APPLICATION OF AN AUDITORY STEADY-STATE RESPONSE TEST TO EVALUATE THE ATTENUATION OF HEARING PROTECTION DEVICES

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Abstract. *The purpose of this research was to determine the levels of attenuation of Hearing Protection Devices (HPDs) using a test called Auditory Steady-State Response (ASSR). The ASSR test is an electrophysiological examination that uses electrodes to capture the electrical activity of the auditory nerve and the brainstem without depending on the individual's response, thus eliminating the subjectivity of personal factors such as attention, response time, hearing ability, etc. This paper presents the results of a test which evaluated the hearing threshold of ten individuals, by first stimulating the hearing system without a protector and subsequently with a hearing protector. The measurements presented lower attenuation values than those measured using the method described by the ANSI S12.6/1997 standard – Method B: Real Ear (subject-fit). The ANSI method indicated an attenuation of 16 dB for ear plugs, while the value found in this work was 5.4 dB; for ear muffs, the ANSI method indicated 21dB while the value found here was 16.5 dB. The results showed good reproducibility, with a small standard deviation, indicating that the method is precise and can be used in the attenuation evaluation of HPDs.*

Keywords*: Hearing Protection, Sound Attenuation, Subjective and Objective Hearing Protection Evaluation Method, Hearing Protection Devices, Auditory Steady-State Response.*

1. INTRODUCTION

Fernandes and Queiroz (2009) discussed the effects of noise on humans, pointing out that, among the physical phenomena existing in nature, sound may be the one to which humans are the most sensitive, for, just as soothing music can be relaxing or a well-known piece can evoke a happy or sad mood, noise – a dripping tap, for example – can be irritating or prevent sleep. Industrial development and the growth of large urban centers have led to the elimination of much of the planet's silence. Fernandes (2001) affirms that modern man has been forced to become accustomed to the absence of silence.

The use of hearing protection devices (HPDs) to preserve the auditory health of thousands of workers has therefore become increasingly common, since the hearing impairment sustained by workers subjected to excessive sound pressure levels (SPLs) in their occupations, as well as by the population in general in many leisure activities, is widely known.

2. THEORETICAL REVIEW

2.1. Auditory Physiology

The shock or disturbance of an elastic medium causes air molecules to vibrate, generating waves through their successive displacement. This sound energy penetrates the hearing system (Fig. 1), where a complex physiological system transforms it into acoustic (mechanical) energy, from there into hydraulic energy, and lastly into electrochemical energy that is conducted along nerves to the brain, which decodes the external sound into intelligible information.

Sound energy enters through the ear canal, causing the outer side of the tympanic membrane to vibrate, while the inner side transmits this vibration to a set of tiny bones (the body's smallest bones), called the ossicular chain (Fig. 2), attached to each other by ligaments. One of the tips of the first bone, the hammer (malleus), articulates with the middle of the eardrum (tympanic membrane) while the other tip articulates with the second bone, the anvil (incus). The anvil, in turn, is attached laterally to the stapes (the third ossicle), whose extremity, called the footplate, is attached medially to the oval window (fenestra ovalis) through a flaccid connection, which allows for compression-decompression movement that transmits the vibration to a fluid, the endolymph, in the inner ear.

Sound vibration could undoubtedly reach the inner ear directly, but without the energy amplification system, the sound intensity would be imperceptible to the human auditory system. The eardrum and oval window have an average area of 55 cm^2 and 3.2 cm^2, respectively. This ratio (17-fold higher), multiplied by the force produced by the set of levers of the ossicles (equal to 1.3-fold), is able to generate a 22-fold higher pressure than the pressure that reaches the eardrum, in order to move the inner ear fluid which is more viscous than air (Fig.2).

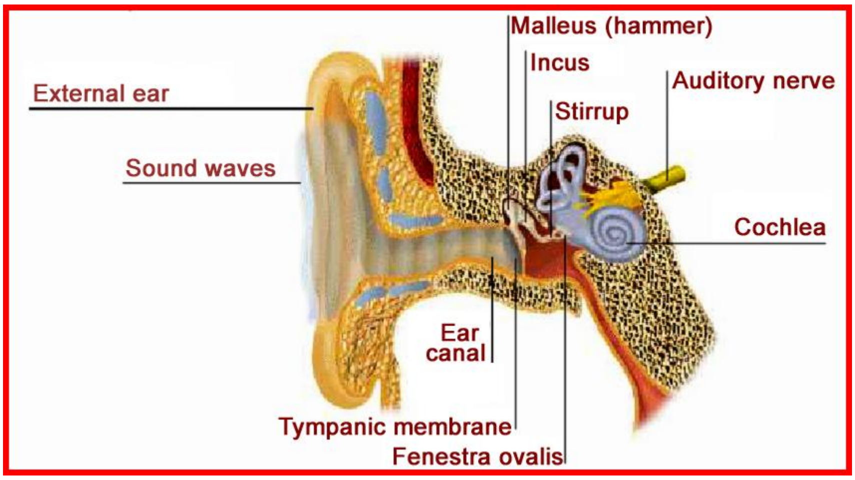

Figure 1 – Middle and Inner Ear
Source: O Corpo (1998)

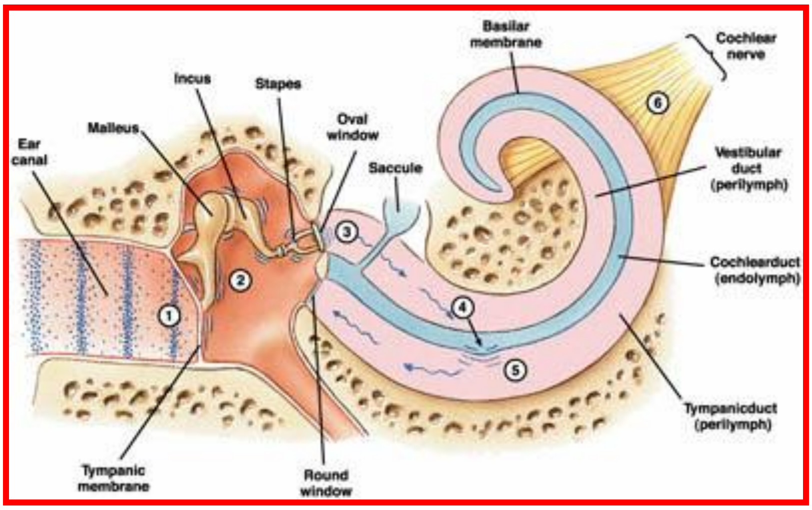

Figure 2 – Detail of the middle and inner ear
Source: Fernandes (1996)

Located in the inner ear, the spiral-shaped cochlea (Fig. 1) consists of a system of coiled tubes: the vestibular ramp (scala vestibuli), the tympanic ramp (scala timpani), and the cochlear duct (scala media) located between them. The vestibular ramp is separated from the cochlear duct by the vestibular membrane, or Reissner's membrane, while the cochlear duct is separated from the tympanic ramp by the basilar membrane, upon which is located the organ of Corti (Fig. 3), containing the electromechanically sensitive hair cells where nerve impulses are generated (electrical energy). These impulses are conducted along the auditory nerve to the cerebral cortex, where the information contained in the initial sound energy is decoded.

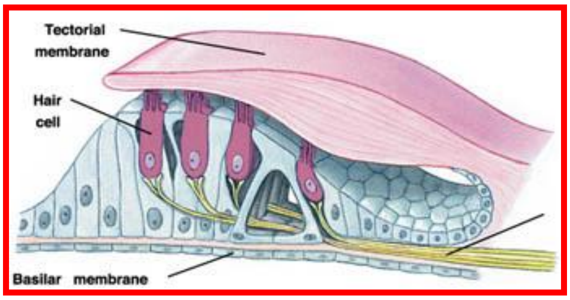

Figure 3 – Organ of Corti
Source: Guyton; Hall (2002)

The basilar membrane (Fig. 3) contains 20 to 30 thousand stiff hairs attached at one end to the bone structure and free at the other, enabling their movement. These auditory hairs at the base of the cochlea (oval and round windows) are about 0.04 mm long, reaching a length of about 0.05 mm at the cochlear apex, the helicotrema. However, their diameter decreases by up to 100-fold from the base (oval and round windows) to the apex (helicotrema). Thus, the hairs work as a diapason or tuning fork, resonating in response to the external vibrations that make up the sound. Human hearing is known to cover a spectrum of frequencies ranging from 20 to 20,000 Hz due to the stiffness of the hairs close to the base, which resonate better at high frequencies, while the hairs in the apical region resonate better at low frequencies.

The organ of Conti contains approximately 12 thousand outer hair cells (OHCs) and about 3.5 thousand inner hair cells (IHCs) (Fig. 4), which are specialized nerve cells. The hair cells perform synapsing, which stimulates the network of cochlear nerve fibers to carry the signal to the spiral ganglion, whose approximately 30 thousand axones (central nerve fibers) send it to the cochlear nerve and from there to the central nervous system.

The OHCs are embedded at one end in the reticular lamina while the other remains on the surface of the overlying tectorial membrane, located in the rampa media; the lamina is supported by Corti's rods, which in turn are connected to the basilar fibers. This set (basilar fibers, Corti's rods, and reticular lamina) moves uniformly, so that when the basilar membrane vibrates, the reticular lamina moves up and down, causing the OHCs to touch the tectorial membrane in an upward and forward motion, followed by a downward and backward movement. Therefore, when the basilar membrane vibrates, the OHCs are excited.

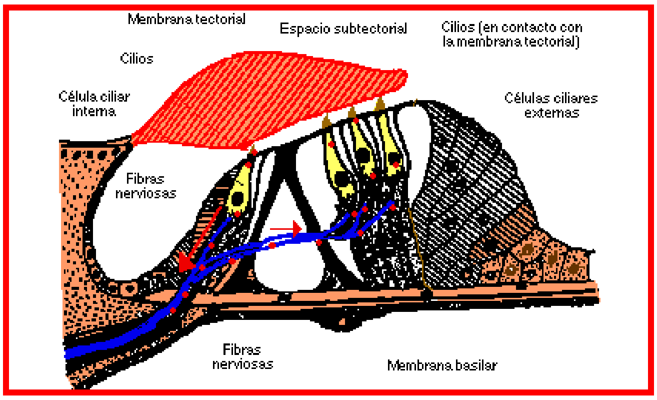

Figure 4 – Detail of the cells and membranes and transmission of the electric signal to the cochlear nerve
Source: Fernandes, 1996

A phenomenon, called the endocochlear potential, occurs in the organ of Corti: the rampa media, or cochlear duct, is filled with a potassium-rich fluid called endolymph, while the vestibular and tympanic ramps contain sodium-rich perilymph. The difference in constant potential between these fluids, of + 80 millivolts, is the endocochlear potential. When the hairs bend forwards and backwards toward the vestibular ramp, 200 to 300 cation-conducting canals open. This allows for the rapid transfer of potassium ions, which flow from the rampa media towards the ends of the hairs, depolarizing them Thus, when the basilar fibers bend towards the vestibular ramp, the hair cells become depolarized, and on their return, hyperpolarized, generating a receptor potential. This, in turn, stimulates the nerve endings in the cochlea, which synapse with the bases of the hair cells. This electric potential sensitizes the cells, enabling them to respond to the lowest sound energy level.

2.2. Hearing Protection Devices (HPDs)

The purpose of HPDs is to prevent high sound pressure levels (SPLs) from reaching the auditory system (Fig. 1) of people engaged in noisy activities. However, to ensure their effectiveness, these devices must undergo strict quality tests to check their real attenuation of noise. If they pass the test, they receive a Certificate of Approval (CA) issued by the Ministry of Labor and Employment (MTE) and can then be sold by their manufacturers or importers.

The HPDs (Fig. 5) available on the market today vary in shape and materials from one manufacturer to another. The basic models are circum-aural (ear muffs) and intra-aural (ear plugs or pods).

2.3. Determination of attenuation

The noise attenuation of HPDs is measured in a suitable acoustic environment by laboratories accredited by INMETRO and the MTE, whose procedures follow national or international standards.

Figure 5 – Models of hearing protection devices

The international methodology usually adopted is that of the REAT (*Real Ear Attenuation at Threshold*) based on the ISO 4869-1/90, ANSI S3.19-1974, ANSI S12.6-1984 and ANSI S12.6-1997 A/B standards. These standards describe the procedures to evaluate the protection afforded by the tested HPD, exposing the listener to a field noise generated by acoustic boxes inside a specific chamber for such tests. This procedure differs from audiometric examinations on two counts: it does not use earphones and the emitted sound is composed of octave bands or frequency ranges, so the sound is not pure. Thus, the auditory threshold of the listener is determined with and without hearing protection, and the HPD's attenuation is ascertained based on the difference between these measurements.

To measure the attenuation of an HPD, the ISO 4869, ANSI S3.19-1974, S12.6-1984 and ANSI S12.6-1997 (A) standards recommend that evaluations be performed under ideal conditions, i.e., in the laboratory, by people trained in the use of the equipment and with the help of a specialized technician in charge of the procedures. This methodology favors the highest levels of attenuation, but does not find values that correspond to reality in the field, when HPDs are used by workers without adequate training. This attenuation value is called the Noise Reduction Rating (NRR).

For the above stated reasons, the American National Standards Institute (ANSI) S12.6 (1997) also presents Method B: Real Ear (Subject-Fit), a methodology also adopted in Brazil by the National Department of Worker Safety and Health (DNSST), subordinated to the Labor Inspection Bureau (SIT) of the Ministry of Labor and Employment (MTE) under Administrative Rule 48 of 03/25/2003. In this procedure, the listener reads the manufacturer's instructions and fits on the device himself, without the help of an instructor. The group of listeners is changed after a few tests to eliminate biases. The attenuation results in the tested frequencies are then recorded on a chart, whose result is called the Noise Reduction Rating – Subject Fit (NRRsf). This procedure leads to attenuation values that are more in line with reality.

Figure 6 compares the two methods.

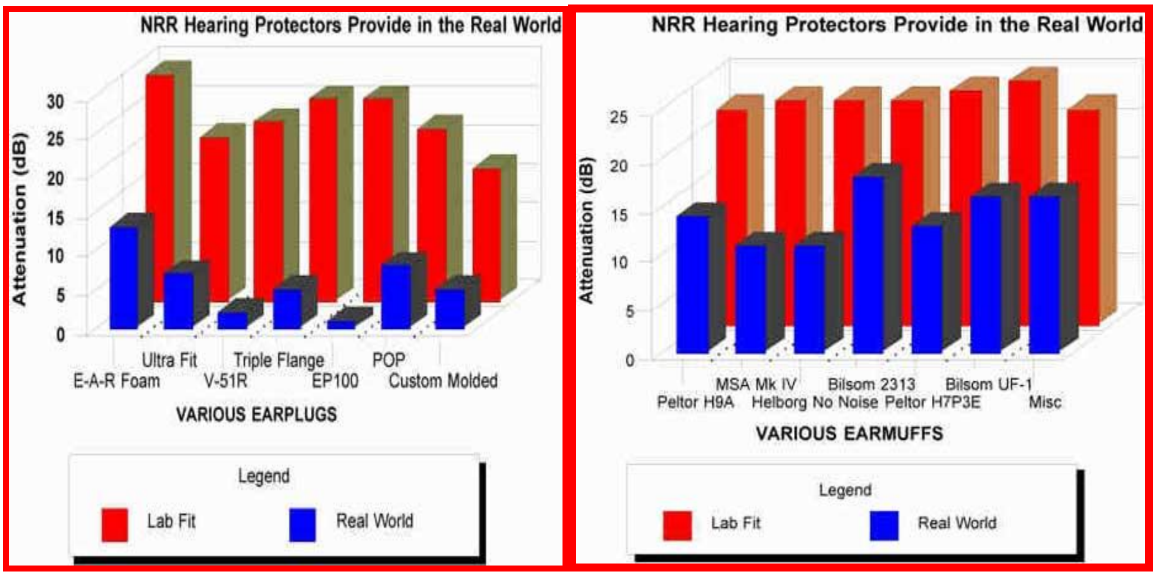

Figure 6 – Comparison of the NRR obtained in the laboratory (ANSI S3.19-1974 standard) and real data obtained in the field for ear plugs and ear muffs. Source: NIOSH, 1996

It is therefore evident that tests should never be based on a single or very small sampling, and it is reasonable to have a sufficient number of listeners to render the final results of the tests reliable (GERGES, 2000).

As can be noted, the test has a very important element – **its subjectivity** – which depends on the listener's psychoacoustic conditions, the way he fits the HPD on his ears, his physical and psychomotor conditions at the time of the test, and his ability to distinguish sound.

2.4. Auditory steady-state response

The Auditory Steady-State Response (ASSR) is an electrophysiological procedure that allows for the simultaneous evaluation of auditory threshold times with frequency specificity and by ear, thus reducing the testing time. Moreover, it allows for the stimulation of near-field levels up to very high SPLs, which are applied to patients with severe hearing loss, making it possible to measure their hearing ability (DUARTE, 2007). It is also a new technique introduced in hearing assessments in children, since these patients do not respond well to subjective tests.

The ASSR consists of capturing the electrical activity of the auditory nerve and brainstem by means of 3 electrodes attached to the mastoid process and the forehead. A modulated sound in the frequencies of 500, 1000, 2000 and 4000 Hz is emitted in various sound intensities in order to stimulate the auditory system. The sound decays to adjusted levels until the electrodes cease to capture an electrical signal.

According to Duarte (2007), another major advantage of the ASSR is its analytical mode. Unlike other tests that analyze responses in the time domain, the ASSR detects responses in the frequency domain, using algorithms applied to the electroencephalogram (EEG) signal to analyze the magnitude and the phase of brain activity corresponding to the frequency modulation of the acoustic signal. Thus, the response is determined through a statistical analysis, reducing the evaluator's participation in the analysis of the response.

Steady-state responses are known as a physiological measure of the brain's sensitivity to a periodic stimulus and have been described for all the sensory modalities. On the other hand, the ASSR is obtained by presenting a stimulus with a sufficiently fast manifestation rate so that the nervous system does not have enough time to return to its initial condition, thereby generating a superimposition of responses. This continual neural response is called steady state, and typically, it follows the same waveform as the continuous stimulus that is being presented to the individual.

3. METHODOLOGY

3.1. Materials

The following materials were used in this research:

- A Madsen Midimate 622 audiometer, with TDH 39 supra-aural headphones;
- MASTER (Multiple Auditory Steady-State Response) system, version 2.04.i00 (Bio-logic Systems Corp.);
- Fz (active electrode), Oz (reference) and Fpz (ground) disposable electrodes
- A large audiometric booth (Fig. 7);
- An audio dosimeter (Fig. 8);
- A calibrator for the audio dosimeter;
- Two nationally manufactured hearing protection devices: Ear plugs CA n. 11512 with 16 dB NRRsf, made of silicone (manufactured by Maxxi Royal Ind. e Com. de Produtos Auriculares Equip. de Prot. Seg. Indiv. Ltda) and Ear muffs CA n. 15247 with 21 dB NRRsf, composed of two Thunder T1 padded ear muffs connected by a headband, manufactured by Bilson and commercialized in Brazil by Sperian Produtos de Segurança Ltda.

3.2 Procedures

Participation in this research was ten listeners without any history of exposure to noise and with normal hearing ability, which was verified by tonal audiometry in the frequencies of 0.25, 0.5, 1, 2, 4, 6 and 8 kHz.

The procedures employed here were based on brainstem audiometry, which is used in phonoaudiological evaluations, as follows:

a) The electrodes were attached to the head of the listener, who lay comfortably on an examining table and was asked to relax or, if possible, to sleep, since the test is independent of his response. The audiometric booth was dark and devoid of background noises, in order not to impair the test.

b) A field sound signal was emitted from an acoustic box at a measured distance of 30 centimeters from the subject's right and left external ear pavilions. The test sound was modulated and began with an intensity of about 80 dBal (decibels Auditory Level), gradually decreasing according to the gradient adjusted by the operator. The first test was performed without a hearing protection device.

c) An audio dosimeter was kept in the booth and its microphone placed 5 centimeters from the subject's ear pavilion, in order to determine the equivalent NPS (Leq) during each test (without protection, with ear plugs, and with ear muffs).

d) After determining the audibility threshold without the HPD, the same method was applied with the HPDs.

Figure 7 – Audiometric booth

Figure 8 – Audio dosimeter

4. RESULTS

The subjects' auditory thresholds using the ear plugs and ear muffs and without hearing protection are shown in Table 1. Ten experiments were performed to validate the methodology by comparing the auditory thresholds.

Row	**Condition**	**Frequencies (Hz)**			
		500	**1000**	**2000**	**4000**
		Means in dBAL			
A	Without protection	46,5	40,0	27,5	31,5
B	With ear plugs	64,5	55,5	52,0	58,5
C	With ear muffs	73,0	71,0	60,0	62.5
D	Attenuation with ear plugs	18,0	15,5	24,5	27,0
E	Attenuation with ear muffs	26,5	31,0	33,5	31,0

Table 1 – Steady-State Response Thresholds without hearing protection, with ear plugs and with ear muffs

Table 2 presents the data with standard deviations.

Frequencies (kHz)		0,5	1	2	4
Data for the ear plugs					
1	Std derivations	12,5	11,2	12,6	12,5
2	* Threshold + Std deviations	41,0	35,7	15,6	17,0
Data for the ear muffs					
3	Std derivations	9,7	16,1	10,1	6,1
4	** Threshold + Std deviations	29,7	21,5	5,1	6,6
* Difference of rows A e D (table 1) and row 1 (table 2);					
** Difference of rows A e E (table 1) and row 3 (table 2);					

Table 2 – Standard deviations and mean attenuations (dBNA)

The calculation of the unique value of attenuation is presented in Table 3.

Row	Procedure	Results
A	Logarithmic sum of row A (table 1)	47,5
B	Logarithmic sum of row 2 (table 2)	42,1
C	Logarithmic sum of row 4 (table 2)	31,0
D	Difference of rows A e B (this table)	5,4
E	Difference of rows A e C (this table)	16,5

Table 3 – Protectors attenuation calculation (dBNA)

The result of the row D (table 3) corresponds to the total ear plug attenuation (5.4 dB). The result of the row E (table 3) corresponds to the total ear muff attenuation (16.5 dB).

Table 4 presents the comparative values between the attenuation provided by the manufacturer and the results of this research. Comparisons should be considered that the frequencies of the tests do not coincide: to determine the NRRsf of hearing protectors (ANSI) are used the third octave center frequencies, while the equipment this search (ASSR) has its standard frequency at 500, 1000, 2000 and 4000 Hz. Table 6 presents a data comparison.

Protector	NRRsf	This research
Ear plug	16	5,4
Ear muff	21	16,5

Table 4 – Protectors attenuations comparison (dB)

5. CONCLUSIONS

Although the results presented here were obtained in this research, the method of evaluation of attenuation of HPDs using brainstem audiometry proved to be very efficient and accurate. The main advantage of the method is its objectiveness (non-subjectiveness), which ensures it is devoid of errors caused by human perception.

The non-subjective nature of the tests led to results with good reproducibility, with a small standard deviation, indicating that the method has good precision and can be used for the attenuation evaluation of HPDs.

The values of attenuation were lower than those measured by the method of the ANSI S12.6/1997 standard: 42% lower with the ear plugs and 4.3% lower with the ear muffs.

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