Abstract

The surface of the tympanic membrane defines the amount of acoustic energy received and transferred to the ossicles and was taken as a parameter of analysis in the study of the middle ear impedances. Low sound pressure stimuli creates in the middle ear the need to transfer the entire content of energy incident on the outer surface of the tympanic membrane to the cochlea. For this to happen, the middle ear must maximize the effective pressure on the oval window, in respect of which affects the tympanic membrane. However, it is not convenient to transfer all incident energy in the tympanic membrane to the inner ear when levels of sound pressure are high, since they are harmful to hair cells. In this paper physical model is developed to explain the energy transfer mechanism of the tympanic membrane.

Keywords: physiology, bioacoustics, tympanic membrane.
# Tympanic membrane physiology

## 1 Introduction

The outer surface of the tympanic box is formed by a flanged bone called tympanic groove. This is the place where the tympanic membrane is located and the limit of the middle and outer ear. The tympanic groove is completely filled by the tympanic membrane which inserts itself thanks to the Gerlach annular impeller. It is the annular thickening that allows the tympanic membrane to grab the tympanic groove. On the membrane the manubrium of malleus inserts and turns it concave to the outside. The umbo is down the center part of the tympanic membrane. Above the hammer there is the thinner part of the membrane, which is translucent and is called pars flaccida or Scharnnell's membrane. This forms an inverted triangle above the manubrium of malleus. The other part of the tympanic membrane is called pars tensa or Condensa. Both parts are divided by anterior malleolar fold and superior malleolar fold. The Figure 1 shows the eardrum partitions and their designations.

![Figure 1: Eardrum partitions](image)

Source: (John Schweinfurth on emedicine.medscape.com, 2015)

The tympanic membrane is tri-laminated and it is formed by different fiber class, which varies their elasticity and position on the membrane. These are the ones which provide elasticity and resistance to the tympanic membrane. For this reason the study of the deformation of these fibers is very important to describe the mechanical impedance of the membrane, which allows making an analysis in terms of power transmission to the ossicular chain [1]. These fibers shown in the Figure 2 are classified in: parabolic, radial, annular, circular and semi lunar.
The physical characteristics of the tympanic membrane allow a pressure increasing on the oval window. The difference of size in order of 20:1 between the membranes causes a higher pressure on the oval window. This pressure is up to 24 times higher than the pressure on the tympanic membrane. This mechanism is called middle ear impedance matching function. Many studies show that this function is related to frequency and intensity and changes depending on the animal species.

2 Previous concepts

Many measurements made with interferometer and holograms methods show that the tympanic membrane presents a complex movement with the important characteristic of presenting normal vibration modes up from 1 KHz and the appearance of phase difference on different membrane zones. Down from this frequency the maximum displacement take place on few places and the membrane appears not to show important phase differences between the parts which form it [2] [3] [4].

There are many studies which allow a frequency response analysis of the middle ear. The tympanometry was introduced as a clinical tool in 1940, and it make possible to know directly the state of the ossicular chain. Tympanometry permits to measure the compliance of the tympanic membrane and the ossicular chain when a variation of the pressure is presented in the ear canal. The Wideband Reflectance study (WBR) was described for first time in 1980, presenting a new equipment and measurement methods; improving the gathering and representation of the data obtained by the impedance meter. The Figure 3.a shows a scheme of both types of measurement methods.
The tympanometry and WBR measurements grounds are the same. The ear is stimulated and with a microphone sealed in the ear canal the reflected wave is captured. In this way, the impedance between the eardrum and the ossicular chain can be expressed in terms of incident and reflected energy, like is described in Figure 3.b.

![Diagram](image1.png)

(a) Source: (Dr. Mona Selim, 2012)

![Diagram](image2.png)

(b) Source: (Dr. Santos Tieso, 2013)

Figure 3: (a) Tympanometer and WBR (air pump) measurement scheme; (b) Propagation reflected sound through the ear canal. The sum of the incident and reflected wave is measured by the microphone. Zmi corresponds to the impedance of the middle ear.
Many studies made with the WBR technique [5] show that the tympanic normal response is presented like a high pass filter because of its elastic reactance, but the ossicular chain generates a low pass filter because of its mass reactance. Both systems conform a pass band filter of extended bandwidth. In pathologic conditions, such as serious seromucous otitis (in which the middle ear is filled with mucous liquid) and otosclerosis (in which there is a fixation in the ossicular chain), an increasing of the cut off frequency occurs. The authors state that the decrease of stiffness due to the damage in the ossicular chain causes a decrease in the cut-off frequency.

3 Tympanic membrane model

The characteristics of the tympanic membrane at a given frequency and sound pressure level define the quantity of acoustic energy received and transferred to the ossicular chain [6] [7]. It is possible to divide in two successive parts the power involved in the tympanic membrane behavior. First the transferred power through the tympanic membrane; and second the power which is communicated by this last one to the manubrium of malleus. The concept regarding the transmission of energy in the middle ear can be seen in the Figure 4.

![Figure 4: Incident, transmitted and reflected energy in the ear canal.](source: (Alila Medical Media, 2016))

The threshold sound pressure stimulus, create in the middle ear the necessity of transferring the total power of the outer part of the tympanic membrane to the cochlea. To make this possible the middle ear must increase to the maximum level its effective pressure multiplier function. It is not convenient to transfer all the incident energy when the sound pressure level is high, due to the fact that these levels cause damage to the hair cells. The tympanic membrane impedance behaves like a little resistance with a minimum elastic reactance component, at threshold sound pressure level. On the other hand when it is exposed to a high pressure level it presents a high
elasticity and resistance affecting mainly the transmission to the malleus. The threshold sound pressure stimulus, create in the middle ear the necessity of transferring the total power of the outer part of the tympanic membrane to the cochlea. To make this possible the middle ear must increase to the maximum level its effective pressure multiplier function. It is not convenient to transfer all the incident energy when the sound pressure level is high, due to the fact that these levels cause damage to the hair cells. The tympanic membrane impedance behaves like a little resistance with a minimum elastic reactance component, at threshold sound pressure level. On the other hand when it is exposed to a high pressure level it presents a high elasticity and resistance affecting mainly the power transmission to the malleus.

The efficiency degree in its impedance matching function is determinate by the total transferred energy to the malleus in relation with the transmitted energy through the tympanic membrane. At high sound pressure levels the above mentioned impedance matching function generates a decrease in the efficiency providing an important protection to the ear. It is very important to make a difference between the real membrane area and the effective area to talk about energy transmission because these areas are going to depend of the mechanical characteristics such as mass, elasticity and damping on every part of the membrane, as it is represented in 5.

Figure 5: Description about the model of elasticity and damping on the membrane.

The effective area oscillates without elastic deformation when it is stimulated transmitting all the power to the ossicular chain. This area is related with the frequency and intensity of the stimulation. The most efficient tympanic membrane is the one which oscillate without any elastic deformation like a diaphragm with minimal power loss due to friction with the tympanic groove.
At threshold sound pressure level, almost all the tympanic membrane area is effective. In relation to this, the elastic reactance and mechanical resistance are going to be minimal. Then the high relation between the effective area and the oval window determines the maximum pressure multiplication on the oval window.

At high sound pressure levels the strongest dampers and elasticities are involved in the oscillatory movement, as a consequence the elastic reactance and mechanical resistance increases. The decrease of the relation between the effective area and the oval window area determines a minimal pressure multiplication on the oval window and maximum power dissipation on the tympanic membrane.

In the model it can be noticed that when the sound pressure level increases, the strongest dampers and elasticities acquire a vibrating movement, as a consequence the elastic reactance and the mechanical resistance of the membrane increase as the effective area decreases. The whole system takes the characteristics of a high pass filter and the impedance matching function is decreased.

4 Pathology qualitative analysis and its relation with the proposed model

Every increase or decrease of the static pressure in the tympanic cavity causes a membrane displacement which involves the lower elasticities and dampers on the membrane model increasing the stiffness and a low frequency transmission loss. The simple tube obstruction is a frequent pathology which illustrates this affirmation. In this pathology the tympanic membrane gets into tympanic cavity increasing the stiffness of this one and the whole middle ear, which behaves as a high pass filter.

The decrease of the static pressure on the tympanic cavity is responsible of conductive low frequency hearing loss which appears in the tube obstruction. In this case, the compliance decrease and resistance increase.

In case of tube obstruction with sweat, not only there is a stiffness increase because of the tympanic box pressure decrease, but also there is an increase of the mass reactance because of the leak. Retraction of the tympanum also translates into an increase of air elastic reactance which is enclosed in a lower volume a fact which is magnified by the air replacement with fluid liquid. On the other hand when the tympanic membrane is in contact with the liquid it does not transfer power to the manubrium of malleus as a consequence the effective area is decreased and all frequencies thresholds rise. The leak location causes a mass reactance increase when it is in contact with the oval window which causes a high frequencies loss. The fluid liquid contact with the ossicular chain causes a mechanical resistance rise which is evident with the loss of all frequencies. Some patients experience a change in their audition when they move their heads this is because it depends of the tympanic box and attic location of the liquid. The viscosity increase of the fluid is translated into a mechanical resistance increase when it is in contact with the ossicular chain. In relation with this there is a displacement of the tympanometric curve and a displacement of the flattened peak into negative pressure.
Serious seromucous otitis affects the tympanic box filling it with viscous liquid. In this case the effective area of the tympanic membrane is null so the middle ear adaptation does not exist. In this situation the middle ear decreases the audition threshold 60 dB HL in all frequencies. The liquid contact with oval window is translated into a rise of mass reactance producing a high frequency loss [8].

When there is a perforation on the tympanic membrane, the hearing loss degree depends of its location. The Schrapnell’s membrane perforation causes a mild hearing loss, while other perforations cause higher hearing loss, till 50 dB HL.

5 Conclusions

The proposed model allows a better comprehension of involved mechanisms in auditory perception and is a useful tool to study outer and middle ear diseases. In normal physiology conditions, every sound pressure increase causes a decrease of the middle ear impedance increasing the elastic reactance and mechanical resistance. Then the tympanic membrane behaves as a high pass filter. The middle ear mechanism helps to protect the audition system. This mechanism helps to increase the auditory dynamic range in order of the intensities.

References


