Sound: Production, perception, hearing loss and treatment options

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Abstract

Sound is an important communication tool for humans that contain information about the surrounding environment. It may signify a danger or a reward for an organism. In humans, the mechanism of sound production and perception is complex and sophisticated. Sound is produced by vibrating body in a medium that contains molecules in the surrounding space. The sound perception starts in the human foetus at around the third trimester where it plays a vital role in organising the foetal brain. This process continues after birth and can be exploited by various endogenous and exogenous factors. Many mechanisms that can modulate hearing process at different levels lead to subclinical or clinical presentation of hearing-related problems. It is important to contemplate the mechanisms underlying sound production, perception and pathogenesis of hearing loss. This will facilitate prescribing a relevant treatment option according to the cause and its underlying mechanism. The current narrative review was planned to focus on sound production, its perception, types of hearing loss and available treatment options vited in relevant literature searched by using Google Scholar and PubMed.

Keywords: Hearing loss, Noise, Oxidative stress, Sound.

DOI: https://doi.org/10.47391/JPMA.4051

Introduction

All animals and humans produce and perceive sounds to communicate within their social groups. Horowitz considers that humans have a special quality of speech, different languages and music performance as well as perception.[1] Hearing and speech abilities are required to fulfill functions during daily activities. A sound heard by a person means the sound is detected, discriminated, localised and identified, and the information is processed by the brain. Sound is used to signal our location in the dark or from a distance, and to communicate other information. According to Horowitz, the brain is really a wet, sloppy drum machine desperately seeking rhythms; not only rhythm, but patterns in pitch too, that have a mathematical regularity that captures the brain's attention. Familiar voices have a positive effect on the listeners as they have their own set of rhythms and tones. Similarly, sounds in nature, such as that of birds, insects and rain, also have positive impact. People living in rain forest areas incorporate the falling rain rhythms into their music.[1]

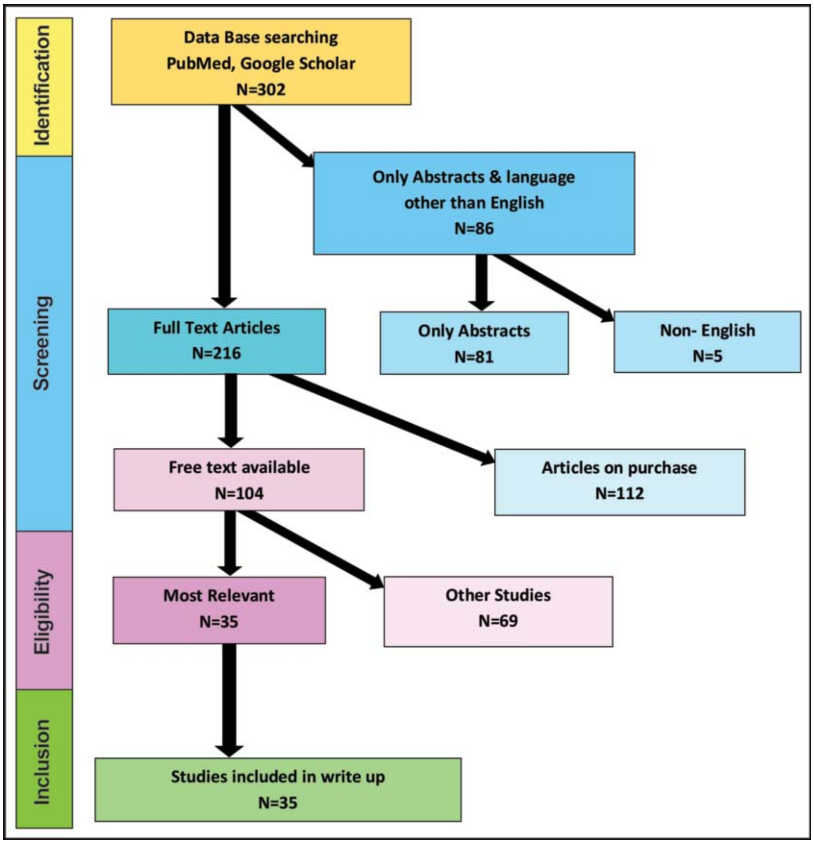

Figure-1: Study flowchart.

The current narrative review mainly encompassed sound production, perception, types of hearing loss and their possible treatment options. Literature search related to studies published in the English language in the last 20 years (2001-2021) with free text being available was conducted through Google Scholar and PubMed using

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key words hearing loss, noise, oxidative stress and sound, and phrases, such as sound perception by human ears, processing of sound in human brain and hearing loss. Of the 302 studies found, 35(%) were reviewed in detail (Figure-1).

Sound Production

Sound is initiated by generation of waves that are produced by a vibrating body. These vibrations are the form of the energy that travels from its source through any medium, such as air, water (or any other liquid) or solid matter.[2] Sound waves are alternative condensation and rarefaction in the particles of a material medium. Thus sound cannot be transmitted through vacuum.[3] Sound waves have few main characteristics and there are some definitions related to the sound phenomenon (Table).[4,5]

The human voice is generated in the larynx by the vibration of the vocal folds. The air in the lungs is expelled with pressure through the larynx, producing voice by vibrating the vocal folds. Vocal folds also prevent any object to enter into the larynx.[6] Humans use their voices to express emotions, both as nonverbal bursts of emotional sounds, such as laughter, yells, screams[7,8] pride, guilt or boredom,[9] and as modification of the intonation of speech. Poetry is a good example of the latter one.[10] Vocal emotions, such as anger, fear, surprise, sexual pleasure, happiness,[7] sadness and disgust, are processed in the limbic system.[8]

Voice disorders may arise due to problems being encountered upon movement of air through respiratory passages that is lungs, vocal cords, throat, nose, mouth and lips. There may be damage to nerves supplying the muscles of vocal cords, laryngeal webs or clefts, polyps, nodules, cysts, granulomas, papillomas, or ulcers on the vocal cord, cancer of the throat, cleft palate or other palate problems. Vocal abuse, like screaming, continuous singing or clearing the throat, are some other reasons. There may be difficulties in the process of speech sound-generation, such as due to genetic abnormalities, emotional stress, infection or trauma to brain. Both phonological as well as articulation disorders may contribute to such scenarios. Thus, changes in the structure or shape of the muscles and bones are involved in the production of speech sounds, such as cleft palate, tooth problems and cerebral palsy (CP) involving nerve damage. The prevailing hearing loss due to any reason contributes to both voice and speech disorders, making communication impractical.[11]

Sound Perceiving (Hearing) and Interpretation

Human ears serve the purpose of sensing both the sound and the balance. The audible frequency for human ear lies between 20Hz and 20,000Hz. A lower-frequency sound is called subsonic, and a higher frequency sound is called ultrasonic. A frequency range of 200Hz to 5,000Hz is of the highest sensitivity, which is used for interpreting speech signals.[12] Sound waves have pitch and intensity that are perceived as spectral pattern and loudness, respectively. Sound mostly reaches human ears as a compound wave of vibrations. These vibrations are transmitted to stereocilia of the cochlea which are innervated by neurons of the spiral ganglion. Their axons ascend as auditory nerve to auditory nuclei of the brain stem. Both sensitivity and selectivity of the wide range of audible frequencies are determined at the level of cochlea. If there is change in frequency of a pure tone, there will be a shift in the site of the activated region.[3] These fibres then reach multiple areas of brain, including cochlear nuclei, superior olivary complex, inferior colliculi, medial geniculate body and primary auditory cortex in that order. The superior olivary complex is involved in the identification of angle and location of sound source and difference between time and intensity of sounds reaching each the ear.[13]

Sound can only be perceived if it reaches the auditory cortex and is processed in this area. The auditory cortex was previously divided into primary and secondary

Table: Sound characteristics and their units of measurement.[3,4]

Characteristic	Description	Unit
Wavelength	It is the minimum distance between two identical points of sound waves.	Meters
Amplitude	Amplitude of a sound wave is the height of a wave.	Pascals (Pa)
Time-period	Time period of a wave is the time it takes for one complete oscillation.	Second (s)
Frequency	Frequency of sound wave (also called as pitch) is the number of vibrations per second. If the time period of a wave is 2 seconds its frequency will be 1 divided by 2 that is 0.5 Hz.	Hertz (Hz)
Velocity or speed	The speed of sound is the distance travelled per unit time by a sound wave as it travels through an elastic medium. In air sound velocity is about 0.33 km/sec, in water it is 1.5 km/sec and in steel it is 5 km/sec. All sound waves travel with the same speed in air regardless of their frequency.	Meters/seconds (m/s)
Intensity	Sound intensity is the amount of energy that travels in a unit time through a unit area in a direction vertical to the travelling of sound waves.	Decibel (dB): a ratio

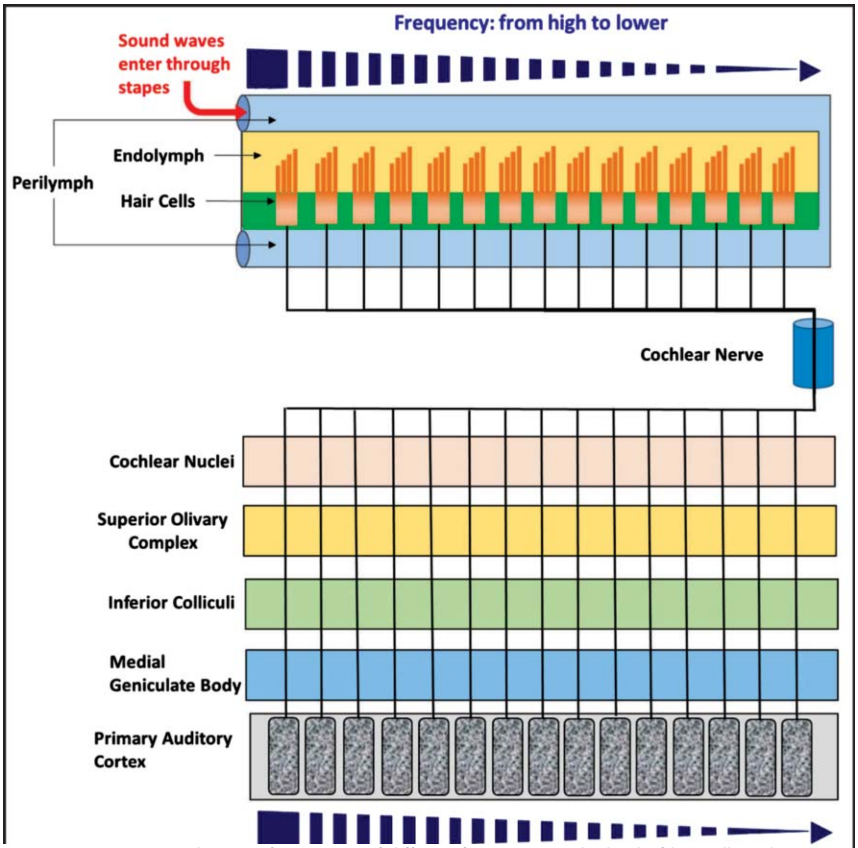

Figure-2: Tonotopy mechanism of perception of different frequencies at the level of hair cells and auditory cortex.[15]

cortex. Auditory cortex is recently divided into core (which includes primary auditory cortex A1), the belt (secondary auditory cortex A2), and the parabelt (tertiary auditory cortex A3). The belt is the area immediately surrounding the core, and the parabelt is adjacent to the lateral side of the belt.[14] The neurons of the primary auditory cortex are selective for specific frequencies and are organised in isofrequency bands that are tonotopically organised (Figure-2).[15] From the primary auditory cortex emerges the ventral (in recognition of sound, and drawing out meaning from sentences) and dorsal (responsible for speech repetition and articulation, working memory such as names) streams that comprise fibres directly to the anterior superior temporal gyrus and the sulcus and the middle temporal gyrus. These connections are involved. The secondary cortex, or the belt located in frontal and parietal lobes, interconnects the primary cortex with the superior temporal gyrus and the sulcus as well as with the frontal lobe. It helps localise the sound source and interprets animal vocalisations, human languages and auditory memory.[15] Speech sound is perceived by specific auditory cortex area which is not sensitive to other sounds from the surroundings. But still this area is not selectively perfect, as some non-speech sound stimuli can elicit activity in speech-sensitive auditory cortex. The dorsal part of speech-sensitive auditory cortex is activated by language-related lip movement. Thus, this area is involved in multimodal integration of the auditory and the visual information related to speech perception. Additionally, different tasks may modulate the activity of this area top-down differently, signifying the connections of this area to different parts of the brain involved in different types of tasks.[16] Hence, the process of hearing begins in the external visible part of the ear called pinna. It is funnel-shaped, receives the sound waves and guide them to the auditory canal to strike the eardrum or the tympanic membrane. It is a tightly stretched and highly sensitive membrane that vibrates with the waves, and transmits them into the middle ear via three tiny bones called the ossicles comprising malleus, incus and stapes. The vibrations are ultimately relayed to the membrane covering the opening of the cochlea, which is snail-shaped and is filled with liquid and contains the cilia.[16]

Hearing Shapes the Brain

Vibration is everywhere and it indicates something in the surrounding. The sensitivity to vibration is observed in all living organisms, including even bacteria. It is important for an organism to know if these vibrations are signifying a danger or it may be related to a reward, such as food.[5]

i. Listening in the perinatal stage

Babies start to hear about 3-months before birth. They are listening to their mother's voice mostly along with other sounds.[17] Mother's voice and her heartbeat provoke auditory plasticity in the brain of the foetus during intrauterine (IU) life.[18] It is reported that the foetus forms memories of the perceived sounds, the process is sometimes called "foetal learning". Thus the foetus may remember the mother's voice as well as some more sounds from the surroundings, with a big ability of discrimination. Chelli documented an inherent musical capability of the human brain.[19] Most high-frequency sounds are filtered out and their decibel (dB) levels are reduced by the maternal abdomen and the uterus. However, preterm infants in the neonatal intensive care unit (NICU) have no such protection. The sensitive environment around newborn infants and preterm babies change suddenly. They are frequently exposed to a wide range of sound frequencies that may not be safe for them. Preterm infants exposed to loud sound in NICU from any source have been reported with sleep disturbances[20] and undesirable effects on vital signs and oxygen saturation.[21] Similar to other parts of the brain sensory areas, the function of the adult primary auditory cortex (A1) is strongly affected by the sounds perceived in early life. A study conducted on animal models documented that if a single frequency sound is exposed to rats on 11-13 days post-birth, a 2-fold expansion in the representation of that frequency in A1 is observed. It is noted that this change is retained for the rest of the life of that animal. But if the same sound is exposed outside this period, the modification in the tonotopy of A1 does not last.[22] A group of Scientists studied the crying sounds of French and German newborn babies; French babies had a cry tune with low intensity at the starting with a subsequent rise. The cry of the German babies showed a tune with high intensity at the start, with a subsequent fall. These cry tunes resembled the tunes of French or German languages. German is similar to English, where words are stressed at the beginning, while the French stresses words toward their endings. It is astonishing that the cry melodies of French and German newborns are similar to adult speech stress patterns.[17] Newborns of age one day were examined for processing language and other sound stimuli. It was observed that the left temporal language area is involved in the processing of the native language, while the right hemisphere deals with non-native language through prosodic processing. Non-linguistic stimuli produce brain responses bilaterally.[23] Gender differences in the auditory cortex are also observed in humans. Planum temporale is a cortical area behind the auditory cortex (Heschl's gyrus) in the Sylvian fissure. It is located at the centre of Wernicke's area, the area related to the function of language. The planum temporale, including Wernicke's region, is noted to be larger in volume in females, thus demonstrating the relationship between gender hormones and asymmetrical brain development.[24]

ii. Listening in childhood

Children practising musical instruments frequently were found better at frequency discrimination, reading and spelling skills. Magnetic resonance imaging (MRI) also correlated an enhanced change structure as well as function.[25]

Hearing Loss and its Treatment

Hearing loss is an incomplete or a complete incapability to hear that can affect all age groups, resulting in ineffective verbal communication. In adults, hearing loss mainly occur in age group 60-69 years, where males have two-fold risk compared to females.[26] Similarly, non-Hispanic white are more prone to develop hearing loss compared to other ethnicities, and occupational noise exposure is a leading cause of bilateral hearing loss in adults. The disease may involve one or more parts of the ear. There are three types of hearing loss based on the underlying pathology and part of the ear involved; conductive, sensorineural and mixed hearing loss.[26]

i. Conductive hearing loss

In this type of hearing loss, the conduction of sound is blocked either through the external ear, or the middle ear, or both. The causes may include cerumen impaction, middle ear infections and abnormalities of middle ear bones. Similarly, foreign bodies that have accidentally entered the auditory canal should be removed with the help of an instrument. The skin of the auditory canal can be infected, called otitis externa, commonly by staphylococcus (S.) aureus pseudomonas (P.) aeruginosa. The auditory canal may be blocked by swelling and infectious debris, resulting in conductive hearing loss. The pulling of ear pinna results in pain sensation. In such cases removal of the debridement is necessary that is followed by the application of local antibiotic drops. Additional intake of oral antibiotics is useful. Some benign bony growths, such as exostoses (bilateral with a history of swimming in cold water) and osteomas (unilateral), inside the auditory canal may reduce the cerumen migration, resulting in conductive hearing loss. Surgery is rarely required in these conditions.[27] Rare conditions associated with conductive hearing loss include sebaceous cysts, and benign or malignant tumours, like adenomas or fibromas. In a suspected malignancy case, biopsy should be performed to confirm the diagnosis.[27] Middle ear pathologies result in perforations of the tympanic membrane due to trauma or otitis media. In otitis media a hearing loss of around 20-30 dB results due to decreased mobility. Hearing is resumed once the effusion is resolved. Debridement is required in otitis media with a subsequent use of ototopical antibiotics, such as ofloxacin, along with oral antibiotics. Patients with chronic or recurrent acute otitis media or otitis media with hearing loss >30dB may benefit from myringotomy tubes. In case of perforations of the tympanic membrane, surgery is recommended in case of perforation >2mm or if the hearing loss persists for >2 months. Squamous epithelial cell debris in the middle ear is known as cholesteatoma. Cholesteatomas can be both congenital and acquired. In congenital cases, white debris is found behind a normal tympanic membrane with a resultant unilateral conductive hearing loss. In acquired cases, the squamous epithelium may grow into the middle ear through a perforated tympanic membrane with an ingrowth of the epithelium. Cholesteatomas invade the surrounding tissue, including ossicles, leading to conductive hearing loss. Cholesteatomas are treated surgically. Irregular white patches consisting of calcium on the tympanic membrane are called myringosclerosis. Extensive myringosclerosis manifests as conductive hearing loss due to the hardening of the membrane. Otosclerosis is another condition where the footplate of stapes is fixed due to abnormal bone deposits. Hearing loss is progressive and bilateral and more commonly found in middle-aged white women. It is managed by using hearing aid or surgical intervention.[27]

ii. Sensorineural hearing loss

In sensorineural hearing loss, the impairment is inside the cochlea or in the neural pathway to the auditory cortex. Sensorineural hearing loss results from genetic disorders, noise pollution and age-related degenerative changes (presbycusis). In the mixed hearing loss, both conductive as well as sensorineural impairment is observed.[26]

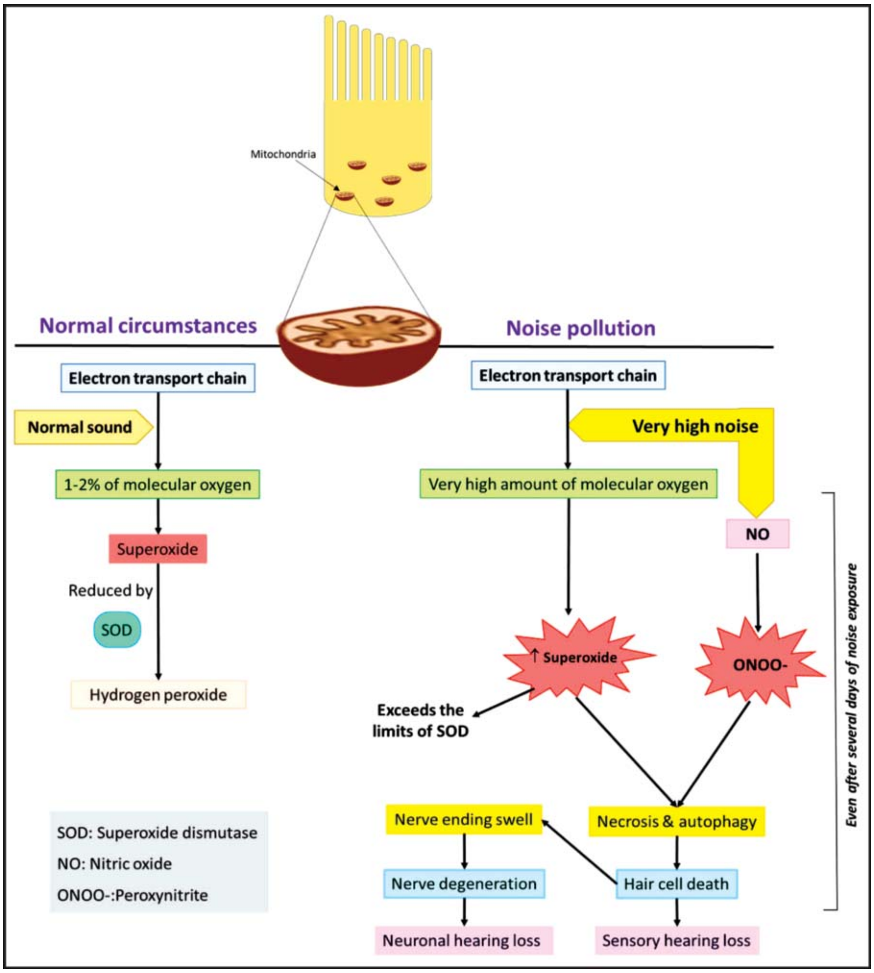

Figure-3: Mechanism of noise-induced hearing loss (NIHL).[26,27]

The damage to cochlear hair cells is permanent and these cells cannot regenerate. Even spiral ganglion neurons may degenerate secondary to hair cell death, decreasing the efficacy of cochlear implants that excite the spiral ganglion neurons directly. It is more common in the adult age group, but children may be born with hereditary or non-hereditary hearing loss. Mode of inheritance in the hearing losses is mostly autosomal recessive. This type of hearing loss is a concomitant feature of many syndromes. Smoking, obesity, cardiovascular disease risk and diabetes mellitus have shown strong associations with compromised hearing.[27]

Normally the human sound is conveyed at around 60dB, but the auditory range is wider on both extremes. Impairment in hearing may result from chronic or frequent exposure to sounds as loud as 85dB and above. These types of sounds include noise of chainsaws, lawnmowers or small machinery, and loud music heard with the help of earphones. Similarly, firearms or guns used by army personnel as routine will impart hearing damage. There is degeneration of hair cells in the cochlea and swelling of nerve fibres attached to them. Thus, noise exposure exerts mechanical insult to the hair cells and manifest as permanent hearing loss in those hair cells as these cells cannot be regenerated. Noise trauma results in the generation of free radicles in hair cells that exceed the normal antioxidant mechanisms. Oxidative stress leads to apoptosis of these cells (Figure-3)[26,27] while superoxide (O_2^-), nitric oxide (NO) and peroxynitrite (ONOO-) have been reported to increase in the cochlea, adding to the oxidative stress.[28] Noise-induced hearing loss can be prevented by the use of antioxidants. In vulnerable situations, the use of antioxidants for the prevention of hearing damage is beneficial. Antioxidant compounds include N-acetylcysteine (NAC), glutathione (GSH), D-methionine, ebselen, resveratrol, ascorbic acid and water-soluble coenzyme Q10 vitamins A, C and E.[28,29]

Age-related degenerative changes in sensory and neural pathway are called presbycusis, which is a bilateral progressive decline of hearing with increasing age in the elderly. Both genetic and epigenetic factors contribute to this type of hearing loss. Epigenetic factors mainly include noise exposure and smoking. This type of hearing decline affects high-frequency perception and speech discrimination and is accompanied by tinnitus. Proper clinical examination and audiometry should be performed before deciding about the amplification aids. Among the epigenetic factors, noise-induced damage can be prevented or reduced through different strategies. Ear muffs and ear plugs are helpful in avoiding noise induced damage by 30dB. Another acquired cause of sensorineural hearing loss is consumption of ototoxic drugs, such as aminoglycosides and cisplatin, which should be cautiously administered in patients with compromised kidney function and patients of old age. Other drugs that may affect hearing include diuretics and salicylates. Autoimmunity can also be sometimes an underlying mechanism for progressive bilateral deterioration in hearing. Impairment of hearing may be accompanied by some autoimmune disorder. Such cases may benefit from oral prednisone administration or low-dose methotrexate.[27]

Unilateral sensorineural hearing loss may occur due to temporal bone fractures if the fracture crosses through the bony labyrinth. Surgical intervention may be required on an urgent basis. Fistula may form due to leakage of perilymph in the middle ear. There is immediate loss of hearing, tinnitus and vertigo. Forceful sneezing, coughing or straining may also lead to fistula formation. Strict bed-rest for 3-6 weeks may be helpful in recovering completely, or, else, surgical intervention may be required. Meniere's disease is another progressive unilateral sensorineural hearing loss that presents as intermittent hearing loss with lower frequencies affected first, followed by higher frequencies. There is an associated feeling of fullness, tinnitus and vertigo. Although the cause of Meniere's disease is not known, an increased endolymphatic pressure is reported in such cases. Low-salt diet and diuretics are used for decreasing the symptoms. The use of gentamicin for chemical labyrinthectomy is a nonsurgical intervention as the last resort. Idiopathic unilateral sudden hearing loss is a serious condition that occurs within 3 days with a 30db hearing decline. It is also accompanied with auditory fullness, tinnitus and vertigo. Viral infections or vascular disorders may be the causative mechanisms. Oral steroids are effective if used to within 3 weeks. Asymmetric sensorineural hearing loss may be caused by brain tumours in the relevant areas. Brain scanning with MRI is the standard for the diagnosis of tumours. In such cases, mostly surgery is the option of treatment.[26]

Sensorineural hearing loss cannot be restored. Hearing aids are devices used to amplify sound perception and compensate for the hearing loss. Hearing-assistive technologies available in markets include amplified audio and video devices. Severe or complete sensorineural hearing damage are offered with cochlear implants that are surgically rooted. Cochlear implants restore limited hearing capability, enabling the person to communicate socially.[27] Cochlear implants are composed of a series of electrodes placed inside the cochlea. They directly stimulate the auditory nerve cells without involving the hair cells. Upcoming models of implants enable various spots present on them to respond to different levels of pitch. These implants can help the deaf children, especially if they are implanted early enough, making the children learn to speak, often in the same way as children born without any hearing loss.[26]

Prolonged exposure to loud sounds leads to sensorineural hearing loss by ultimate damage of the cilia. Individuals constantly exposed to operating noisy machinery without using any appropriate ear-protective measures are at a high risk of developing hearing loss. Similar is the case of people listening to loud music using headphones, engaging in hobbies like hunting or motorcycling. Sound intensity of 85dB or more can cause damage to the hearing process more so upon repeated exposure. Sounds intensity of >130dB are particularly dangerous even upon infrequent exposure. Ringing or buzzing, called tinnitus, is also produced by some damage to cilia.[27]

iii. Mixed hearing loss

It is the hearing loss which results from combined conductive impairment in the outer or middle ear and sensorineural damage in the inner ear hair cells and nerve fibres at any point. It is treated by targeting both conductive and sensorineural components separately.[27] Damage to specific areas of the brain, such as stroke or brain injury, may affect the hearing pathway processes described above. Wernicke's aphasia is an example in which the patient hears unknown language and is therefore unable to understand it.[30] Auditory agnosia is the inability to recognise upon referring to an object verbally by someone.[31] Amusia is the inability to recognise or reproduce tones or musical rhythms.[32]

Besides disorders that cause impaired hearing, a person may hear sounds that are not actually present around him, like tinnitus where constant ringing is heard by the patient. Sometimes erroneous activation of the auditory cortex occurs that leads to threatening hallucinations, as happens in schizophrenia.[33] There may be sound processing auditory disorders also that are often associated with attentional and literacy problems, such as in attention deficit hyperactivity disorder (ADHD) children. A longitudinal comparison revealed a very high stability of auditory cortex morphology and gray matter volumes, suggesting that the combined anatomical and functional parameters are neural markers of musicality and attention deficits.[25]

Conclusion

Understanding the mechanisms of sound production, perception and problems related to hearing are of great importance because the treatment of hearing loss varies according to the underlying aetiology. Sometimes only removal of the causative agent is sufficient, while in other cases intervention with drugs, surgical procedures or hearing aids is required.

Disclaimer: None.

Conflict of Interest: None.

Source of Funding: None.

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