Original Article

Investigating the Effect of Ear Canal Length on Improving Earplugs and Earmuffs Performance at 400 and 500 Hz Frequencies

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Abstract

Aim: The aim of this study was noise reduction at 400 Hz and 500 Hz frequencies using earplugs and earmuffs, by varying the length of a simulated ear canal. **Methods:** This descriptive, analytical, and cross-sectional study was conducted in a laboratory environment using a simulated human hearing system based on the anatomical characteristics of the ear. Two types of earplugs and two types of earmuffs were tested. Using LABVIEW software, sound at 400 Hz and 500 Hz frequencies was generated by an ev-av150e sound generator at an 80 dB sound pressure level (weight A) with pink noise through a desktop speaker. A measurement microphone (1/2", B and K brand) placed at the end of the ear canal, acting as the tympanic membrane, transmitted the received waves to a Data AcQuisition (DAQ) processing center system. Measurements were conducted for ear canal lengths of 20, 25, and 35 mm to assess the noise reduction capabilities of the hearing protection devices at these lengths. The data, reflecting sound attenuation across different lengths and devices, were evaluated and analyzed using SPSS version 26 for comparison under variable conditions. **Results:** There was a significant relationship between changes in the length of the external ear canal and the amount of noise reduction at 400 Hz and 500 Hz frequencies when using earplugs and earmuffs ($P < 0.05$). **Conclusion:** The results indicated that the performance of earplugs and earmuffs differed at these frequencies. Specifically, the effectiveness of earplugs increased with longer ear canal lengths, whereas the effectiveness of earmuffs decreased with longer ear canal lengths.

Keywords: Earplug, hearing protection, noise, outer ear canal, sound reduction rate

Introduction

Occupational exposure to industrial noise pollution is an important factor in causing permanent sensorineural hearing loss in workers.[1] One of the health problems that occurs in the face of excessive noise is hearing loss. Hearing loss, as a result of exposure to noise in the workplace, is one of the most important diseases that can affect a person's safety and performance, but its importance is often neglected.[2] The need to address the problem of noise and prevent hearing loss because of exposure to noise can also be economically justified. Problems with noise exposure do not only lead to hearing loss[1] but also cause physiological changes such as high blood pressure, changes in the walls of the arteries, and the possibility of heart attack.[2]

In many industrial environments, such as oil or petrochemical industries, it is not possible or cost-effective to reduce or technically control noise in the short term. Therefore, using hearing protection devices as a temporary and complementary solution can protect workers from the adversary effects of noises. Although the use of protective equipment is considered a temporary program, in the industrial environments of the country, for various economic and social reasons, it is often considered a permanent solution.[3] Hearing protection devices are divided into two categories: earmuffs and earplugs.[4]

One of the main features of protection earplugs is the noise reduction rate, which is an important indicator for expressing

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protection performance regardless of the type and level of ambient noise pressure, which has been accepted by the American National Standards Institute. The hearing conservation program relies more on hearing protection devices to reduce noise instead of interfering with sound engineering control.[5] There are several sources in the environment and industry known as low-frequency noise sources, including sources, such as air, road and sea traffic, pumps, fans, boilers, ventilation systems, air turbines, heavy industry, electrical equipment, drilling and fireworks, cooling towers, and amplified music.[6]

The actual attenuation of earplugs at low frequencies is very small. One of the key causes is the lack of adequate coverage of the earplug on the user's ear in real conditions of use, which causes sound leakage into the ear.[7] At low frequencies, sound also has greater potential for transmission through pores and leaks. Therefore, the attenuating power of the earplug is affected at these frequencies.[8] Among the reasons for the defects of hearing protective devices, the following items could be mentioned: (a) comfort, (b) utilization, (c) fit, (d) compatibility, (e) readjustment, (f) deterioration, and (g) abuse.[9]

The angle of the eardrum with the horizontal axis of the ear canal is about 40°. The average diameter of the outer ear canal is 6.5 mm horizontally and 9 mm vertically. The length of the lower part of the external ear canal is 25 mm and the upper part is 41 mm. The volume of the external ear canal is also between 830 and 1972 cubic mm.[10] One of the diseases caused by exposure to low frequencies is vibroacoustic disease (VAD).[11] VAD is detected in aviation technicians,[12] pilots, and flight crews,[13] as well as in the population of an island exposed to environmental Low-frequency noise (LFNs).[14] VAD cases are also reported among ship workers[15] and in residential areas.[16] At low frequencies, if the sound insulation input improves, there will be a slight improvement in protection, which may be related to the depth of the earplug in the ear canal, which requires further study,[17] Because of the weakness in noise attenuation of hearing protection devices at low frequencies, it is necessary to increase the attenuation coefficient by intervening in determining factors, and because of the low cost, a quick and simple method using the parameters of protectors (for example, geometric diversity of the human earlobe, ear canal, the type of hearing protection and its size, the effect of wearing and connection conditions, the effect of design parameters such as materials, tolerance, and geometric shape) can be made available.[3,18]

Based on research on changes in resonance frequency and length of the external auditory channel in relation to age by Jeong *et al.*,[15] aging increases the length of the external ear canal, and the longer length of the outer ear canal reduces the amount of sound resonance, which itself shows better performance of longer outer ear canal versus shorter length.[19]

A study by Tufts *et al.*,[16] based on the relationship between sound attenuation and the length of earplug placement, showed that a decrease in the length of the earplug resulted in a decrease in the amount of sound reduction. This decrease was greater at frequencies of 1000 Hz and lower than at frequencies above 2000 Hz.[20] The aim of this study was noise reduction at 400 Hz and 500 Hz frequencies using earplugs and earmuffs, by varying the length of a simulated ear canal.

Materials and Methods

This research is based on the the Articulated Test Fit (ATF) method, the hearing mannequin simulation method, and the ISO 4869-3:1990 standard.

Earlobe

The earlobe was designed by examining anatomical schematics and real angles, by molding a natural human ear with gypsum and polyester materials that are used in technical orthopedic molds for earlobe prosthesis. The shape of the earlobe, like a natural ear, had all angles [Figure 1].

The earlobe was made by injecting liquid silicone rubber into the prepared mold [Figure 2]. This material, which has USP and ISO standards, is used as a material for earlobe prosthesis in technical orthopedics all over the world due to its elastic state and physical state close to human pinna tissue. Spagnol *et al.*,[17] as well as Kunov and Giguère,[18] have used the same method in their research.

External auditory canal

The cast iron canal groove is inserted as a 6.2 mm diameter outer ear canal into the 5.7 mm diameter earlobe prosthesis hole to approach the human hearing system to collect sounds. The thickness of this groove was 1 mm, which made the inner diameter 6 mm. The difference between the outer diameter of the outer canal groove and the diameter of the earlobe prosthesis hole was due to the elasticity of the silicone prosthesis for the complete adhesion of the silicone of the earlobe to the metal canal.[19,20]

The external canal was constructed in such a way that its inner diameter increased from 5.8 mm from the area closest to the eardrum to 7.8 mm to the tympanic membrane and inside it was covered with soft polyamide with a thickness of 1 mm.

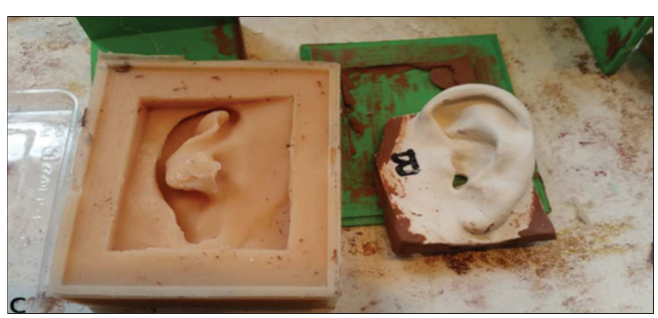

Figure 1: Mold taken from the earlobe

This size was selected based on the anatomical size of the inner ear canal.[21,22]

The outer material of the outer ear canal is high-density cast iron, which is chosen to prevent energy loss and lack of resonance, and the inner material is made of soft polyamide, which is more like the outer ear canal of the human ear.

According to Todd NW's research in the article Tympanum – canal angles anteriorly, Antero-inferiorly, and inferiorly: a postmortem study of 41 adult crania, the tympanic membrane angle of the patients was between 27° and 60°. On the other hand, this study considers the angle range of the tympanic membrane to be a standard range between 40° and 60°.[23] Therefore, it was decided that in this study, angle 40 was to be used as the angle of the tympanic membrane, which was a number closer to Thorsten Lim's theory and was in the standard range of the angle of the tympanic membrane, in terms of Torsten Liem.[21] In fact, at the end of the external channel, a 1/2 inch measuring microphone (B and K brand) was placed as a sound receiver at a 40° angle to the horizontal to transmit audio to the DAQ [Figure 3].

Ear canal length

According to research by Michel *et al*., the average length of the external auditory canal was 26.9 mm (22.5–35.3),[21] and according to research by Ahmad *et al*., the mean canal length was 27.7 (range: 20–34.8) mm.[22]

Therefore, three external ear canals were made in three lengths of 20, 25, and 35 mm with the mentioned structure.

Table 1: Four models of earplugs and two models of earmuffs

Type	Model
1	Elvex EP-401 Quattro ear plugs
2	Parsafe EP-2020 earplugs
3	Maxon earmuffs
4	Decibel earmuffs

Figure 2: Artificial silicone earlobe

Personal protective equipment

Four types of protective earplugs and earmuffs were used within the simulated canal, the specifications of which are as follows [Table 1].

Sound production and reception

The noise was emitted by the ev-av150e sound generator at 400 Hz and 500 Hz at an 80 dB sound pressure level in weight A with pink noise by LabVIEW software. A desktop speaker was placed directly at a distance of 1.5 m in front of the simulation object, and we connected it to the sound processing card DAQ through a measurement microphone 1/2" B and K which was placed at the end of the simulated external ear canal and was calibrated at a frequency of 1000 Hz and a sound pressure level of 94 dB before each change in the length of the external ear canal. The sound processor card used in this design was made by National Instrument USA, and finally, the sound processor card connected to the computer. MATLAB software was installed on the computer, and it was used to draw a frequency analysis curve. After that, the SPSS version 25 program was used to obtain the relationship between the amount of length and the amount of reduction of the earplugs and earmuffs at 400 Hz and 500 Hz [Figure 4].

Analysis method

LabVIEW program and repeated measurement method in the SPSS program were used to analyze the data.

Results

The amount of sound attenuations in Elevex earplug at 400 Hz and 500 Hz

The amount of sound attenuation by Elevex earplug at 400 Hz increased with increasing canal length, and based on repeated measurement statistical analysis, there is probably a significant relationship in this frequency. (P =0.011) [Chart 1-1] Furthermore, at 500 Hz, the length changes had a significant relationship with the amount of sound attenuation (P = 0.032) [Figures 5 and 6].

The amount of sound attenuation in par safe earplug at 400 Hz and 500 Hz

The amount of sound attenuation in Parsafe earplug at 400 Hz

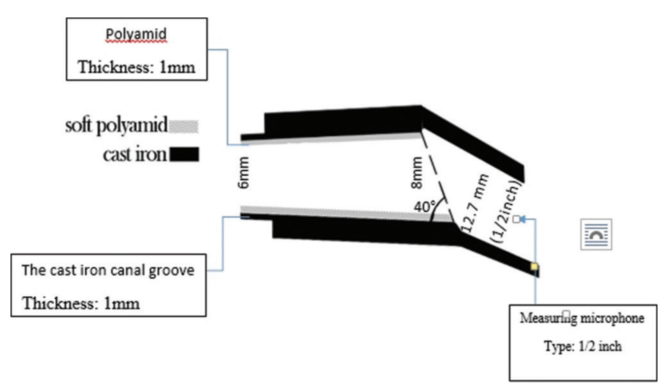

Figure 3: The structure of the simulated external ear canal

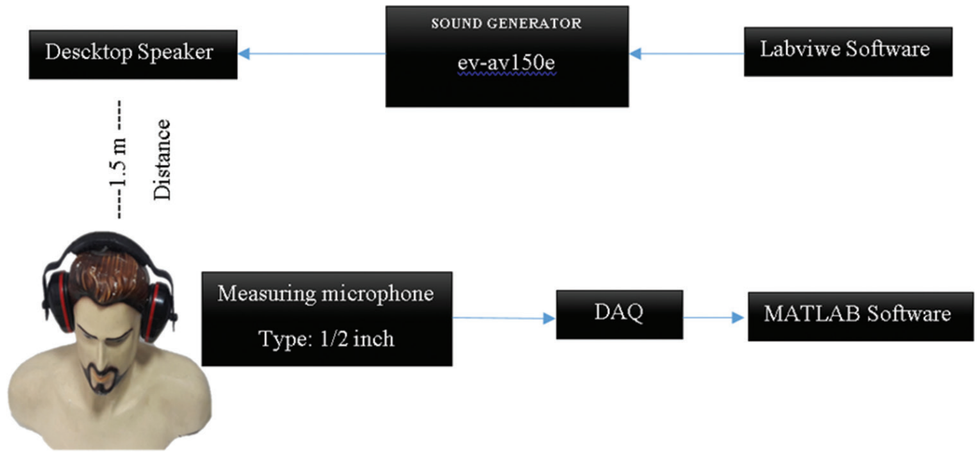

Figure 4: Sound production and reception system

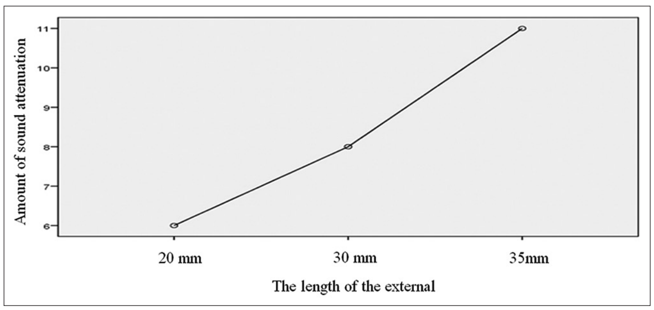

Figure 5: Average changes of Elevex earplug in three lengths at a frequency of 400 Hz

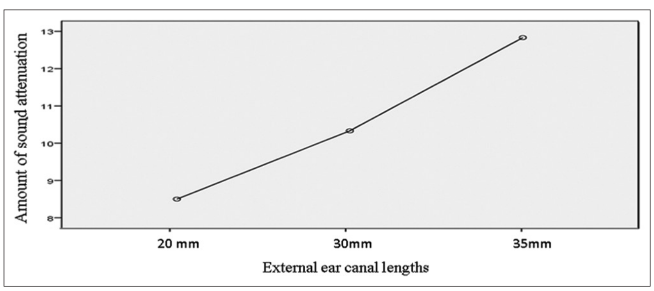

Figure 6: Average changes of Elevex earplug in three lengths at a frequency of 500 Hz

increased with increasing channel length, and based on repeated measurement statistical analysis, there is probably a significant relationship in this frequency.) P = 0.011.(Furthermore, at 500 Hz, the length changes had a significant relationship with the amount of sound attenuation (P = 0.032) [Figures 7 and 8].

The amount of sound attenuation in maxon earmuff at 400 Hz and 500 Hz

The amount of sound attenuation in maxon earmuff at 400 Hz frequency is decreased with increasing channel length, and based on repeated measurement statistical analysis, there is probably a significant relationship in this frequency (P = 0.031) and also at 500 Hz frequency, the length changes are significantly related to the amount of sound attenuation ([P = 0.002]) [Figures 9 and 10].

The amount of sound attenuation in decibel earmuff at 400 Hz and 500 Hz

The amount of sound attenuation in decibel earmuff at 400 Hz frequency decreased with increasing channel length, and based on repeated measurement statistical analysis, there is probably a significant relationship in this frequency (P = 0.033) and also at 500 Hz frequency, the length changes are significantly related to the amount of sound attenuation (P = 0.006) [Figures 11 and 12].

Discussion

In this study, the effect of different lengths of the ear canal on the performance of four types of hearing protection, including two types of earmuffs and two types of earplugs, was investigated at low frequencies. To do this, an artificial silicone ear was used. This study was evaluated in three lengths of 20, 25, and 35 mm from the ear canal. One of the variables that affect the amount of attenuation is the length of the channel segment, with longer segments providing more attenuation.[24,25] A longer canal section increases the likelihood of an air seal in the ear canal[26] and reduces the ear canal-ear wall area available for vibration. These two types of hearing protectors are effective and have different effects on the reduction of hearing protection based on the type of protection so that the performance of these two types of protectors was the same so that as the length of the ear canal increased, the amount of sound reduction decreased in the earmuff type and the performance of earplug was increased; with the increase in the length of the channel, the amount of sound attenuation in earplug increased. In a study based on a semi-plastic earplug reported by Zwisloki, it was shown that the attenuation levels were much higher when the plug was placed deep in the ear canal than when it was placed shallowly in the cartilaginous part of the ear.[24] In earplug-type hearing protection, the performance of earplugs in reducing noise improved with increasing frequency and the length of the ear canal in both models. In the study of Jeong *et al.*, which was conducted on the effect of age on the length of the canal, it was found that the

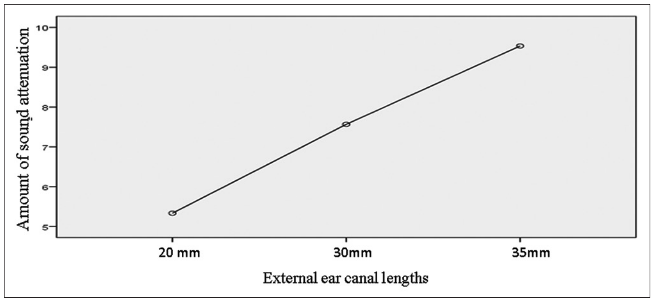

Figure 7: Average changes of Parsafe earplug in three lengths at a frequency of 400 Hz

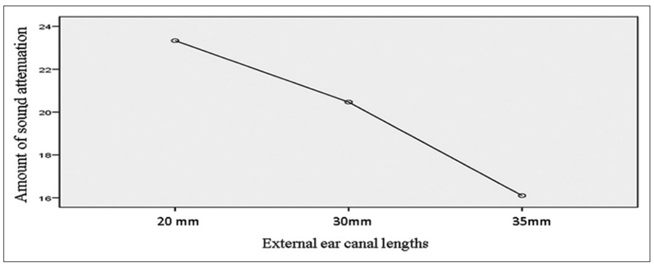

Figure 9: Average changes of maxon earmuff in three lengths at a frequency of 400 Hz

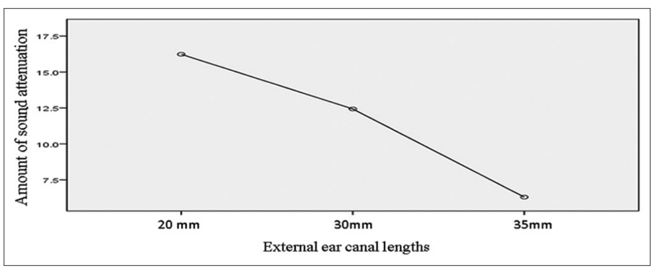

Figure 11: Average changes of decibel earmuff in three lengths at a frequency of 400 Hz

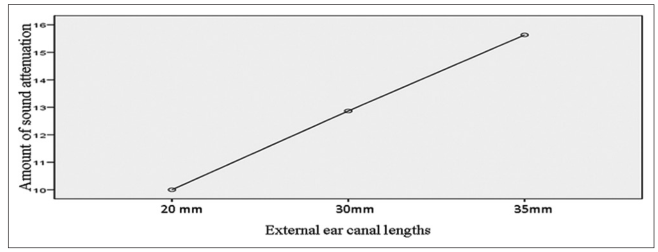

Figure 8: Average changes of Parsafe earplug in three lengths at a frequency of 500 Hz

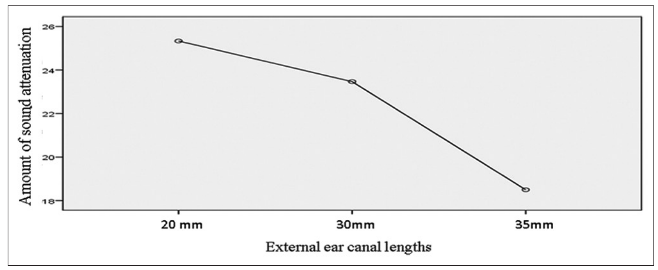

Figure 10: Average changes of maxon earmuff in three lengths at a frequency of 500 Hz

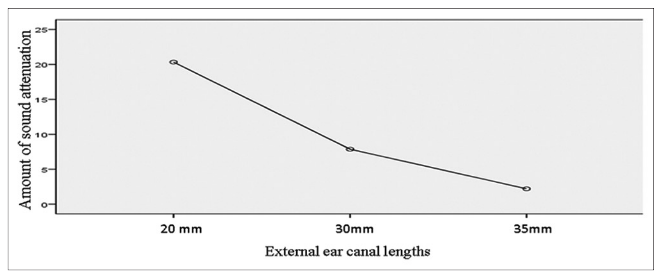

Figure 12: Average changes of decibel earmuff in three lengths at a frequency of 500 H

length of the canal increases with age, which in turn reduces the amount of sound resonance. At 400 Hz and 500 Hz, it was true when using earplugs.[15] On the other hand, in another study, it was found that by reducing the length of the earplug, the attenuation, and its performance decreased, which, in line with other studies, proved that greater depths of the ear canal and greater length of the earplug are effective on the amount of sound reduction.[24] However, the likelihood that one would place and use earplugs at a depth of 35 mm is low for various reasons. The classic EAR™ foam earplugs (approximately 20 mm total length) used during the study had only 13% of the earplug fully inserted (i.e. 100% insertion or 20 mm insertion depth). Twenty-eight percent of users had 75% insertion (i.e. insertion depth is 19–15mm), 46% of users had 50% insertion (i.e. insertion depth is 10–14mm), and the remaining 13% of users. It had only 25% insertion (i.e. the insertion depth is 5–9 mm). Insertion depth among users who participated in this survey averaged 13.6 mm (or 50% insertion).[27] In earmuff-type hearing protectors, it was found that with the increase in frequency and the length of the ear canal, the attenuation performance of the earmuffs decreased so that the amount of attenuation of the earmuffs decreased from the channel length of 20 mm and the average value of 25 dB – 5 dB in length. For maximum attenuation, the canal section should extend beyond the second bend of the ear canal. Due to the fact that in earmuff-type hearing protectors, the coverage area covers only the area of the ear cavity, as the sound is reflected toward the second bend of the ear canal, the ear canal due to its reflection in the walls of the canal leads to a decrease in the performance of the earmuff and a decrease in the amount. As shown in this study, the amount of attenuation decreases with the increase in the length of the channel.[28] On the other hand, due to the resonance in the earmuff cup, the amount of sound attenuation decreases according to the type of Earmuff.[29] In the use of earmuffs, the amount of sound attenuation is greater in shorter lengths than in earplugs, and this means that at frequencies of 400 Hz and 500 Hz, shorter lengths of earplugs are more successful. Considering that the longer length of the canal leads to discomfort in the individual, one of the limitations of this study is the impossibility of checking the comfort of using hearing protection devices in different lengths of the ear canal, and it is suggested to address this feature by designing other studies.

Conclusion

According to the results obtained in this study and according to the different sizes of ossification and the relationship between gender in the anatomy of people as well as the body of people, it can be concluded that in these frequencies, large sizes and older ages have better success in protecting. They have earplugs, but people who are small or young will have more protection with earmuffs.

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Ethics code

This research has an ethics code number IR.MUI.REC.1396.3.466.

Conflicts of interest

There are no conflicts of interest

Authors' contributions

Hossein Ebrahimi: Methodology, Writing – original draft; Farhad Forouharmajd: Conceptualization, Methodology, Project administration; Siamak Pourabdian: Validation, Writing – review and editing; Kamyar Nazaryan: Data collection, Formal analysis, Methodology, Writing – original draft.

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