Hearing Aid

Prof. Dr Balasubramanian Thiagarajan

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Preface

This book fills up an important gap that existed in the post graduate learning resource. Otolaryngologist had a poor insight as far as this topic is concerned. The author feels that all practicing otolaryngologist should have a basic understanding of hearing aid, how it functions, and how to prescribe them. More than anything else they should also be aware about the limitations of the hearing aid.

This book should enlighten the students of otolaryngology on this vital topic. This topic is a little bit boring because of the physics involved. The author wishes to allay the fears of the student that prior knowledge of acoustic and electro-physics is not needed. All the basic stuff have been explained on a need to know basis with clear illustrations.

Standard text books in otolaryngology don't cover this topic with clarity leaving the otolaryngologist to fend for themselves when it comes to hearing aids.

The author feels a practicing otologist should have a clear understanding of the concept of hearing aids and the development that have been taking place in this field. Clear idea of this topic will ensure that the otologist to whom the patient first lands up give proper guidance to the patient. Otologist should also be in a position to offer alternate non invasive options of improving the patient's hearing. The author is of the opinion that proper motivation of the patient to use hearing aids will help them to avoid risky surgical procedures to improve hearing in otosclerosis.

As far as sensorineural hearing loss hearing aid happens to be the only viable solution that is available to the patient. The author also wishes to stress on the importance of using bilateral hearing aids in patients with bilateral hearing loss (be it conductive or sensorineural hearing loss).

This book attempts to impart vital knowledge on this topic using below upwards concept, making it easy for a novice to understand the topic. The author hopes that this book will be useful to the students of otolaryngology as well as the practitioners of otolaryngology.

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Introduction

Hearing disability happens to be one of the most common disability in human population and presents a challenge to the individual in speech recognition, communication and language acquisition. In daily life speech is often heard among a variety of sounds and noisy backgrounds which makes communication even more challenging. It has been proven the processing of ongoing auditory streams increases the cognitive load imposed by the listening task. This increase in the cognitive load by the listening task causes increased levels of mental stress and fatigue, lack of energy and stress related sickness. These patients tend to be withdrawn from leisure and social roles.

It has been estimated that hearing loss affects nearly 250 million people in the world. Humans are highly dependent on their senses. The sense organs play an important role in shaping both physical and psychological growth and behavior. All sense organs play an important part in shaping both physical and psychological growth and behavior. Hearing and vision happen to be distant senses and are the most crucial ones.

Hearing aids are typically used to correct the loss of audibility introduced by hearing impairment. Modern hearing aids provide a range of signal processing algorithms. These include amplitude compression, directional microphones and noise reduction. The basic purpose of these algorithms is to improve speech intelligibility and listening comfort. If hearing impairment increases the listening effort, then it is essential to investigate whether hearing aids can reverse this aspect of hearing loss. The most prevalent degree of hearing loss ranges between mild-to-moderate affecting more than 90% of all adults with hearing loss. This figure is based on an UK study. Sensitivity of hearing can be assessed according to pure-tone thresholds across five different octave frequencies (0.25, 0.5, 1, 2, 4, kHz).

Hearing level in mild hearing loss = 20-40 dB

Hearing level in moderate hearing loss = 41-70 dB in the better hearing ear.

Audiological rehabilitation is efficacious when it reduces communication difficulties, enhances psychosocial well-being. It should be stressed that even though hearing aids constitute the single most important part of auditory rehabilitation process, they constitute only one part and may not be even indicated for certain hearing-impaired individuals. Hearing aids are not taken up by nearly 60% of these patients due to so many reasons, the most common happens to be social taboo. Despite the fact that hearing deterioration gradually increases from the age of 55, hearing aids are not typically adopted till they reach the age of 70. It should be stressed that hearing aid fitting from earlier age can result in substantial benefits. Conventional hearing aids do not restore hearing but makes sounds more audible through electro-acoustic amplification. Hearing aids are regulated medical devices that deliver sound into the ear canal via air / bone conduction. Bone conduction hearing aids / Bone anchored hearing aids are indicated for patients with external auditory canal atresia which could make wearing hearing aids rather difficult to comply.

Depending on the type of technology used hearing aids can be classified into:

Analog

Digital

Depending on the model they can further be sub-classified into:

Body worn hearing aid
Behind the ear hearing aid

In the ear hearing aid
Receiver in the canal hearing aid

Physical characteristics of sound waves that should be understood before deciding on use of hearing aids include:

Frequency:
This is the rate at which the sound fluctuates.

Pitch:
This is the time taken for a repetitive fluctuation to repeat.
Wavelength:
This is the distance over which its wave form repeats.
Diffraction:
This is the way the sound bends around obstacles
Pressure / Sound pressure level:
This is the strength of the sound wave
Spectrum:
This is a breakup of a complex sound into pure tone components at different frequencies.

Amplifiers present inside the hearing aids can be classified into linear and nonlinear. For sounds of a given frequency, linear amplifiers amplify by the same amount regardless of the level of the signal, or what other sounds are simultaneously present. Whereas nonlinear amplifiers vary with the amplitude of the signal input to the amplifier. The degree of amplification can be represented as a graph of gain versus frequency (gain: frequency response), or as a graph of output versus input level (I-O curve). The highest sound level produced by the hearing aid is known as the saturation sound pressure level (SSPL). SSPL is usually estimated by measuring the output sound pressure level for 90dB SPL input (OSPL90).

Patients with sensorineural hearing loss have several deficits to overcome. Some sounds could be inaudible, other sounds can be detected because part of the spectra is audible, not identifiable because other parts of their spectra remain inaudible. The range of levels between the weakest sound that can be heard and the most intense sound that can be tolerated is less for a person with sensorineural hearing loss than for a normal hearing person. Ideal hearing aid should amplify weak sounds more than they amplify intense sounds. In addition, sensorineural impairment diminishes the ability of a person to detect and analyze energy at one frequency in the presence of energy at other frequencies. These patients also have difficulty in hearing a signal that rapidly follows or is rapidly followed by a different signal. These problems could mean that noise, or even other parts of the speech spectrum, will mask speech more than would be the case for a normal hearing person.

Sensorineural hearing impairment needs a signal to noise ratio greater than normal in order to communicate effectively, even when sounds have been amplified by a hearing aid. In conductive hearing loss there is simple attenuation of sound as it passes through the middle ear, so amplification provided by hearing aids helps in restoring hearing to normal levels.

The size of the hearing aid has shown a constant trend of decreasing. The currently available hearing aids are so small they can fit fully into the external auditory canal making it nearly not visible to others.

Problems faced by patients with sensorineural hearing loss:

1. Some of the sounds could be inaudible.

2. Some sounds could be detected but would not be correctly interpreted because part of their spectra could be inaudible. This is more so for the high frequency spectrum.

3. The range of sound level between the weakest sound that can be heard and the most intense sound that can be tolerated is less for a person with sensorineural hearing loss when compared to normal individuals. In order to compensate for this effect, hearing aids will have to amplify weak sounds more than that of intense sounds.

4. Sensorineural hearing loss impairs the ability of a person to detect and analyze energy at one frequency in the presence of energy at other frequencies.

5. In these patients there is also a decreased ability to detect and analyze energy at one frequency when it is rapidly followed by another signal.

6. Hearing impaired persons find problems in separating sounds on the basis of the direction from which they arrive.

The decreased (frequency, temporal and spatial) resolution would cause a noise or even other parts of the speech spectrum to mask speech much more than normal individuals.
Patients with sensorineural hearing loss will need a signal to noise ratio greater than that of normal hearing individuals to comprehend spoken voice. This is true even when sounds are amplified by hearing aid. This should be contrasted with that of patients with conductive hearing loss where there is attenuation of sound as it traverses the middle ear cavity. Amplification provided by hearing aids in these patients restores hearing to a great extent.

Causes of sensorineural hearing loss:

Loss of inner hair cell function

Loss of outer hair cell function

Reduction in the cochlear electrical potential

Changes in the mechanical properties of cochlea

Types of Amplifiers that are present in the hearing aid:

Amplifiers inside hearing aids can be classified as linear or non linear.

Linear amplifiers - Amplifies the sound by the same amount regardless of the frequency. It also amplifies the background noise also.

This is an electronic circuit whose output is proportional to its input and is capable of delivering more power into a load. Not all linear amplifiers are equal and circuits that go into their design provides trade offs. So there is nothing like 100% amplification of input sound and they are classified into three classes based on their amplification ability.

Class - A amplifiers are very inefficient and their efficiency in amplification does not exceed 50%. The semiconductor / vacuum tube in this class of amplifiers conduct throughout the entire RF cycle.

Class - B amplifiers can at the most be 60-65% efficient. The semiconductor in this device conducts through half the cycle but needs lots of power to run.

Class - C amplifiers are more efficient and can be about 75% efficient in amplifying sounds.

Non linear amplifiers - Amplification provided by nonlinear amplifiers varies with the amplitude of the signal input into the amplifier.

The amount of sound amplification can be represented graphically as a graph of gain versus frequency (gain-frequency response) of as a graph of output level versus input level (I-O curve).

The highest level of amplification provided by hearing aid is known as saturation sound pressure level (SSPL). This value is usually estimated by measuring the output sound pressure level for a 90 dB SPL input.

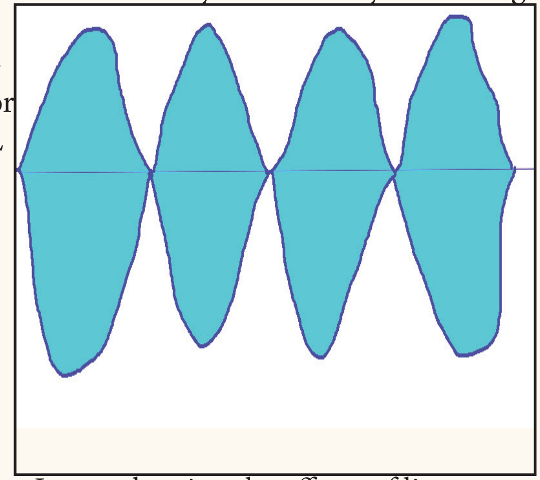


Image showing the effects of linear amplification

Non linear amplifiers - Amplification provided by nonlinear amplifier varies with the amplitude of the signal input to the amplifier. Only the weak signals are amplified in this set up. Non linear amplification is widely used in hearing aids for the following reasons:

1. Already loud sounds will not be amplified (peak clipping effect). In fact the amplitude of loud sounds a clipped thereby preventing those sounds from excessively stimulating the cochlear hair cells.

2. Cochlear hearing loss are usually non linear in nature. In this type of hearing loss sensitivity for weak sounds are impaired whereas for loud sounds it is unaffected. This reduces the auditory dynamic range for certain frequency regions.

Automatic Gain Control:

The difficulties associated with decreased dynamic range can be reduced by the use of automatic gain control (AGC) according to Steinberg & Gardner (1937). Automatic gain control system works on the basis of signal levels. It amplifies weak sounds more than the stronger ones, resulting in the wide dynamic range of the input signal being compressed into a smaller dynamic range at the output. Hence all the AGC systems are known as "compressors".

AGC reduces the volume if the signal is strong and raises it when it is weak. For this to happen the signal should pass through a detector stage before reaching the amplifier. Only the signal that needs to be amplified goes to the amplifier containing a diode and capacitor.

Automatic Volume Control:

Automatic volume control systems are intended to adjust the gain automatically for different listening situations to relieve the user of the need to adjust the volume control manually. If the recovery time of the AGC circuit is set greater than a few hundred milliseconds then the gain changes slowly with changes in the sound level.

Automatic volume controls provide more amplification for soft voices when listening conditions are quiet and less overall amplification when sounds and conditions are loud.

Many newer hearing aids now have:

Automatic volume controls that provide more amplification for soft voices when the listening conditions are quiet and less overall amplification when sounds and conditions are loud.
Directional microphones that improve the ability of the hearing aid user to understand conversation in background noise by reducing amplification for sounds coming from behind the listener and maintaining amplification of speech coming from the front. Some hearing aids can also be adjusted to reduce amplification for sounds coming from one side and maintaining amplification for speech and sounds coming the opposite side; this would be helpful in a situation such as traveling in a car.
Noise reduction circuitry that improves the user's listening comfort in louder environments by reducing amplification for pitches where constant noise is detected.
Automatic phone programs that "turn on" when the phone receiver is near and "turn off" when hanging up and moving away from the phone.
Circuits that recognize music and adjust the hearing aid settings for improved music sound quality.
Feedback cancellation circuits that monitor for hearing aid "whistling" and reduces, eliminates or prevents it.
Impact-noise sensors that reduce amplification for sudden loud sounds such as a door slam or a shout.
Wind-noise sensors that identify the presence of wind and actively reduce the loudness and annoyance of that signal.

Hearing problems in S/N hearing loss

Decreased audibility

Hearing impaired persons don't hear some sounds at all. Individuals with severe / profound sensorineural hearing loss may not hear speech sounds at all. For them to hear speech sounds they should be shouted at a close range. Persons with mild to moderate hearing loss could hear some sounds but not the others. Classically softer phonemes (usually the consonants) may not be heard at all.

These patients also have trouble in understanding speech because essential parts of some phonemes are not audible at all. In order to recognize speech sounds, the auditory system needs to determine which fequencies contain the most energy.

The vowel oo is differentiated from the vowel ee by the location of the second most intense region (i.e. the second formant). If the hearing loss involves the frequency where the second most intense region is present then both these vowels would sound identical to the patient. Both these sounds are heard but cannot be differentiated into two different sounds (Fig 1).

High frequency components of speech are weaker than that of low frequency components. In 90% of adults and in majority of children the degree of hearing loss extends from 500 Hz to 4 KHz. Commonly hearing impaired people would miss out on the high frequency information. It must also be stressed that the loudness of the speech generally originates from the low frequency components. These patients will hence say that the speech is loud enough, but is not clear.

In order to overcome this problem the hearing aid should amplify the weakest component of the speech and also the the frequencies at which the hearing loss is the greatest.

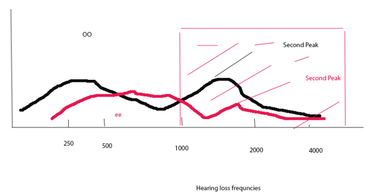


Image showing two peaks for two vowel sounds i.e. OO (Black curve) and EE (Red curve). Red box indicates the frequencies involved in hearing loss. It becomes difficult to hear the second peak and hence these two vowels will not be differentiated.

Figure 1 showing two peaks of vowels OO and EE.

The selection of appropriate hearing aid should involve adjusting the amount of gain provided at each frequency.

Decreased Dynamic Range

Soft / weak sounds can be made audible simply by amplifying them. It should be pointed out that it is not appropriate to amplify all sounds by the same amount that is used to amplify the soft sounds. Sensorineural hearing loss increases the threshold of hearing much more than it increases the threshold of loudness discomfort. In patients with mild / moderate hearing losses there is likely to be very little increase in loudness discomfort level, even though the threshold for hearing has increased by a value up to 50 dB.

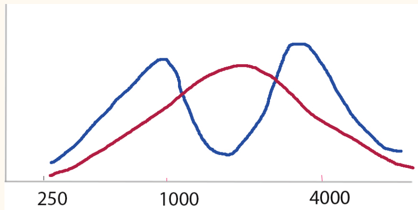
The dynamic range of the ear with sensorineural hearing loss (the amount by which the discomfort threshold exceeds the threshold of audibility) will be less than that of the normal hearing ear.

Dynamic range compression is a concept in audio signal processing that reduces the volume of loud sounds / amplifies quite sounds thereby reducing or compression the audio signal's dynamic range.

Decreased frequency resolution

Patients with sensorineural hearing loss have difficulty in separating sounds of different frequencies. It should be noted the different frequencies are sensed by different regions of cochlea. In normal persons a narrow band sound (sound which concentrates power within a restricted range of frequencies) produces a clearly defined region of relatively strong vibration centered at one position of basement membrane, causing a clearly defined region of activity within the auditory cortex.

In the presence of background noise that contains some energy at the frequency close to one of the components of speech sound, normal ear can do a great job of sending seperate signals to the brain, one for each region of intense activity in the cochlea. (Fig 1.1) The brain can consider all the spatial information that it is getting, as well as visual information about the context of the message (if it is speech) and could ignore the background noise. The ear has frequency resolution that is precise to enable brain to separate speech from noise, provided the speech component and the noise are sufficiently separated in frequency.



Blue cure showing two peaks the first one belongs to noise spectrum and the second peak belongs to the speech spectrum. (Normal hearing).

Red curve which has merged the two peaks as they cannot be differentiated this happens in a deaf ear.

Figure 1.1 showing the response of normal ear when speech is heard along with noise (blue curve) and the response of a deaf ear (red curve) to the same.

Person with sensorineural hearing loss has decreased frequency resolution. The outer hair cells of the cochlea are known to increase the sensitivity of the cochlea for frequencies to which the corresponding part of the cochlea is tuned. Loss of outer hair cells will cause that portion of the cochlea to lose their amplifying ability, and the cochlea hence loses some of its frequency selectivity. Psycho acoustically, this shows up as flatter masking curves and tuning curves. This deficit causes a single broad region of activity in the cochlea rather than two separate regions (in the presence of noise and voice). This causes difficulty for the brain as it is unable to untangle the signal from that of noise.

The degree of reduced frequency selectivity, and its impact on understanding speech increases with the degree of hearing loss. It is also pointed out that even normal hearing people have poorer resolution at high intensity levels than at lower levels. People with hearing impairment (that too those with profound hearing loss) will have to listen at high levels if they are to achieve sufficient levels of audibility. They hence face difficulty in separating sounds, due to the fact that the cochlea is damaged and partly due to the need to listen the sound at elevated levels.

If the speech and noise are in the same frequency region and they happen to arrive from the same direction and get mixed together inside the hearing aid, there is no way the hearing aid could separate these two sounds to enhance intelligibility. The currently available hearing aids can only minimize the problems caused by decreased frequency resolution. This is usually done by:

1. Keeping noise out of the hearing aid by picking up the signal remotely and transmitting it to the hearing aid.

2. Using a directional microphone to emphasize wanted sounds coming from one direction / or partially suppressing unwanted sounds coming from other directions. This is commonly used in hearing aids where the sounds coming from the front of the person wearing the aid is emphasized more than that coming from other directions. This increases speech intelligibility quotient.

3. By providing an appropriate variation of gain with frequency so that the low frequency parts of speech or noise do not mask the high frequency parts of speech. Hence frequency regions dominated by noise are not louder than frequency regions dominated by speech.

Decreased temporal resolution:

This is a very general term. Intense sounds can mask weaker sounds that immediately precedes them or immediately follow them. This is known as temporal masking in lay terms. This tends to occur more commonly in patients with sensorineural hearing loss than those with normal hearing thereby affecting intelligibility of speech. The increased temporal masking is caused by impaired cochlea which is unable to increase its sensitivity after the masking sound ceases as it happens in a normal cochlea.

In real-life scenario noise tends to fluctuate rapidly, and normal hearing individuals can extract useful bits and pieces of information during the weaker moments of the background noise. This is known as listening in the gaps. Persons with hearing impairment lose this ability to hear during gaps in the presence of a masking noise. This is particularly true of elderly people. This ability to hear weak sounds during brief gaps in a more intense masker gradually decreases as hearing loss get worse. The common reason for decreased gap listening ability is that even the so called normal listeners lose some of gap listening ability as the signal to noise ratio increases. Increased signal to noise ratio is commonly needed for hearing impaired persons to understand speech.

There is another aspect of temporal resolution that is the ability to use the information contained within the cycle-by-cylce timing of the wave form at any point on the basilar membrane. This is also known as the temporal fine structure of the wave form. Those persons who are unable to sue it are also least able to understand speech during the gaps in a masking noise. This decreased ability to use temporal fine structure may be caused by reduced precision in the timing of neural firing.

Hearing aids can help a little bit in compensating for decreased temporal resolution ability. Fast acting compression, where the gain is rapidly increased during weak sounds and rapidly decreased during intense sounds will make the weaker sounds more audible in the presence of preceding stronger sounds and could make them slightly more intelligible. This can also make unwanted weak background noises more audible.

Physiology of hearing loss

Abnormalities occurring within the outer / middle ear can cause conductive hearing loss. These abnormalities include:

1. Atresia of external auditory canal

2. Perforated ear drum

3. Ossicular chain fixity / discontinuity in the middle ear

4. Fluid accumulation inside the middle ear following infections

Inside the cochlea the inner hair cells or outer hair cells or both could cease to function normally. This can occur in some portion of the cochlea or can cover the entire extent of the cochlea.

If only the outer hair cells cease to function normally, then thresholds of hearing are elevated, dynamic range of hearing is reduced, and frequency and temporal resolution are both degraded. If only the inner hair cells cease to function then thresholds of hearing is elevated, but frequency resolution remains normal or close to normal.

The timing of signals within the brain-stem could become less precise due to a reduced number of functioning inner hair cells or a reduced number of synapses connecting to each inner hair cell. When the inner hair cells cease to function then it is common for the spiral ganglion cells to which they are connected to die progressively during the course of six months.

Sometimes the hair cells could function sub-optimally because the cochlear battery (stria vascularis) generates insufficient voltage. Hearing loss caused by inadequate stria operation is called as strial sensorineural hearing loss.

Another cause of hearing loss within the cochlea is a change that occurs to the physical properties of cochlear membranes (increased stiffness / decreased stiffness) can cause cochlear conductive hearing loss. Any defect that interferes with the conversion of vibrations in the cochlea to nerve signals is known as sensorineural hearing loss.

When the cochlea is normally functioning and there is a defect in the connection to auditory nerve or defective transmission along the auditory nerve, then the hearing loss is referred to as neural hearing loss. When the outer hair cell functions normally, and either the inner hair cell of their connection to the auditory nerve, of the auditory nerve itself are defective. This defect is known as the auditory neuropathy spectrum disorder. This condition is common in children who are born with the condition or due their spending long duration in neo-natal intensive care unit.

If the inner hair cell in some region of the cochlea completely stops functioning and ceases transmission of information to the auditory nerve then that portion of the cochlea is known as the dead region. Tests to detect these dead regions are available.

Sensorineural hearing loss is considered to be mostly caused by defective Inner hair cells / outer hair cells function and should ideally be called as sensory hearing loss. But it is commonly termed as sensorineural hearing loss as there could be associated deficit in auditory nerve conduction because of loss of synapse in the spiral ganglion. Causes of hearing loss has been simplified under three categories:

1. Conductive hearing loss

2. Sensorineural hearing loss

3. Auditory neuropathy spectrum disorder.

Hearing deficits that occur in combination

The various aspects of hearing loss which include:

Decreased audibility

Decreased dynamic range

Decreased frequency and temporal resolution

Occurrence of dead regions

They all cause a reduction in intelligibility of sound. Any combination of these can cause a hearing impaired person to understand much less than a normal hearing impaired person to understand much less than a normal person. A hearing impaired person needs a better signal to noise ratio for speech understanding than normal person.

Signal to noise ratio deficit can occur in auditory processing disorders. These disorders include disorders of brain-stem, mid-brain, or auditory cortex and can exist independently of any peripheral hearing loss and can be a consequence of impaired cochlea sending deficit signals to the brain-stem.

One of the auditory processing disorder that has been studied extensively is the ability to separate a target from competing speech on the basis of direction of arrival. The deficit in signal to noise ratio observed in hearing impaired persons is much greater when the target speech and the competing sounds are spatially separated, and they all come from the same direction. This is known as spatial processing disorder.

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