MEASURING THE TYMPANIC MEMBRANE THICKNESS USING OPTICAL COHERENCE TOMOGRAPHY

A.A. Novozhilov[1,2], *P.A. Shilyagin*[2*], *V.A. Novozhilova*[2], *D.D. Smirnova*[1,2], *A.A. Slepanov*[1], *A.L. Dilenjan*[1,2], *M.B. Klimycheva*[1], *G.G. Gelikonov*[2], *V.M. Gelikonov*[2], *A.V. Shakhov*[3]

[1] Privolzhsky Regional Medical Center, 20a M. Voronova St., Nizhny Novgorod, 603950, Russia;
[2] Institute of Applied Physics, Russian Academy of Sciences, 46 Ulyanova St., Nizhny Novgorod, 603950, Russia;
[3] Privolzhsky Research Medical University, University Clinic, 190 Rodionova St., Nizhny Novgorod, 603950, Russia.

* Corresponding author: paulo-s@mail.ru

Abstract. Introduction: the average thickness of the tympanic membrane (TM) normally fluctuates around 100 μm. Most of the measurements of the TM thickness presented in previous works were performed on cadaveric material. The anatomical parameters of the TM can be measured using optical coherence tomography (OCT). Materials and methods: we used spectral-domain OCT with a non-contact probe to study the structures of the middle ear. The results of OCT examination of 58 tympanic membranes of patients without middle ear pathology were analyzed. Quantitative analysis of OCT images was performed using the ImageJ program. The thickness of the tympanic membrane was calculated manually at 5 randomly selected points. To convert optical values into metric ones, we used an average refractive index of 1.45. Results: the TM thickness in patients without ear pathology was 138 μm (±29). Conclusions: OCT is an effective method of non-invasive examination of the TM and can be successfully used to measure the TM thickness. Improving the algorithms for processing OCT images in order to automatically calculate the TM thickness and make TM topographic maps remains a crucial task and its solution is expected to significantly improve the diagnostic properties of the method.

Keywords: optical coherence tomography; tympanic membrane thickness.

List of Abbreviations

OCT – optical coherence tomography
OME – otitis media with effusion
EAC – external auditory canal
TM – tympanic membrane
CT – computer tomography
MRI – magnetic resonance imaging

Introduction

Studying normal anatomical and topographic parameters of the human body structures and organs is one of the most important tasks of modern medicine. Determining the reference range is necessary to differentiate pathological conditions.

According to the results obtained by D.J. Lim, the thickness of the pars flaccida (Fig. 1) can range from 30 μm to 230 μm, while the pars tensa thickness varies from 30 μm to 90 μm (Lim, 1970). According to Ruah at al., the TM thickness depends on age and ranges from 80 μm in the elderly to 2,400 μm in children in the pars flaccida (Ruah *et al.*, 1991), while fluctuations in the TM thickness in the pars tensa are less pronounced, from 30 μm in the anterior and posterior quadrants in adults to 1,500 μm in children (Kuypers *et al.*, 2006).

However, despite the high diagnostic potential, normal and pathological values of the human tympanic membrane (TM) thickness have been studied rather poorly. Most of the measurements of the TM thickness presented in studies were performed on cadaveric material. Due to irreversible cadaveric changes (for the elements of the inner ear described in (Cho *et al.*, 2021), for the cornea of the eye described in (Napoli *et al.*, 2016)), these data cannot be used as a reference when assessing the TM thickness in a living organism. The same problem refers to the measurements made on surgical material. To date, the most common method for studying biological tissues is histological examination. However, this method is invasive which means that there is a significant time interval between sample collection and analysis, in which case the measured values may also vary and differ from those *in vivo* (De Greef *et al.*, 2016; Ruah *et al.*, 1991).

The *in vivo* examination of the structures of the middle ear is performed using tomographic

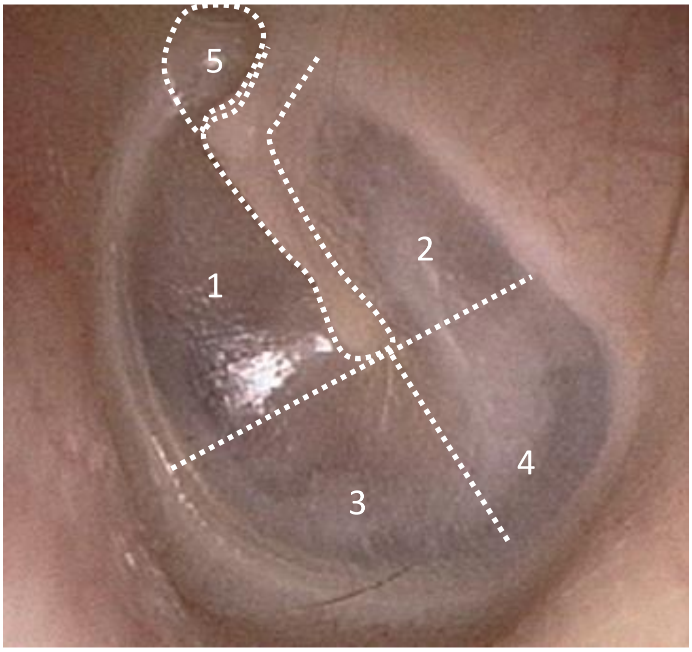

Fig. 1. Otoscopic image of a normal tympanic membrane. Pars tensa: 1 – Anterior superior quadrant, 2 – Posterior superior quadrant, 3 – Anterior inferior quadrant, 4 – Posterior inferior quadrant, 5 – Pars flaccida

diagnostic methods (CT and MRI), which are indispensable in otorhinolaryngology, but require expensive equipment, highly qualified personnel, specially equipped rooms and in CT case expose patients to radiation (Boboshko *et al.*, 2003; Pont & Mazon, 2017; Swartz & Harnsberger, 1990). In addition, although the resolution of CT and MRI reaches the submillimeter level (up to a maximum of 125 μm), this is not enough to effectively measure the TM thickness (Kerkfeld & Meyer, 2018; Linden, 2012).

Optical coherence tomography (OCT) is an *in vivo* non-invasive method for examining biological tissues (Boppart, 2003). A distinctive feature of OCT is a high resolution, from 5 to 15 μm, and a small, but sufficient for examining the structures of the middle ear, probing depth – from 1 to 3 mm (Adhi & Duker, 2013; Monroy *et al.*, 2017; Novozhilov *et al.*, 2020; Rubinstein *et al.*, 2009). The OCT method is based on probing tissues with light in the near-infrared and analyzing back-reflected waves to measure the depth in which the reflection occurred. In general, OCT is not a measuring tool, since the physical principles the technology is based on allow to measure with high accuracy only the magnitude of the wave delay, which is related to the real geometric dimensions of the medium through a refractive index that varies depending on the biological tissues. An additional hindering factor to effective use of OCT as a measuring tool is soft tissue deformation when using contact probes (Agrba & Kirillin, 2016). However, this problem has been solved by non-contact probing (Novozhilov *et al.*, 2020a; Shilyagin *et al.*, 2018). The geometric thickness can be calculated in this case if a refractive index of a particular biological tissue is known. The value of the refractive index in biological tissues generally depends on the presence of water and for most soft tissues ranges from 1.335 to 1.560 (Khan *et al.*, 2021), while individual structures can have a significantly narrower range of refractive index values. For example, the refractive index of collagen fibers varies from 1.44 to 1.47 (Khan *et al.*, 2021; Van der Jeught *et al.*, 2013).

The first measurements of the TM thickness were performed on cadaveric material, but the introduction of OCT probes combined with otoscopes and otoendoscopes made it possible to obtain both 2D images (Meller *et al.*, 2014; Shilyagin *et al.*, 2018) as well as *in vivo* 3D images (MacDougall *et al.*, 2016; Park *et al.*, 2017; Van der Jeught *et al.*, 2013). This allowed in 2015 to present the measurements of the TM thickness in acute and chronic otitis media, localized changes, tympanosclerosis (Guder *et al.*, 2015; Hubler *et al.*, 2015), although the total numbers of patients were considerably small.

In addition, small groups of patients were examined in the studies (Hubler *et al.*, 2015; Monroy *et al.*, 2015) and (Pande *et al.*, 2016) published in 2015 and 2016, respectively. An important aspect of these works is the determination of the average refractive index of the TM. In (Pande *et al.*, 2016) the index was 1.45, while in (Hubler *et al.*, 2015) the index was 1.44, which coincided with the value determined for the TM ex vivo in (Van der Jeught *et al.*, 2013). The listed works, however, are focused, to a greater extent, on demonstrating the possibilities of OCT rather than on identifying statistically substantiated regularities.

The purpose of this study is to measure the *in vivo* thickness of the normal TM.

Materials and Methods

The research was approved by the local ethical committee of Privolzhsky Research Medical University (Protocol No.7 July 03, 2017). The research was made in the ENT department of Clinic No.3, Privolzhsky Regional Medical Center (Nizhny Novgorod, Russia).

We examined 58 patients without middle ear pathology. The examined group of patients included 24 men and 34 women aged 18 to 76 years. Examination of patients was performed in the otorhinolaryngological office in the outpatient clinic. All patients were examined for complaints, anamnesis and general somatic status. All patients underwent a routine otorhinolaryngological examination as well as otomicroscopy, tone threshold audiometry and tympanometry. All the subjects signed written informed consent for the study.

After examination and diagnosis, all patients underwent an OCT examination of the middle ear with the use of a diagnostic microscope without anesthesia in the sitting position.

For the study, data were selected from the patients who had not been diagnosed with an inflammatory process, OME, etc., and who had no history of chronic otitis media in any form.

We used an approved for clinical use compact spectral optical coherence tomograph with a non-contact probe developed at the Institute of Applied Physics of the Russian Academy of Sciences (Nizhny Novgorod) (Shilyagin *et al.*, 2021).

The OCT image of the TM was recorded in real time on a computer screen. The TM thickness was measured using OCT in the pars tensa, at the same distance from the annulus fibrosus and where the malleus is attached to the TM, in the anterior-inferior and posterior-inferior quadrants, in the line-of-sight zone. Quantitative analysis of the acquired OCT images was performed using the ImageJ open-source software. To do this, the OCT image in the selected section was converted into a separate file in a graphic format with a linear brightness coding.

The thickness of the tympanic membrane was calculated manually, at five randomly selected points, at equal distances from each other (Fig. 2).

With this method of measurement, the values of the TM thickness are measured in arbitrary units – pixels. The conversion of the measured values of the TM thickness *d* from arbitrary units to metric units was carried out using the following formula:

$$D = \frac{1}{n} \cdot \delta \cdot d \,,$$

where n is the refractive index of the medium, δ is the metric value of the image resolution element, determined by the following ratio:

$$\delta = \frac{D_{max}}{d_{max}} \,,$$

where D_{max} and d_{max} are values of the maximum imaging depth of the OCT system in metric and arbitrary units, respectively. For the OCT system used in the study, these values were D_{max} = = 3,200 μm, d_{max} = 256. The value of the refractive index (n) was 1.45.

The measurements were recorded and analyzed using the MS Excel program. Statistical analysis was carried out using the Statgraphics Centurion, v.9 software package. The data are presented as M ± m, where M is the mean value, m is the standard deviation.

The interpolation of experimental data by Gaussian curve was made using Mathcad's built-in fitting function.

Results

In the examined group of patients, in all cases, normal otoscopy status were observed, all patients had normal audiometric parameters: tympanometry type A, no air-bone interval. A typical OCT image of the TM is shown in Fig. 3.

The absolute values of the geometric thickness of the TM in the examined patients calculated according to the described method were 138 (±35) μm. The biggest obtained value was registered at level 223 um, the smallest – 90 um. The median registered value was 133 um (±13um), which is slightly different from mean value.

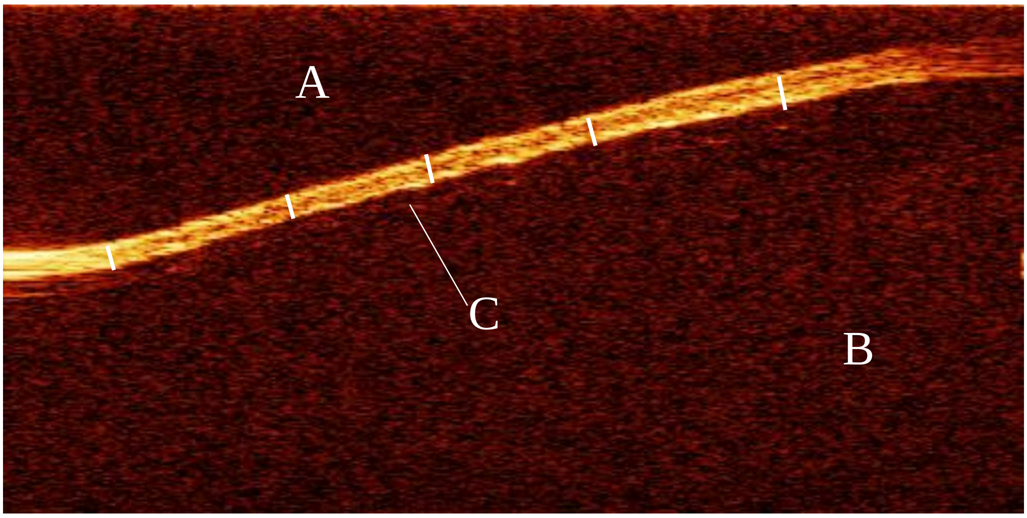

Fig. 2. Method for measuring the thickness of the tympanic membrane. A – external auditory canal, B – tympanic cavity, C – TM. The lines indicate the places where the thickness was measured

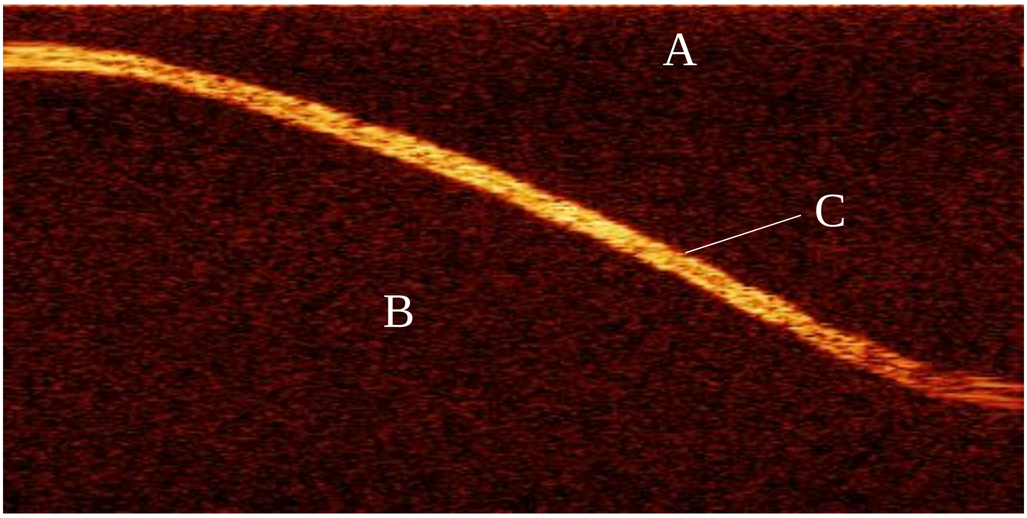

Fig. 3. OCT image of the normal TM. A – external auditory canal, B – tympanic cavity, C – TM

Discussion

The obtained measurements of the thickness of the normal TM generally correspond to the results obtained by other researchers. At the same time, it should be noted that, in general, the TM thickness values obtained by OCT (*in vivo*) are higher than post-mortem ones both in this investigation and other OCT-based measurements.

The distribution of thickness in registered data was calculated with a step of 10 um (Fig. 5). It looks close to normal (Gaussian) distribution with center at 125 um and FWHM 24 um.

These once again indicate the need for large-scale intravital studies of the value of the TM thickness.

It seems necessary to pay attention also to the range of thickness values recorded in each individual case. In most cases (83%) the standard deviation calculated for 5 measurements does not exceed 20%, but the highest deviation was registered to be 44%. This is caused by the inhomogeneity of TM profile and indicates the need for clarify the area of interest of these measurements. The best way to take the TM thickness inhomogeneity would be the use of area mapping techniques similar to ones used in retinal and corneal OCT imaging (Napoli *et al.*, 2016) and reported for TM in (Kuypers *et al.*, 2006) and (Pande *et al.*, 2016; Van der Jeught *et al.*, 2013) for cadaveric material.

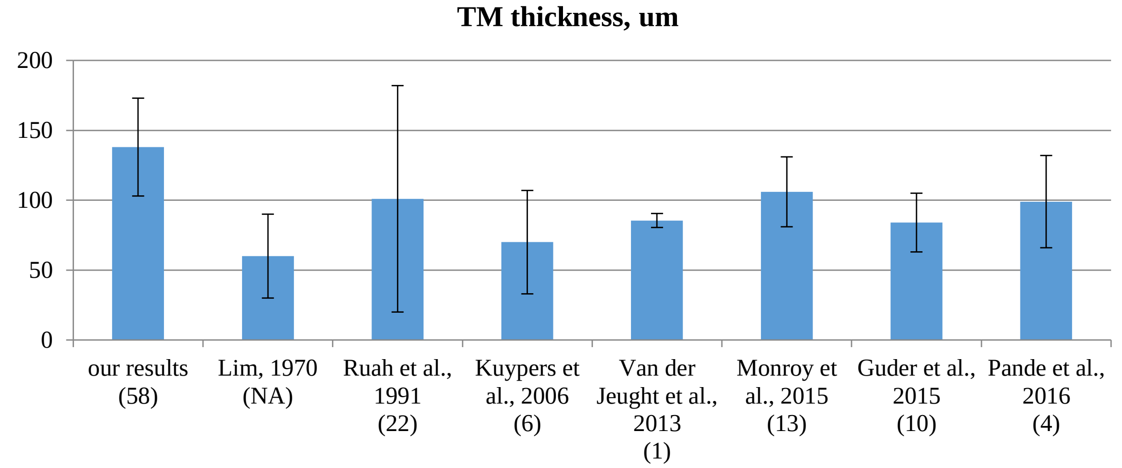

Fig. 4. TM thickness measured in our study and by other researchers. Parentheses indicate the size of the sample of patients for whom the given data were obtained

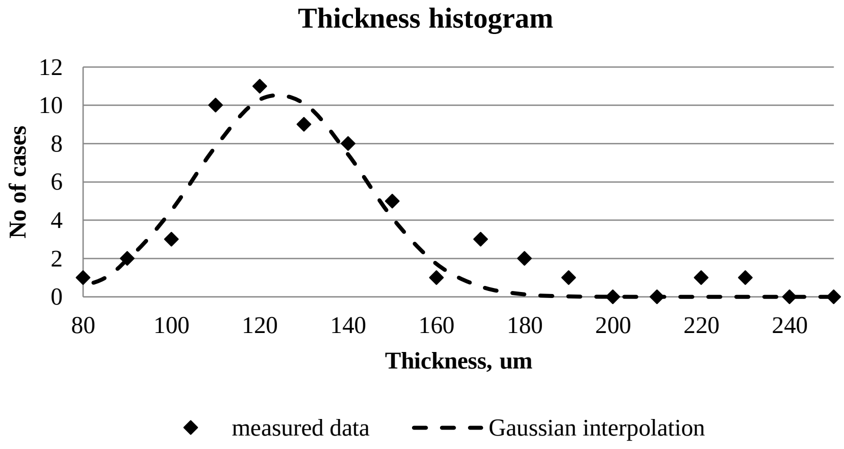

Fig. 5. Measured TM thickness distribution

Conclusions

OCT is an effective method of non-invasive examination of the TM and can be successfully used in the diagnosis and study of the nature of structural changes resulting from pathological conditions.

Improving the algorithms for processing OCT images in order to automatically calculate the TM thickness and make TM topographic maps remains a crucial task and its solution is expected to significantly improve the diagnostic properties of the method.

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