2 Background

2.1 The Hearing Sense

People hear by detecting sounds vibration. Hearing is one of the five senses (sight, hearing, taste, smell, and touch) that humans possess.

The human ear consists of the outer ear, the middle ear, and the inner ear (Figure 1). The outer ear can be further split into pinna, concha, external auditory meatus (ear canal), and ear drum. The middle ear is located behind the ear drum and consists of three ossicles (malleus, incus, stapes), which transmit vibration of the eardrum into vibrations of the oval window membrane. The oval window membrane is the point of entrance for sound vibration from the middle ear to the inner ear. The inner ear consists of cochlear and vestibular system. The cochlear is responsible for conversion of vibration to electrical signals that are communicated via neurotransmitters to many thousands of nerve cells. Then the neurons transform the electric signals into electrochemical impulses, which travel along the auditory nerve to structures in the brainstem for further processing.

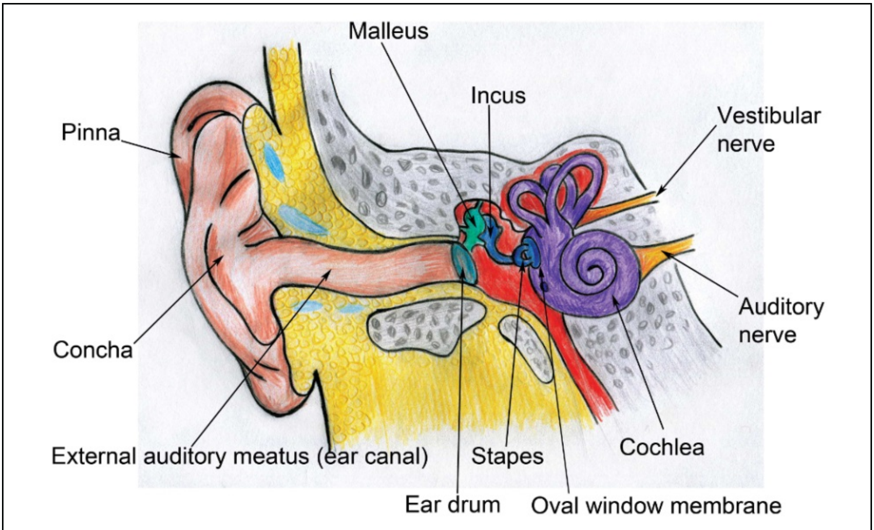

Figure 1: Anatomy of the Human Ear.

A. Boltyenkov, *A Healthcare Economic Policy for Hearing Impairment,*
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The pinna and the outer third of the ear canal are internally made of the elastic cartilage and are different for different individuals. The bony part forms the inner two thirds of the ear canal. The ear canal is typically “S” shaped with a diameter of a pencil and a length of 25 to 30 mm in adults. It has two primary functions. The first function of the outer ear is to protect the ear from external bodies such as dirt, debris, and insects. The second function of the outer ear is to channel sound into the ear. In addition, with the help of the outer ear, direction-dependent deformation of the incoming acoustical signal is performed. It is used for detecting the location of the sound source. This means that if the pinna is chopped off, it will be impossible for the ear to detect the direction from which the sound is coming. The ear canal combined with the pinna effect leads to the gain increase of 15-25 dB (decibel). In this research, gain represents the measure of power increase on a logarithmic scale in dB.

The middle ear is located in the tympanic cavity. The tympanic cavity is filled with air and is connected with the pharynx through the Eustachian tube. During swallowing and yawning the Eustachian tube widens making the atmospheric pressure on both sides of the ear drum equal. The middle ear function is passing and transforming the relatively low impedance[1] of the acoustical waves of the air in the outer ear to the high impedance of fluid in the inner ear. Without this function the big part of the sound energy would be lost during the transformation from air to liquid mediums, which in turn will cause significantly smaller sensitivity of the human ear to sounds. Thus, the middle ear adds about 27 dB of gain to the sound vibrations going from the ear drum to the oval window.

The inner ear consists of the series of canals and cavities filled with fluid. It functions as the organ of hearing and the organ of balance at the same time. The cochlear is the part of the inner ear responsible for hearing. Inside it, there are sensory receptors of auditory system called hair cells. They are located on the basilar membrane, and play a crucial role in sound waves transfer to the brain. The basilar membrane disperses the incoming sound waves to separate frequencies spatially. This means that the sound input of certain frequencies vibrates hair cells in certain locations more than in others. In particular, high frequency sounds lead to maximum vibration at the base of the basilar membrane, while low frequencies result in maximum vibration at the apex of the basilar membrane. In response to vibration, the hair cells release neurotransmitters triggering a nerve impulse. Due to the fact that the sound “wave” always passes through the base first, sensorineural hearing loss occurs initially at high frequencies.

[1] Impedance is the measure of responsiveness of a medium to vibrations caused by the sound pressure. It is measured as a ratio of sound pressure to particle velocity in a given medium. Low impedance means that it is easy for the sound to travel in the medium. High impedance means that it is difficult.

After a nerve impulse is triggered by hair cells, it travels along the nerve cells passing through different “stops” along the neural pathway. The majority of nerve fibers cross from one side of the brain to the other. This means the right half of the brain processes the sound signals from the left ear, and the left half of the brain processes the sound signals from the right ear. The signal ends in the auditory cortex of the brain, where it is interpreted.

It is important to note that the brain uses input from both ears for optimal processing. Binaural summation of sounds from both ears adds about 3 dB to the resulting sound. Due to the effect of binaural redundancy, the same sound is heard twice, and the brain is better equipped to identify the source of the sound. In addition, hearing with both ears allows understanding speech better, even in noisy environment, because of the binaural noise suppression by the brain. Therefore, in case of hearing loss in both ears, two hearing aids are highly recommended.

2.2 Types and Causes of Hearing Loss

Some hearing impaired people cannot hear any sounds at all. Others can comprehend speech only when shouted close to their ears. There are hearing impaired people who are able to hear some sounds, but not all. This is an especially dangerous situation, as a hearing impaired person might not be aware of her/his impairment. In such a case, she/he attributes her/his lack of speech understanding to the fact that other people in her/his presence mumble or speak unclearly.

Many hearing impaired people with mild to moderate sensorineural hearing loss can hear the vowels but have trouble hearing the consonants.[2] This may lead to a particularly difficult and embarrassing situation for a hearing impaired person: she/he hears the speech, but often misunderstands what is being said. For example: “the sequence of sounds i e a ar, might have originated as pick the black harp, but could be heard as kick the cat hard.”[3] As can be seen from this example, simply amplifying the sound at all frequencies at the same amplification will not help a hearing impaired person to understand the speech correctly; it might just make the wrong acoustical information sound louder. A correctly fitted hearing instrument outputs the acoustical information in such a way and at such frequencies that it enables a hearing impaired person to understand correctly what is being said. Therefore, a hearing instrument needs to be individually adjusted to the hearing loss profile.

[2] Macrae & Dillon, 1996.

[3] Dillon, 2001, p.2.

An audiogram is a standard way of representing a person's hearing loss profile. Audiograms show frequency of sounds in speech on the horizontal axis, typically on the logarithmic scale, in hertz (Hz). Intensity of sound, or simply put loudness[4], is presented on the vertical axis on the linear scale in decibels (dB). On an audiogram, one can clearly see the degree of hearing loss at each frequency.

There are two main types of audiograms. They are the air conduction audiogram and the bone conduction audiogram. The former shows the hearing loss measured when the sound travels all the way from the outer ear, through the middle ear to the inner ear. It demonstrates the performance of the patient's whole hearing system in one of the ears. As a rule, loudspeakers or earphones are used for air conduction testing.

The bone conduction audiogram shows the hearing loss in the inner ear. A bone vibrator is used for bone conduction testing. It is placed behind the ear to send vibrations directly to a patient's skull. Those vibrations bypass the outer and the middle ears, and are directly transformed into movements of the hair cells on the basilar membrane. This makes it possible to measure the hearing loss precisely in the cochlear.

The air and the bone conduction audiograms help to determine the type of hearing loss a patient suffers from. In the diagrams of the figures, the solid line represents an air conduction audiogram; the dashed line is a bone conduction audiogram.

The audiogram in Figure 2 shows normal hearing. A person with normal hearing has no difficulty in speech understanding.

The audiogram in Figure 3 shows a mild hearing loss. A person with this hearing loss may have difficulty understanding very quiet speech in noisy environment, or distant speech.

[4] Although loudness is shown on the linear scale in dB, the measure of sound loudness itself (dB) is a logarithmic unit.

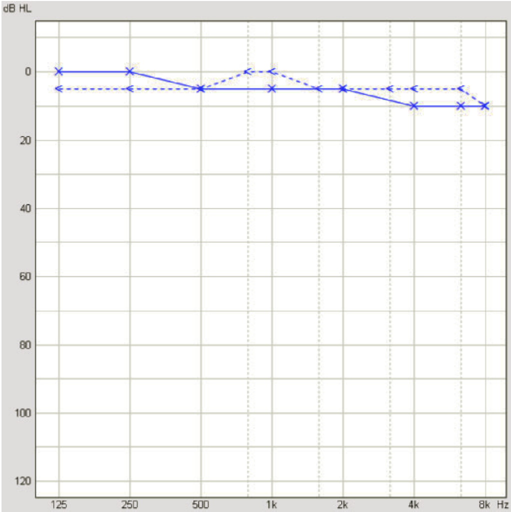

Figure 2: Normal hearing.[5]

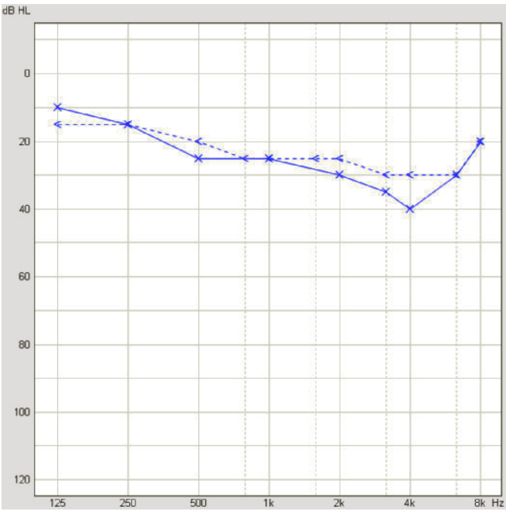

Figure 3: Mild hearing loss.[6]

5 Own illustration using Connexx 6.5.

6 Own illustration using Connexx 6.5.

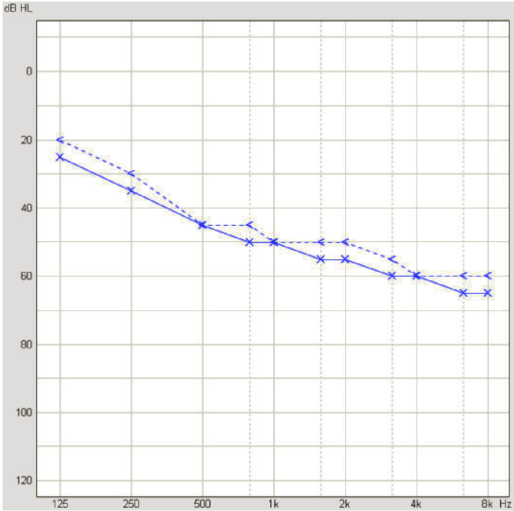

Figure 4: Moderate hearing loss.[7]

The audiogram in Figure 4 shows moderate hearing loss. With this hearing loss, a person understands conversation only at a distance of no more than 3 meters. In areas with background noise a person does not comprehend up to 50% of speech.

The audiogram in Figure 5 shows severe hearing loss. In case of this hearing loss, conversation must be loud to be heard without amplification. A person is aware of loud voices about 30 cm from the ear without amplification but most likely to rely on vision for communication.

The audiogram in Figure 6 shows profound hearing loss. In this case, a person is unable to understand speech even with the help of amplification.

[7] Own illustration using Connexx 6.5.

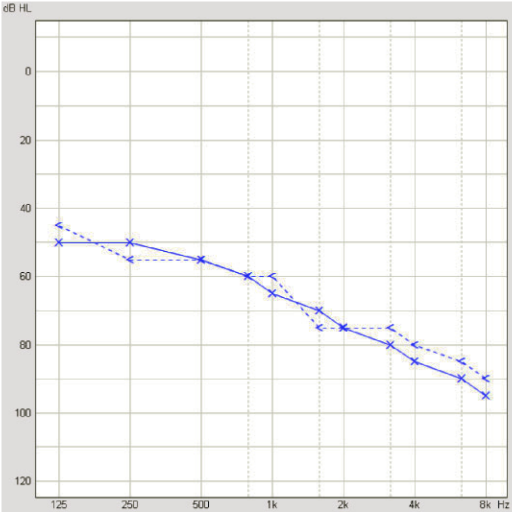

Figure 5: Severe hearing loss.[8]

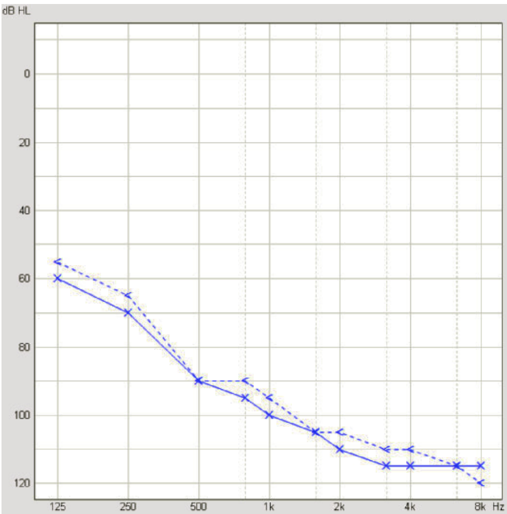

Figure 6: Profound hearing loss.[9]

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8 Own illustration using Connexx 6.5.

9 Own illustration using Connexx 6.5.

World Health Organization grades hearing loss as shown in Table 1.

Table 1: Table of grades of hearing impairment.[10]

Grade of impairment	**Corresponding audiometric ISO value (Average of 500, 1000, 2000, 4000 Hz)**	**Performance**	**Reccomendations**
0 **No impairment**	**25 dB or better** (better ear)	No or very slight hearing problems. Able to hear whispers.	
1 **Slight impairment**	**26–40 dB** (better ear)	Able to hear and repeat words spoken in normal voice at 1 metre.	Counselling. Hearing aids may be needed.
2 **Moderate impairment**	**41–60 dB** (better ear)	Able to hear and repeat words using raised voice at 1 metre.	Hearing aids usually recommended.
3 **Severe impairment**	**61–80 dB** (better ear)	Able to hear some words when shouted into better ear.	Hearing aids needed. If no hearing aids available, lip-reading and signing should be taught.
4 **Profound impairment Including deafness**	**81 dB or greater** (better ear)	Unable to hear and understand even a shouted voice.	Hearing aids may help understanding words. Additional rehabilitation needed. Lip-reading and sometimes signing essential.

10 World Health Organization, (1991), p. 2.

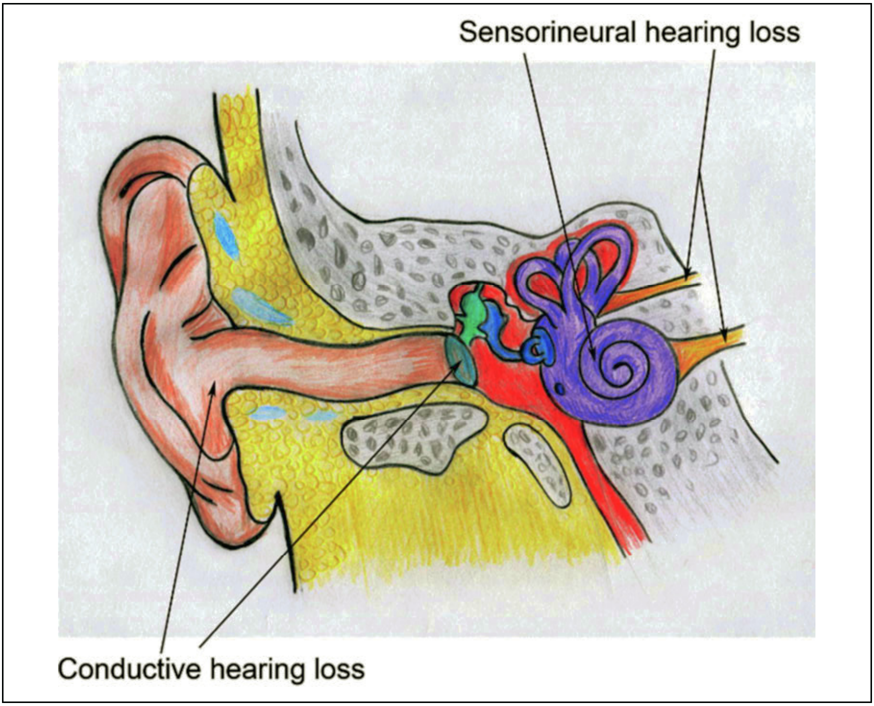

Figure 7: Hearing loss.

Due to the complexity of the hearing organ and the mechanisms used for transferring the sound from the environment to the brain, various disruptions on the way may result in hearing loss. There are three main types of hearing loss (Figure 7):

- Conductive hearing loss. Typically caused by the middle ear infections or malformations.
- Sensorineural hearing loss. Typically caused by the damage of the inner ear and/or the inner cells, or by the damage of the neural structures.
- Mixed hearing loss. A combination of conductive and sensorineural hearing loss.

Conductive hearing loss occurs when the conduction of sound waves from the outer ear to the inner one does not work properly. The problem in conducting sound waves from the outer to the middle ear is most often caused by excess of ear wax, debris in the ear or tumor. Excessive ear wax often, not always though, can be removed with the proper cleaning procedure. Besides, malformations of the pinna and the ear canal may also lead to the blockage and conductive hearing loss. Moreover, disruptions of sound transfer in the middle ear result in conductive hearing loss. These disruptions may occur due to punctures in the ear drum, inflammations of the middle ear such as otitis media, dysfunctional Eustachian tube etc. It is possible to diagnose sound wave conduction problems mentioned above via the analysis of a patient medical history, otoscopy, or/and via the analysis of the difference between audiograms of the air conduction and the bone conduction. If an ear shows hearing loss at the air conduction audiogram, and no hearing loss at the bone conduction audiogram, this means a patient has conductive hearing loss.

In most cases, conductive hearing loss may be treated by an ENT doctor, who can clean the outer ear, or with the help of drugs, like, for example, in case of the otitis media. In rare cases, a surgery is required. Therefore, individuals with only conductive hearing loss are rarely in need of a hearing instrument or an implant. It is always important to diagnose the type of hearing loss in order to select the right treatment.

In case of sensorineural hearing loss, the disruption happens at the point of transformation of vibrations, which enter cochlear, to neural patterns of excitation. The disruption may occur either in the inner ear, the vestibulocochlear nerve, or in the brain itself. Due to the fact that the exact differentiation between these three points of disruption is not possible, hearing loss associated with the sound sensation is called sensorineural hearing loss. Sensorineural hearing loss can range from mild to severe, and even can result in profound deafness. It is about four times more prevalent than conductive hearing loss.

Most often, sensorineural hearing loss is caused by malfunction of hair cells on the basilar membrane. The hair cells may be either damaged at birth or during life of an individual. Frequently, the causes for hair cells damage are trauma, disease, exposure to loud noise, aging or deafness genes. In such cases of sensorineural hearing loss, common treatments are hearing instruments or implants. The main reason for that is inability of mammals, including humans, to re-grow new hair cells instead of damaged ones. Therefore, external devices like hearing instruments or implants are needed. Hearing instruments amplify and modulate sound frequencies, where hearing ability is not completely lost. They convert sound frequencies of completely damaged hair cells to sound frequencies of still functional hair cells. On the other hand, cochlear implants generate electric signals in cochlear with the help of an electrode inserted into it, and thus completely replace the hearing function of hair cells with the electrode.

A small number of people may have a mixed hearing loss, where a part of the hearing loss is due to the conductive hearing loss, and another part is due to the sensorineural hearing loss.

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