Volume rendering of the tympanic cavity from micro-CT data

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Abstract: The current study presents volumetric reconstruction of the tympanic cavity obtained from micro-CT scans which pixel size was 18 μm. Thanks to this, osseous components of the tympanic cavity were shown in high optical resolution, causing that their morphological appearance was clearly demonstrated. Particular attention was paid on imaging the medial wall of the tympanic cavity, because its structures are of clinical importance. In this respect we showed spatial relationship between the promontory, the oval window, the round window and other minute structures like the pyramidal eminence, subiculum and ponticulus. Hence, application of the micro-computed tomography allowed to visualize abnormal osseous formation located within the tympanic cavity, which potentially could interrupt normal movement of the auditory ossicles.

Key words: tympanic cavity, temporal bone, micro-computed tomography.

Introduction

The tympanic cavity is a part of the middle ear. It is a small, irregular air space located mainly in the petrous portion of the temporal bone. Posteriorly, the tympanic cavity communicates with the mastoid antrum and mastoid cells, and anteriorly with the nasopharynx through the auditory tube. In adults the tympanic cavity measures approximately $15 \times 15 \times 6$ mm but the width in the center part of the cavity is only 2 mm [1, 2].

The tympanic cavity is divided into 3 parts: the epitympanum which stretches above the tympanic membrane, the mesotympanum located medially to the tympanic membrane, and the hypotympanum lying below the tympanic membrane. The tympanic cavity houses a chain of three mobile ossicles: the malleus, the incus and the stapes which transmit sound vibration from the tympanic membrane to the inner ear. Apart from the auditory ossicles, tendons of the tensor tympani and the stapedius muscles, the chorda tympani (a branch of the facial nerve), the tympanic plexus (fibres from facial and glossopharyngeal nerves) are constant components of the tympanic cavity.

The tympanic cavity and auditory ossicles are almost fully developed at birth and alter only a little during further development and growth of individual. The volume of the tympanic cavity in adults is variable (450–770 mm^3) but it is usually about 1.5 times larger than the volume of the infant tympanic cavity [3, 4]. Studies performed on Turkish population revealed that the volume of the tympanic cavity did not differ between genders and left and right side [5].

The tympanic cavity is bounded by six walls: superior (tegmental wall) forming the roof of the cavity, inferior (the jugular wall) which is the floor, anterior (carotid wall), the posterior (mastoid wall), lateral (membranous wall) and medial (labyrinthic wall). The roof of the tympanic cavity is created by a thin plate of the compact bone called the tegmen tympani which separates the tympanic cavity from the middle cranial fossa. The tegmen tympani is prolonged posteriorly as the roof of the mastoid antrum and anteriorly it covers the semicanal for the tensor tympani muscle. The inferior wall of the tympanic cavity is narrow and appears as thin, convex plate of bone separating the tympanic cavity from the bulb of the internal jugular vein.

The anterior wall of the tympanic cavity is divided into the superior and inferior parts. The superior part of the anterior wall contains opening for the semicanal of the tensor tympani muscle and osseous part of the Eustachian tube. Inferior part of the anterior wall being a thin osseous lamina forms the posterior wall of the carotid canal and is perforated by the small foramina, which transmit the caroticotympanic vessels and nerves.

The posterior wall of the tympanic cavity is the highest wall in the middle ear, wider above than below. Its main feature is a large irregular aperture (the aditus) which leads to the mastoid antrum. Hence, this wall houses the vertical segment of the facial canal and contains the fossa incudis, and three eminences: the pyramidal, chordal and the styloid which represents the base of the styloid process [1].

The lateral wall of the tympanic cavity consists of the tympanic membrane and also contains the ring of bone to which the membrane is attached. The tympanic membrane is situated obliquely and separates the tympanic cavity from the external acoustic canal.

The medial wall of the tympanic cavity contains many important structures like: promontory, oval window (vestibular fenestra), round window (cochlear fenestra), prominence of the facial canal and the prominence of the lateral semicircular canal.

Thus, in our study we concentrated basically on visualizing microanatomical features of the medial wall of the tympanic cavity, imaging its topography towards the inner ear structures.

For depicting morphological structures of the tympanic cavity we applied computed micro-tomography which delivered images with size of pixels ranged in micrometer scale. Such resolution cannot be acchieved by contemporary medical tomographs. However, the vast majority of pathomorphological studies of the ear is based on clinical CT scans because they can be performed directly on the patient. The final goal of this study was to create a three-dimensional reconstructions presenting the surface topography of the medial wall of the tympanic cavity.

Material and methods

Visualization of the human tympanic cavity was performed on the samples harvested from the temporal bones of 3 male infants aged from 1–3 years. The squama of the temporal bone was cut off and the petrous portion was remained intact because it house the tympanic cavity, which medial wall was the region of interest in the current study. Thus, we obtained bony samples which fit in the micro-CT scanner container. The samples of the petrous bones were scanned using Nanotom 180N device produced by GE Sensing & Inspection Technologies Phoenix X-ray Gmbh.

The nano-CT system provides unique spatial and contrast resolution on examined sample because of installed 180 kV/57W ultra high performance nanofocus X-ray tube. The working parameters of X-ray tube were I = 250 uA and V = 70 kV. The reconstruction of measured objects was done with the aid of proprietary GE software datosX ver. 2.1.0 with use of Feldkamp algorithm for cone beam X-ray CT [6]. The tomograms were registered on Hamamatsu 2300 × 2300 pixel detector. The final resolution of reconstructed object was 18 μm. The post-reconstruction data treatment (denoising, croping and 16 bit to 8 bit conversion) was performed by means of the VGStudio Max 2.1 software [7]. Further, series of micro-CT scans were converted into volume image data and processed using CTVox: Volume Rendering software supplied by SkyScan (http://bruker-microct.com/products/downloads.htm). This software enables 3D visualization of volumetric data using volume rendering technique and interactively explores 3D voxel data by adjusting their transparency and color. Appropriate setting of the clipping planes allowed to reveal rendered structures of the tympanic cavity and visualize their spatial orientation.

Results

Volume rendered images obtained from micro-CT scans revealed clearly surface topography of the tympanic cavity and many anatomical details were recognized on its walls.

1. On the medial wall: the promontory, the oval and round window, the subiculum, the ponticulus, prominence of the facial canal, prominence of the lateral semicircular canal and the sinus tympani.

2. The lateral wall of the tympanic cavity was observed in limited degree because we examined dry bones which were without the tympanic membrane. Therefore only the tympanic sulcus and the scutum were recognized as places where the tympanic membrane is inserted to the bone.

3. On the posterior wall: the aditus, the pyramidal eminence and vertical portion of the facial canal.

The anterior wall and inferior wall appeared as delicate osseous laminas which accompanied short osseous trabeculas forming a mesh or small cavities adhering to these walls.

Volume rendering displayed also the osseous portion of the Eustachian tube, the semicanal of the tensor tympani and the cochleariform process.

Reconstructed osseous structures of the tympanic cavity are presented in Fig. 1, Fig. 2A and Fig. 2B focuses on the medial wall of the tympanic cavity because these structures play crucial role in surgical management. All figures display normal anatomy of the tympanic cavity and presented images are representative for examined specimens. The computer reconstructions revealed also spatial relationship between the tympanic cavity and neighboring structures, particularly located within the inner ear Fig. 3 and Fig. 4.
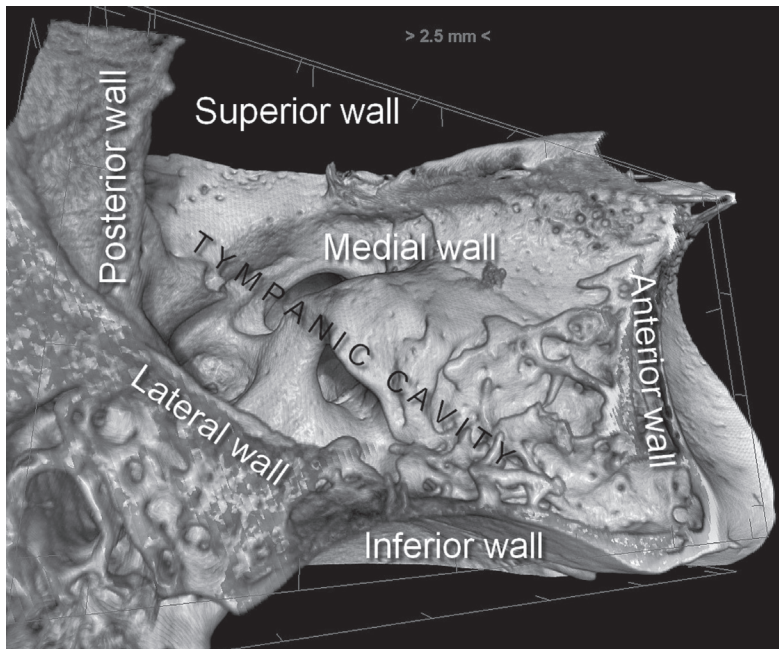

Fig. 1. Walls of the tympanic cavity presented in volume reconstruction. The superior wall is not visible because is cut by the clipping planes used to display interior of the tympanic cavity.

Fig. 2. Medial aspect of the mesotympanum and related structures (A) and close-up view on the medial wall of the tympanic cavity (B); tegmen tympani (TT), prominence of the lateral semicircular canal (PLSC), prominence of the facial canal (PFC), pyramidal eminence (PE), semicanal for the tensor tympani (TTSC), Eustachian tube (ET), promontory (P), oval window (OW), round window (RW), sinus tympani (ST), carotid canal (CC), subiculum (S), hypotympanic cells (HC), cochleariform process indicated by white arrow, ponticulus indicated by the black arrow. Auditory ossicles were removed for better visibility of anatomical details of the medial wall of the tympanic cavity.
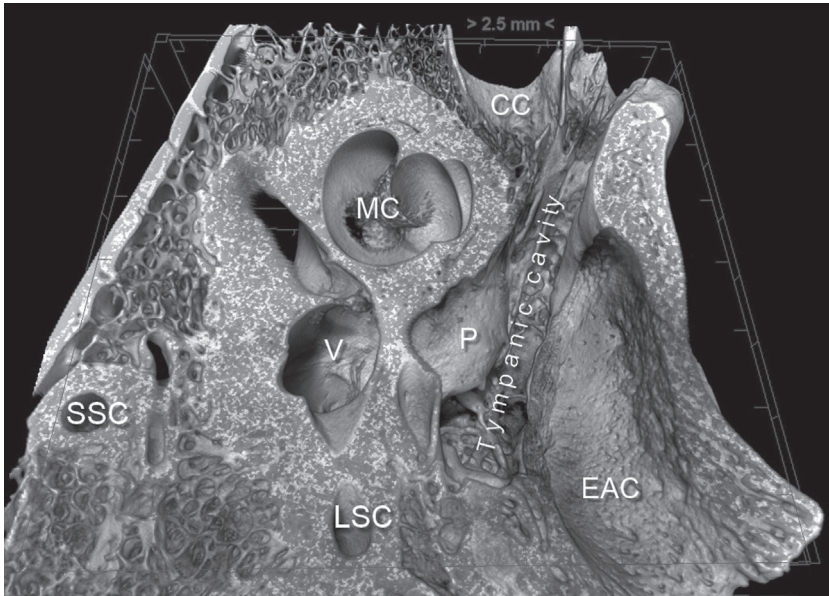
Fig. 3. Postero-superior view on the tympanic cavity and adjacent structures; modiolus of the cochlea (MC), vestibule (V), SSC — superior semicircular canal, LSC — lateral semicircular canal, promontory (P), carotid canal (CC), external acoustic canal (EAC).
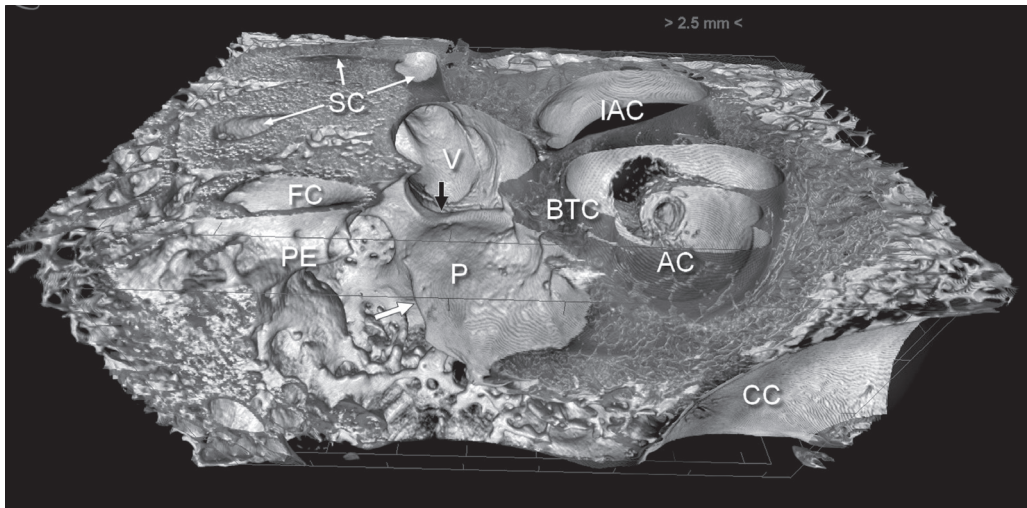

Fig. 4. Topographical relationship between main landmarks of the tympanic cavity and the inner ear components; promontory (P), pyramidal eminence (PE), facial canal (FC), vestibule (V), semicircular canals (SC), internal acoustic canal (IAC), basal turn of the cochlea (BTC), apex of the cochlea (AC), carotid canal (CC). Lower edge of the oval window indicated by the black arrow, white arrow indicates niche of the round window. In the region of the cochlea volume rendering is semitransparent for better presentation cochlear turns and their relations towards tympanic walls.

Discussion

Anatomy of the middle ear has been extensively explored for many years and become well described in many text books. Nevertheless, virtual presentation of the osseous details in high resolution images has not been frequently visualized in three-dimensional aspect [8–10].

Development of radiographic technologies and imaging techniques aided with computer graphical environment gave ability to present morphology of the examined object in volume reconstructions which can be displayed at different projections on the computer screen. Contemporary X-ray micro-CT scanners allow for digital image acquisition in none destructive way for the examine sample. However, technical limitations of this technique hinder its application directly *in-vivo,* and therefore can be only used in preclinical studies [11, 12].

Micro-CT is regarded as a preclinical techniques of structures exploring. However, this imaging modality can add some visual information obtained from dry bony samples which may serve in establishing normal and pathological findings of the ear but it still cannot be used directly for diagnosing patients. Visual perception can be significantly enhanced by volume rendering technique used to display a 2D projection of a 3D discretely sampled data set. Rendered images become realistic and help easily to understand complex anatomy of the ear, particularly by three-dimensional visualization of topographical relations within the temporal bone [13].

One of the most important achievements was to render the niche of the oval window, the round window and the sinus tympani because of their specific morphology - variable shape and orientation which can be demonstrated precisely only in volumetric reconstructions obtained from micro-CT data. These structures are of clinical interest because they can be used as sites of surgical procedures or their malformation may occur during ear development [14–17.]

Results of our study showed the potential power of micro-computed tomography in imaging anatomical details of the tympanic cavity captured in a non-destructive way from bone samples. Three-dimensional computer-assisted reconstructions simplify understanding of mutual relationship among the structures of the medial wall of the tympanic cavity, their orientation in space and reveal a large spectrum of morphological details which cannot be captured by CT scanners used in clinical examination. Demonstrated in high resolution images enhance radiological anatomy and may accentuate morphological anomalies which can be spotted during operations of the ear.

Conclusions

Volume rendering is a valuable computer graphic tool which can be used with success for visualizing data obtained from micro-CT scanning of the temporal bone. It reflects in realistic way microanatomy and topography of the osseous components of the human

ear and facilitates to understand organization of the tympanic cavity and its position towards other structures.

Acknowledgements

Conflicts of interest

None declared.

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