have not been previously fixed in formalin were kept in water at 56 °C for 2-3 months. Since soft tissues on fetal bones decompose much faster they were kept in macerated only for a coupe of days. Fat was removed from bones in benzin-bath which was followed by repeated washing and drying. Finally, bones were soaked in 3% H_2O_2 for whitening.

Bone preparation

Cavities of macerated bones were opened with a surgical drill used in ear surgery.

Sanding

Temporal bones were attached to a log, which was adjustable into a metal-box with a scale bar. The free part of the bone above the plane of the edge of the metal-box was repeatedly sanded with sand paper at a controlled elevation of 0.5mm of the log. Photos were taken in every 0.5mm and semi-three-dimensional (3D) drawings were made.

Preparation
Formalin-fixed specimens were refixed in Patonay-fixative after washed in water for 24 hours. In contrast to classical anatomical preparation, specimens were preparated under a binocular surgical microscope using special scalpel and forceps of different sizes used by horologists. Preparations imitated surgical situations when carried out layer by layer that were systematically photodocumented. Vessels were filled with using barium sulphate for better presentation; larger vessels were canulated and filled under standard pressure with different dilutions of barium sulphate matching the specimens.

Corrosion specimen
In order to study the vessels and cavities of the temporal bone larger vessels were prepared and subsequently canulated and filled under standard pressure with Tensol-cement that polymerized in 24 hours. When polymerization was completed specimens were immersed into undiluted hydrochloric acid for pre-etching for 2-3 days. Hydrochloric acid was thereafter daily changed until the end phase of etching. Finally, hydrochloric acid was removed from the specimen with repated washing in water. For demonstration of cavities Wood-metal was used. Wood-metal is optimal for preparation of molding specimen since it melts at 56 °C. When the metal was melt it was injected into the cavities. Thereafter, bones were cooled and surrounding bone structures were removed.

Histological investigations
Tissue blocks removed within 24 hours after death were fixed in 4% buffered paraformaldehyde for 1-4 weeks depending upon the size if tissues. Since most blocks contained bony tissue fixation was necessarily followed decalcination using 5% nitric acid and 0.23% formic acid for 5-21 days depending upon the size of the blocks. Dehydration using ethanol was followed by paraffin embedding and 7-10 μm thick serial sections were made from the

tissue blocks. Every fifth or tenth section was mounted onto gelatine coated glass slides. For orientation only every tenth section of these series were stained with haematoxylin-eosin. In series of special interest sections were alternatively stained with haematoxylin-eosin or Azan.

Endoscopic investigations

Endoscopy is an ideal tool for the investigation of spaces of temporal bone. For the present investigations rigid OLYMPUS endoscopes (0° és 30°) were used. Since endoscope is a panoramic optics structures can be studies from their immediate vicinity. Endoscope was led into the tympanic cavity from three directions. Firstly, optics was led, as most commonly in clinical practice, through the outer ear. Secondly, the endoscope was introduced through the auditory tube that had been opened by a transverse section and the middle ear was studied from front. Finally, dorsal view of the tympanic cavity was assured through the aditus ad antrum following mastoidectomy.

RESULTS

1. First signs of development of the protympanum are observed during the 21st week in fetal life when carotid canal starts to form. The latter is formed by two plates, superior and inferior, respectively. The upper plate contributes to the lateral wall of protympanum with a process as well. The annulus tympanicus gives rise to the posterior rim of the lateral wall of protympanum only.

2. The basal turn of human cochlea is a bony canal with a complicated form. Its least covered portion locates behind the apex of promontory whereas it is separated ventrally from the carotid canal by a bony tissue of 1-2mm thickness. The bony spiral lamina turns approximately 90° unevenly around its own axis in the basal turn, its most intensively winding part being at the tympanic canaliculus. Human cochlea is divided onto three, i.e. promontorial, muscular and geniculo-tegmental parts in the thesis. The total cochlea is approximately 8.5mm wide but only narrower parts are observed during surgical approaches because of the relative turn. Accordingly, cochlea is 6.0mm or 4.3mm wide when observed through the outer ear or from the direction of facial recess, respectively.

3. The chorda tympani passes in an individual bony canal anterior to the tympanic membrane, consequently, it is not through the Glaserian fissure that it exits the tympanic cavity. This canal starts to form around age two and completes around age five. It is formed from two plates, similarly to the carotid canal. Exit of the canal is a foramen in the dorsal process of the sphenoid bone.

4. The round window niche is an approximately 2-3mm long and 1.5mm wide canal that starts to form on the 16th week of fetal life. Its development is closely related to the so-called cartilage bar of the otic capsule. Anterior and upper wall of the niche shows

membranous whereas posterior and lower walls mainly enchondral ossification. Establishment completes by birth, the thesis classifies eight variants in addition to the major typical phenotype.

5. The tegment tympani is a thin bony plate that forms the roof of the antrum, tympanic cavity and protympanum. Temporal bone forms from two anlages, laterally from squamuous and medially from petrous parts, respectively. The lateral anlage shows membranous whereas the medial anlage as direct process of the otic capsule, enchondral ossification. The medial anlage is a sickle shaped bony plate around the 25th week of fetal life that attaches to the inner ear in front of the geniculate ganglion. At the border of both plates a bony log called tignum transversum that is the major supporting element of the tegmen. The log extends dorsally as a vertically arranged bony plate referred to the septum of Körner that marks the border between both anlages of the mastoid process. The tignum transversum extends to the Glaserian fissure and beaks medially to form the so-called cog.

CONCLUSIONS

1. It is only around the 18th week of fetal life that islets of bony tissue in the future protympanum, the subsequent ossification establish not only the bony shell of the snail but the complete medial wall of the protympanum. Since protympanum arises nearly completely from the processes of petrous part of temporal bone, the development of protympanum depends principally on the ossification of the petrous part. Consequently, development of the bony protympanum starts on the 18th week of fetal life. In contrast to previous studies we could prove beyond doubt that except of the dorsal rim of the lateral wall the total protympanum arises from the petrous part.

The development of the carotid canal is in close topographical relation to the internal carotid artery (ICA) and the ossification that starts on the 18th week of fetal life results in a complete bony shell around the artery. When ICA fails to contact the otic capsule directly, the bony canal is not formed.

Although ICA passes in a complete bony canal, dehiscences occur in the wall of the canal (7%). In patients elder than forty resorption of the bony tissue was suggested for the establishment of these dehiscences, however one could not account for the phenomenon in early childhood (age 1-2). The thesis shows that dehiscences in these cases are formed by the incomplete fusion of the upper and lower anlage plates of the carotid canal.

2. Classical anatomical descriptions illustrate the cochlea; however, its surgical approach of the organ during cochlear implantation occurs through the outer ear of from dorsal direction, i.e. through the so-called facial recess. The medial wall of tympanic cavity and outer ear close 45°, consequently only two-third of its actual length of the cochlea unfolds during the surgical approach through the outer ear because of its relative turn-away. From posterior approach only 4.3mm, i.e. less than half of the total length

of the cochlea is observed because of the further turn-away of the organ.

The snail is divided into three main parts in the thesis because of its significant vertical extension. Promontorial and muscular parts form the medial wall of tympanic cavity and their surgical approach is optimal from the tympanic cavity. The geniculotegmental part lies above the tympanic cavity in close topographical relation of the inner ear.

The lower half of basal turn of cochlea can be approached for introduction of the electrode both from the outer ear and from the facial recess during cochlear implantation. Second and third turns are also approachable from the tympanic cavity, although only small parts of them become superficial beneath the semicanal. To reveal these turns fully, the tensor tympani muscle and the semicanal must be completely removed. The upper half of the first turn locates above the semicanal and below the tegmen; consequently this part can be opened from the middle cranial fossa.

3. It is widely accepted that chorda tympani exits the tympanic cavity through the Glaserian fissure and passes on the surface of the mandibular fossa to reach the lingual nerve. However, the chorda tympani passes in an individual bony canal after it has exited the tympanic cavity similarly to the part between tympanic cavity and facial canal. This canal was referred to in subsequent studies as the anterior chordal canal. At the end of second postnatal life the outlet of the anterior chordal canal is completed in the sphenoid bone and although the inlet is also well formed in the Glaserian fissure the canal itself is still open laterally. The development of the canal completes not until the age of five when chorda tympani becomes separated from the mandibular fossa. Clinical studies suggest that movement of head of mandible; Costen’s syndrom and chorda tympani are related since the nerve enters the space formed by the socket of the temporomadibular joint via the Glaserian fissure. This hypothesis is rejected by the existence of the anterior chordal canal since the nerve is fully

separated from the socket of the joint by the lateral wall of the canal. Mechanical irritation of the nerve may only occur when plates of the canal are not properly developed but remain split laterally towards the mandibular fossa. This bony fenestration results in the chronic strain during mastication or in mechanical lesion during surgery of the temporomandibular joint.

4. Location of round window and developing secondary tympanic membrane are observable during eighth week of embryonic life, but formation of the bony window starts not until the 16th week of fetal life. Ossification is that intensive at this time that round window niche fairly completes within a week. Walls of the round window niche are established by both membranous and enchondral ossification, however, to different degrees, which results in the great variability in the phenotype of the round window niche. The posterior and lower walls ossify mainly enchondrally, only its surface is covered by a thin bony layer established by membranous ossification. Upper and anterior walls of the niche start to ossify enchondrally but complete with membranous ossification. Bony tissue formed by membranous ossification is richly vascularized and shows larger variance in shape and size compared to bone formed by enchondral ossification regarded as avascular in the temporal bone. Depending upon the state of development of upper and anterior walls the plane of the entrance of the round window niche can be horizontal, dorsal or lateral. Development of the round window niche proceeds in the main phases. Firstly, the total window is built up by the cartilaginous otic capsule between 8th and 15th weeks of fetal life whereas the second phase starts with the appearance of the first ossification center during the 16th week and lasts until birth. Postnatal phenotypes of the round window niche can be classified into nine groups as follows: normal, extremely narrow, extended tegmen, descending tegmen, anterior septum, bony membrane, open fundus, exostosis, jugular dome or trabeculated.

5. In contrast to the generally accepted dogma that tympanic tegmen is a simple thin bony plate above the tympanic cavity, it is a fairly complicated structure. Functionally, it separates middle ear from middle cranial fossa and contributes to the fixation of malleus and incus. Ossicles of middle ear are preformed as cartilaginous tissues and their ossification has started when the tympanic tegmen appears. At this time, the tegmen is established only above the ossicles; consequently the space needed for the movement of the auditory ossicles is separated from the intracranial cavity. Parallel to the ossification of the temporal bone, i.e. with the increase of the number air cells the tympanic tegmen extends in anterior, posterior and lateral directions.

The tympanic tegmen is a well structured bony plate above the middle ear with high carrying capacity. A log similar to a balk called tignum transversum traverses from the mastoid process to the Glaserian fissure. This log is the main supporter of the tegmen that does not allow the dura to protrude into the tympanic cavity. In addition to the tignum transversum, the carrying capacity of the tympanic tegmen depends on the lateral and medial processes of the tignum as well. These together establish a structure similar to the nervation of a leaf that assures an evenly distributed mechanic support for the thin and eventually perforated plate of the tympanic tegmen. Thus, the resistivity of the tegmen is determined by the intactness of the described network of the bone instead of on the thickness of the plate.

The pathophysiology of non-traumatic dehiscences of the tympanic tegmen has been unrevealed so far, although the arachnoidal granulation theory and congenital defect theory tried to answer the puzzle. The present thesis shows that the medial anlage of the tegmen turns around the geniculate ganglion as a sickle-shaped bony process to recontact the cochlear part of the otic capsule. Incomplete attachment results in dehiscences on the bone around the geniculate ganglion which suggests that congenital tegmen-defects are caused by deficient development of the tegmental process of petrous part of temporal bone. The bony foramen is formed in the cartilaginous tegmental process and it is the delayed ossification that may lead to tegmen-defects observed in childhood or early adults.

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