OPEN ACCESS GUIDE TO AUDIOLOGY AND HEARING AIDS FOR OTOLARYNGOLOGISTS

FITTING HEARING AIDS: TECHNICAL ASPECTS

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This is the 1st of two chapters on hearing aids. This chapter discusses the technical aspects; the 2nd chapter deals with practical aspects of fitting hearing aids.

Major technological advances in hearing aids and development of hearing instrument technology have led us into the modern era of integrated and digital hearing aids.

Research on digital hearing aids had started by the 1960s. In 1996 the first fully digital hearing aids became commercially available, with a variety of hearing aids in terms of size, placement, amplification, technology and cost. Today most hearing aids manufactured are digital.

The integrated circuit and digital phase also saw the manufacturing of open canal hearing aids, which led to the introduction of receiver-in-the-canal/ear (RIC/RITE) hearing aids. Nowadays technologies such as Bluetooth and wireless signal transmission are incorporated into hearing aid technology, providing more connectivity and communication options for people with hearing loss.

Hearing Aid Circuitry and Technology

Types of amplification used in hearing instruments are divided into 3 categories *(Table 1)*:

1. Analogue technology (linear vs. non-linear amplification)
2. Digitally programmable
3. Digital technology

ANALOGUE TECHNOLOGY

Linear amplification
- Conventional, more basic technology
- All sound (speech frequencies) receive same amount of amplification

Non-linear amplification
- Makes soft sounds louder
- But does not amplify loud incoming sounds

Advantage: Less costly technology

DIGITALLY PROGRAMMABLE TECHNOLOGY

- More sophisticated technology
- Hearing aids connected to computer so that 1-4 programs programmed/selected for different listening situations
- Some have only one program that adapts automatically to different situations e.g. by Peak Clipping
- Often >1 microphone to ensure better speech intelligibility in noisy situations

Advantages
- Can adapt to auditory surroundings
- Speech better understood in noisy background

DIGITAL TECHNOLOGY

- Most advanced technology
- Microchip in hearing aid does millions of calculations/second
- From these calculations, it determines how much amplification is needed to ensure a comfortable, audible sound
- Background noise automatically less amplified
- Technology available in 1 program which adjusts automatically, or in 4 programs controlled by user
- Omni-/directional microphones available

Advantages
- Very natural sound quality
- Optimal amplification of speech ensures better speech intelligibility in background noise
- Less chance of acoustic feedback

Table 1: Three different hearing aid circuits and technologies

1. *Analogue technology*

The *World Health Organisation (WHO)* has guidelines for the preferred profile for hearing aid technology suitable for low and middle-income countries (WHO, 2017).

Even though digitally programmable and digital technologies are currently mostly used in hearing aid technology, it is essential to have knowledge of the more basic analogue technology. Not only does it help the clinician to understand where more advanced technologies originated from, but knowledge of these technologies also assists the clinician to provide support to patients still using older technology. Many developing countries still use older technology as access to computers is limited.

The word "analogue" means "similar" or "equivalent". Analogue hearing aids convert sound waves into electrical waves. The incoming acoustic signal or sound wave is converted into electric current by a microphone. The current is then modified in the amplifier and reconverted by the receiver into sound *(Figure 1)*.

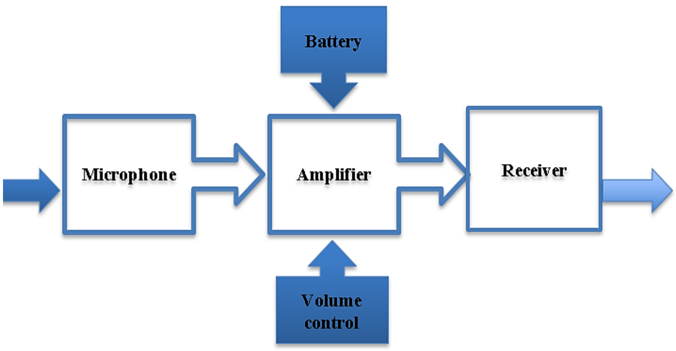


Figure 1: Analogue technology

When a sound signal is transformed from an airborne signal to an electrical analogue signal, the characteristics of the signal remain unchanged. These electrical waves can be modified in a number of ways to accommodate specific hearing losses; this is achieved with filters/trimmers.

Two types of analogue circuitry exist:

- Linear amplification
- Non-linear amplification

Linear amplification: Linear amplification occurs when the ***same preset amount of amplification*** is added to all incoming signals (1:1), regardless of the loudness level of the incoming sound. The amount of amplification is calculated to amplify the incoming signals to such a level that the hearing aid user can hear speech clearly in the ideal listening environment (with no or little background noise). The disadvantage of this kind of amplification is that the softer incoming sounds usually are not amplified enough, while louder incoming sounds are often amplified too much. Peak clipping often has to take place to compensate for these loud sounds, which results in distortion of the final (amplified) outgoing signal.

Non-linear amplification*:** The amplified sound with non-linear technology is usually a more pleasing sound than the sound produced by linear amplification. With non-linear amplification, a ***fixed knee-point attempts to make soft sounds louder, but not to amplify loud incoming sounds *i.e.* softer incoming sounds are amplified more while louder sounds are less amplified. The amount of amplification is adapted according to the intensity of the incoming sound. Up to the kneepoint, the same preset amount of amplification is added to the incoming signal, but once the kneepoint is reached the amount of amplification added to the incoming signal is modified *(Figure 2)*.

Non-linear amplification aims to compensate for factors such as loudness recruitment in hearing-impaired people and is also safe in terms of possible over-amplification, because the loud incoming sounds do not receive too much amplification. The distortion resulting from peak clipping is also less with linear amplification than non-linear amplification.

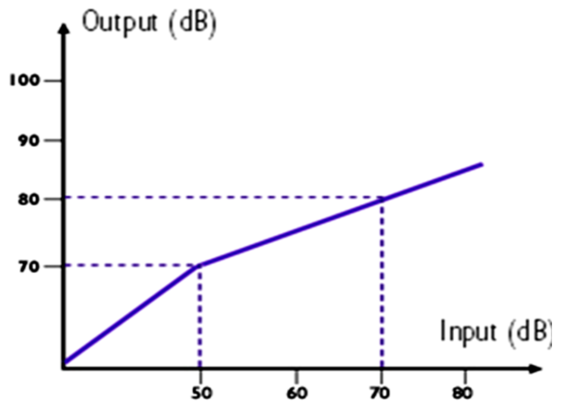


Figure 2: Kneepoint adjustment to hearing aid

2. *Digitally programmable*

These are analogue hearing aids that are fitted and finetuned with the assistance of a computer. The processing of the hearing aid, however, is still analogue – the word "digital" refers mainly to the computer to which the hearing aid is connected during the fitting and finetuning process. In other words, the digital component is purely for programming and reprogramming the parameters of the hearing aid, as illustrated in *Figure 3*.

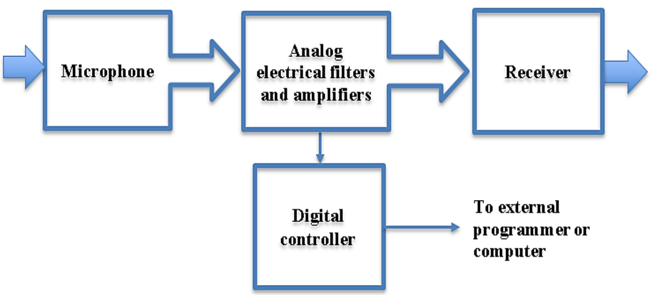


Figure 3: Digitally programmable

Instead of setting trimmers, the frequency response, gain, maximum output and compression parameters of digitally programmable hearing aids are set by attaching the hearing aid to a computer with a cable, or wirelessly. The hearing aid contains a memory chip with selected settings. This component does not perform any signal processing, but only adjusts and stores the control settings.

This type of setting process allows increased flexibility and ease of fitting the hearing aid, but does not necessarily result in improved sound quality. Because the settings of digitally programmable hearing instruments can be manipulated using a cable connection to a computer or a special programming device, several of the hearing aid parameters can be changed and compared simultaneously by the mere press of a button. The possibility of switching instantaneously from one setting to another allows the wearer to judge which setting is the most suitable for a specific situation *e.g.* understanding speech in noise. The various settings can also be stored digitally in the hearing instrument or in a remote control unit and later selected by the user to suit the listening situation.

Digitally programmable hearing aids thus provide more sophisticated technology, different programs for different listening conditions, and more audible speech perception in the presence of background noise.

3. *Digital technology*

Digital hearing aids convert sound waves to a digital (numerical) signal, like what computers use. Because of the precision of digital signals, the sound can be duplicated with much more accuracy. A microchip (microprocessor) processes this information using exact mathematical calculations, resulting in much more flexibility in fitting and fine-tuning. The components of a fully digital hearing aid are illustrated in *Figure 4*.

The 1st and last stages depicted in *Figure 4* are common to all types of hearing aids. However, the intermediate stages are unique to digital systems. These are the Analogue-to-Digital Converter (ADC), the microprocessor and the Digital-to-Analogue Converter (DAC). With digital hearing aids, the acoustic signal therefore must first be converted into a form that can be manipulated by the computer to be proces-sed and finally reconverted back to an acoustic signal.

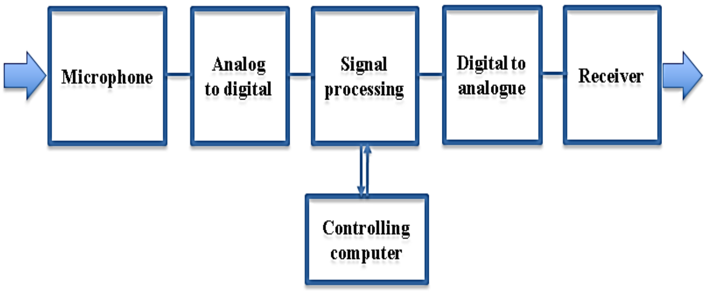


Figure 4: Digital technology

The specific stages followed by digital hearing aids are:

- Incoming sound wave (acoustic signal) converted by microphone into electrical (analogue) signal
- Analogue-to-Digital Converter (ADC) creates digital representation of original electrical (analogue) signal, in order to generate a configuration that can be operated by the microprocessor
- Microprocessor processes the signal, using various algorithms, *e.g.* filtering, noise reduction or speech enhancement (digital signal processing)
- Digital-to-Analogue Converter (DAC) creates electrical (analogue) signal from digital output of microprocessor
- Amplifier amplifies thesignal, which is then reconverted into a sound wave by the receiver and delivered to the human ear

Benefits of digital processing

- Because digital processing allows for more complex and detailed operations, the same hearing aid can be fitted for many different hearing loss configurations
- By translating sound into numerical values and by doing complex mathematical calculations, digital hearing aids provide a better sound quality than any other type of technology
- Digital hearing aids can be customised to suit different hearing loss requirements and specific personal needs
- Digital technology allows production of smaller hearing aids than previously possible with analogue technology

Basic components of a hearing aid

Hearing aids contain a large number of electronic components and controls. The ***main components*** are *(Figure 5)*:

- Input transducer (microphone, telecoil, direct audio input)
- Amplifier
- Receiver (loudspeaker)
- Battery

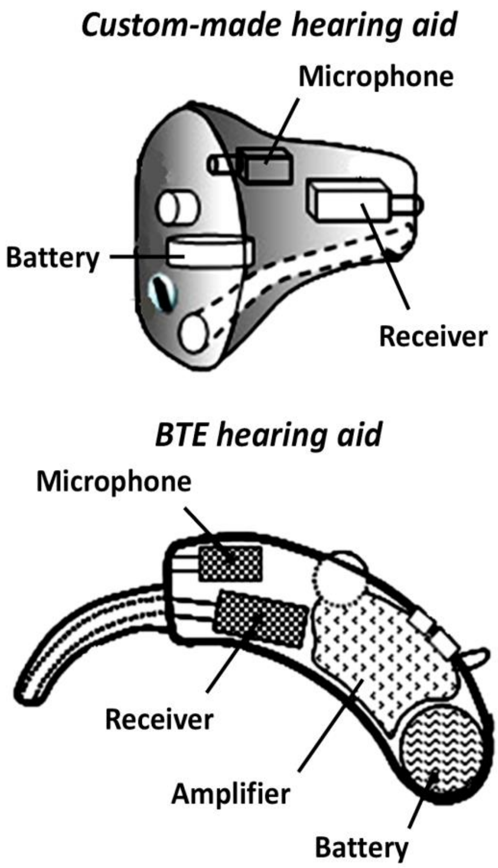
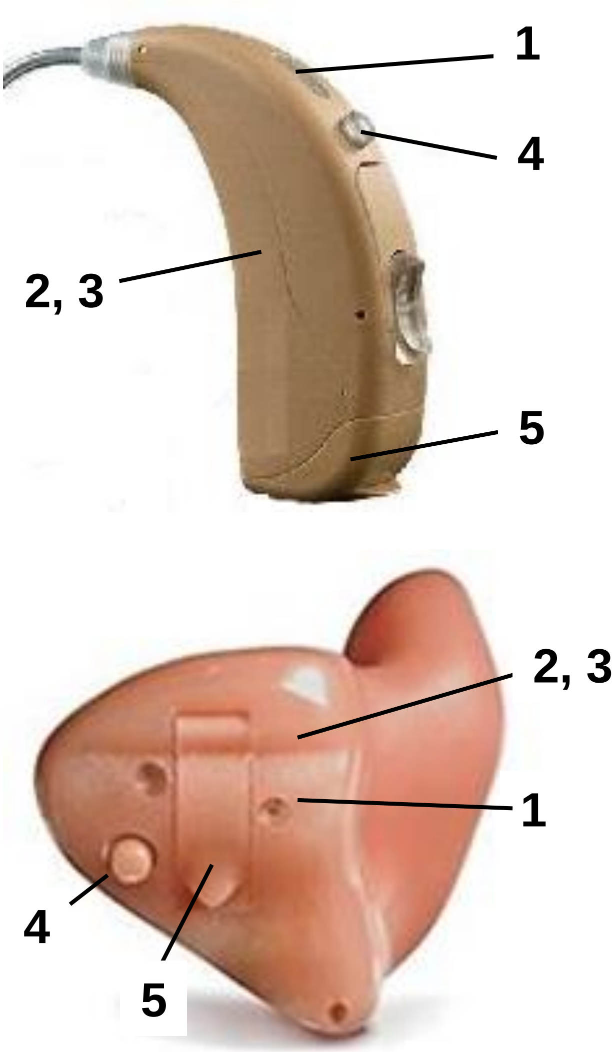


Figure 5: Custom-made and Behind-the-Ear (BTE) hearing aids

How does a hearing aid work? *(Figures 5, 6)*



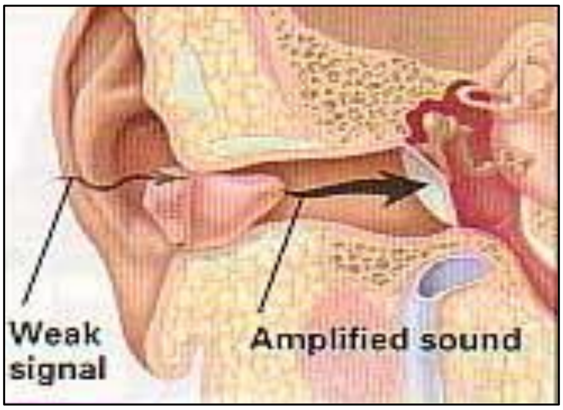


Figure 6: Workings of Behind-the-ear (BTE) and Custom-made hearing aids; The microphone or input transducer (1) picks up the sound and sends it to the amplifier.

The amplifier (2) makes the sound louder and sends the amplified sound to the receiver. The receiver (3) sends the amplified sound into the ear canal. The volume control (4) adjusts loudness. The battery (5) supplies the power

Input transducer *(Figure 6)*

The purpose of the input transducer is to receive information from the environment and to produce a good frequency response and low distortion. The input transducer can be a

1. Microphone
2. Telecoil
3. Direct audio input (DAI): only available in Behind-the-ear aids (BTE's)

1. Microphone

The microphone converts the incoming sound wave energy into electrical energy. Since the frequency and intensity pattern of the sound waves represent coded information concerning the message, they must be duplicated as exactly as possible.

Omnidirectional microphone: Most microphones used in hearing aids are omnidirectional, and are equally sensitive to acoustic energy from 0^{o} to 360^{o} around the listener. They can provide low frequency amplification. However, they provide a reduced signal-to-noise ratio and are not very functional in listening conditions where directionality or localisation is required. Omnidirectional microphones are ideal for severe to profound hearing losses.

Directional microphone (Figure 7): To improve speech discrimination in noise, a directional microphone can be used in BTE hearing aids, where acoustic signals coming from behind the head (180^{o}) are suppressed (up to 20dB at certain frequencies).

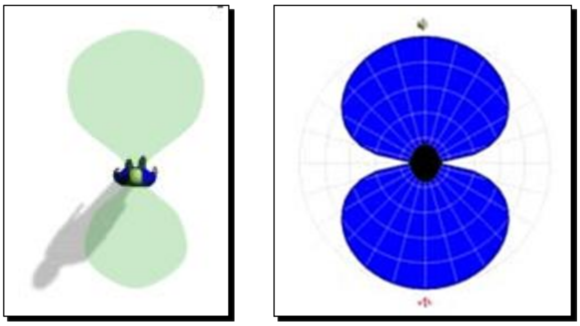


Figure 7: Multi-microphone

This improves a listener's ability to attend to the frontal sound source. Directional microphones provide improved signal-to-noise ratio as well as directionality and localisation in noisy listening situations. However, they often have reduced sensitivity at low frequencies when compared to omnidirectional microphones. Directional microphones are ideal for mild to severe hearing losses.

Multi-microphone system: Most hearing aid microphones pick up sounds equally from the front, sides and back. Multi-microphone systems are different. These systems contain both omni- and directional microphones, making switching between the two different microphones, as required by listening situations, possible. In situations where competing sounds are a problem, the directional mode of this microphone system allows full amplification of sound from the front, while providing less amplification of sounds from the sides and back. In environments where listening to sounds from all directions is required, the omnidirectional mode is more sensitive to sounds all around. Multi-microphone systems can be used with BTE's as well as with certain custom-made hearing aids.

Adaptive microphone systems: These are available in digital hearing aids. They provide the same functionality as multi-microphone systems, but are completely adaptive. These microphone systems will switch automatically between the omni-directional microphone and the directional microphone, depending on the listening environment. The directional microphone component can also adapt its directionality towards the primary sound signal (speech) in noisy environments, as it follows the direction of the primary sound source.

Different types of microphones are available (*e.g.* magnetic and ceramic types), but the *electret condenser microphone* is the one most commonly used. This microphone is more durable than the other types, and is less sensitive to hard impact, humidity and changes in temperature. The electret condenser microphone has a built-in low-noise preamplifier, a smooth frequency response and a low sensitivity to mechanical vibrations. This reduces acoustic feedback.

2. *Telecoil*

This is a simple coil on a soft iron core, and was originally introduced to hearing aids as a telephone aid and can be activated instead of the microphone with the M-T-O (Microphone-Telecoil-Off) switch or a dedicated programme on the device. The telecoil picks up a magnetic field (from a telephone or induction loop system in a room) and converts it by means of induction into electrical energy to be amplified by the hearing aid amplifier.

3. Direct Audio Input (DAI) *(Figure 8)*

An audio input system using an electrical input connection (FM-radio or infrared transmissions) directly on the hearing aid, is often used in educational situations. An input signal is received from an audio shoe which snaps over the bottom part of the hearing aid *(Figure 8)*. The input signal is provided via a 2-pin/3-pin cord, which plugs into the bot-tom of the audio shoe. In this way, a good sound quality can be obtained and interference from background noise is limited, especially when there is a relatively large distance to the sound source.

Figure 8: Direct Audio Input (DAI)

Amplifier *(Figure 6)*

The weak signal generated by the microphone or telecoil is fed to the amplifier, which amplifies the intensity of the original low-energy signal into a powerful electrical signal (increases the voltage amplitude).

Receiver *(Figure 6)*

The function of the receiver is exactly opposite to that of the microphone. Whereas the microphone converts acoustic energy to electrical energy, the receiver transduces the amplified electrical impulses or signals back into acoustic energy / sound waves.

Battery *(Figures 6, 9)*

The battery provides the energy for the hearing aid and makes amplification of the acoustic signal possible. Different sizes (10, 13, 312, 675) and types of batteries are available. The output produced by the amplifier of a hearing aid determines the battery drain. Although battery drain cannot always be exactly specified, hearing aid manufacturers always specify in the products' specification sheets what battery drain can be expected from a hearing aid.

Figure 9: Batteries

Zinc air batteries are the most commonly used disposable type because of long lifespan, high energy density and low environmental impact of used batteries.

Mercury or silver oxide batteries are still used in some countries for extremely powerful or heavyduty hearing aids, although modern highpower zinc air batteries can also supply sufficient power for these hearing aids.

Alkaline batteries are used with body-worn instruments and hearing aid remote controls

Rechargeable batteries are also used in hearing instrument technology for reasons of cost and convenience. Various rechargeable units are commercially available. These include nickel-cadmium (NiCd) Zinc-Ion, and nickel-metal hydride (NiMH), batteries. NiMH is more environmentally friendly and does not build up a memory effect which could potentially decrease the daily longevity of the battery. Most rechargeable systems nowadays have built-in power supply units through which the entire hearing aid unit is charged, although some batteries are charged separately.

Electroacoustic characteristics of hearing aids

Each individual hearing aid has a specific set of characteristics which makes an instrument suited to a patient's specific audiogram and personal needs. The most impor--tant of these physical characteristics are:

- Output
- Gain
- Frequency response

Output

Output is often referred to as the maximum power output (MPO) on hearing aid specification sheets. The MPO is also known as the SSPL (Saturation Sound Pressure Level). Output is expressed as a number that is within the applicable measurement standard *e.g.* ANSI or IEC Standards. The output of a hearing aid can be thought of as the ceiling up to which the hearing aid provides amplification. Amplification beyond this point is not possible due to output limiting systems such as peak clipping (older hearing aid technology) or compression (newer technology) coming into effect when the gain of the hearing aid reaches this point.

Selecting appropriate output is a requirement for a proper fit. The output of a hearing aid should not exceed a patient's *Loudness Discomfort Level (LDL)* or *Uncomfortable Loudness Level (UCL).* Therefore, the MPO of a hearing aid is usually based on this score.

Gain

The number of dBs by which the output level of a device exceeds the input level is known as the gain that the hearing instrument provides ("dynamic range" of the hearing aid). The person fitting the hearing aid should select the appropriate gain by selecting the appropriate prescriptive fitting strategy. Typically, the goal is to provide enough gain to make normal conversational speech easy and comfortable to hear. Selecting the correct amount of gain for a hearing loss is not as straightforward as output.

Any gain calculating approach or prescriptive fitting strategy may be used, but always remember that the gain number represents 2cc coupler measurements and not insertion gain. A 2cc coupler refers to a sound chamber and serves as a substitute for the ear canal, providing a standard-sized cavity into which the amplification produced by the hearing aid is directed, and is a mechanical way to attach a microphone to the hearing aid. The coupler measures the inter-comparison of the hearing aids.

Frequency response

Frequency response is the output or gain curve produced by the acoustical 2cc coupler when the input signal is a sinus sweep with constant amplitude. It presents gain in terms of frequency in a curve form. In other words, this curve reflects the hearing aid's amplification abilities at different frequencies. This can be adjusted by the hearing aid fitter to set the hearing aid's gain at specific frequencies to match the patient's audiogram and needs.

Sound Delivery Systems

A sound delivery system couples the hearing aid to the patient's ear, and delivers the sound to the ear. The three types of sound delivery systems are:

1. Earmould
2. Slimtube and dome/slimtip
3. Shell

1. Earmould

An earmould is an individually fabricated ear insert that is coupled with the *Behind the Ear component* (BTE), and channels the sound produced by the BTE, via the ear canal to the eardrum. Several earmould types/styles are available to which many different modifications are possible to make the earmould best suited to a specific patient or a specific type of hearing loss.

For an earmould to be optimal it must
- Keep the hearing aid in the ear
- Retain the BTE component on the outer ear
- Provide a good acoustic seal to prevent acoustic feedback
- Appropriately modify gain, frequency response and output of the hearing aid
- Be comfortable to wear for extended periods of time
- Be cosmetically acceptable

The shape and style of the earmould is influenced by the
- Type and configuration of hearing loss (audiogram)
- Type of hearing aid prescribed
- Individual anatomy of the ear canal outer ear
- Impression taken (technique and impression material used)

When deciding on an earmould, the following parameters must be considered
- Earmould material
- Earmould style
- Canal length
- Ventilation tubing (venting)
- Special modifications

Earmould material: Three types of material can be used for earmoulds, namely acrylic, silicone and Egger/Dreve
- *Acrylic:* Most commonly used for earmoulds. Used for most patients and hearing losses, except infants and young children and profound hearing loss
- *Silicone:* Provides a soft earmould. Used for infants and young children, profound hearing loss and sometimes for the elderly
- *Egger/Dreve:* Is a hypoallergenic material, and is available in both acrylic and silicone

Earmould style: The style/type of earmould is determined by the audiogram, especially the low frequency thresholds (125-1000Hz). The more severe the hearing loss is in the low frequencies, the less open the earmould should be. For <60dB HL in the low frequencies, a skeleton mould *(Figure 10)* can be considered. Skeleton moulds are usually more comfortable and cosmetically more appealing. Hearing losses >60dB HL in the low frequencies require a full concha mould to better seal the ear and to prevent feedback.

Figure 10: Skeleton earmould

Canal length: Canal lengths are defined as long (16-22mm); medium (12mm); and short (6mm). Short canals favour high frequencies and provide gain for speech intelligibility. Longer canals favour low and mid-frequencies which provide overall gain in acoustic energy. Although it may be less comfortable, it provides a better seal for a more severe loss.

Venting: It becomes necessary to vent an earmould when low frequency thresholds are normal or near-normal. The wider the vent, the less risk there is of occlusion problems. A larger vent also allows for more low frequency sounds to escape, thus improving comfort for someone with normal low frequency thresholds. More severe losses need the low frequencies to be amplified, and there is also a risk of feedback. Therefore, a smaller vent or even no vent is better for more severe hearing losses. Vent sizes differ for each hearing aid manufacturer, but in general, vent sizes may be classified as:

- Large (3.0mm): for low frequency thresholds between 0 and 30dB
- Medium (2.5mm): for low frequency thresholds between 30 and 40dB
- Small (1.3mm): for low frequency thresholds between 40 and 60dB
- Comfort (0.8mm): for low frequency thresholds between 60 and 70dB

Tubing: Acoustically, the inner diameter of earmould tubing has a significant effect on sound transmission. Smaller diameter tubing can be used to reduce average saturation output and gain mid- and high frequencies, and is commonly used for mild-to-severe hearing losses. The wider the inner diameter of the tubing the more gain is achieved and the less risk there is for feedback, which is therefore ideal for more severe hearing loss. The most common tubing sizes used are:

- Paediatric/Small: Infants, and young children
- Medium/Thick: Most hearing losses and populations
- Thicker: Profound hearing loss

Special modifications: To achieve additional gain at certain frequencies, *Libby Horn* or *Cavity* earmould modifications can be considered *(Figure 11).*

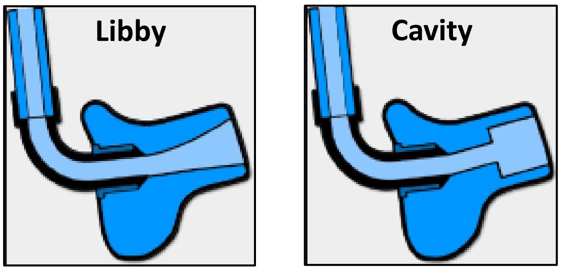


Figure 11: Libby Horn and Cavity modifications

With a *Libby Horn* modification, there is a gradual increase in the diameter of the canal portion of the earmould which provides more amplification over the whole frequency range. With a *cavity* modification, there is a sudden increase in diameter which gives more high frequency amplification.

2. *Slim tube and dome/slim tips*

Slim tubes and domes are used with open fitting hearing aids such as open canal and receiver-in-the-canal (RIC) hearing aids. These hearing aids do not have tone hooks or traditional earmoulds. Instead of a tone hook, a slim tube is attached to the hearing aid. A dome is fitted at the end of the slim tube to secure the slim tube in the ear canal. In the case of a RIC, the dome is fitted over the receiver at the end of the slim tube. If extra gain is required in the lower frequencies, a slim tip instead of a dome can be fitted to the slim tube. Occlusion is not a problem with open fittings.

Slim tubes and domes (Figure 12): Domes can be open or closed domes for both open canal or RIC hearing aids. *When to do open fittings?* Open fittings are indicated for adults with mild-moderate sloping hearing losses, but not for children or the elderly.

Select slim tubes and open domes when: Normal low frequencies, and sloping high frequency hearing loss from 1000Hz.

Select slim tubes and closed domes when: Low frequency thresholds are between 20 and 40dB and for sloping high frequency hearing loss from 1000Hz *(Figure 13).*

Figure 12: Slim tubes and domes

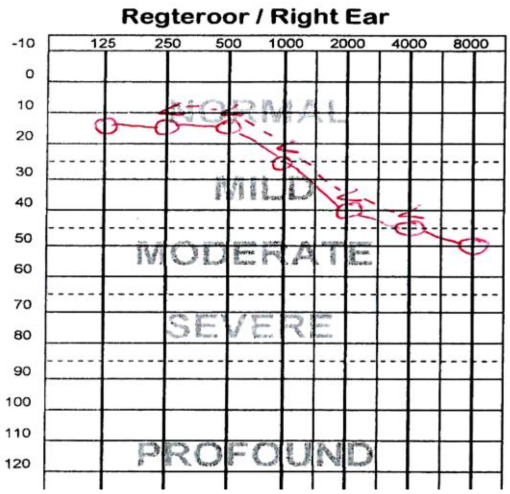


Figure 13. Audiogram specifications for slim tube fitting

Slim tubes and slim tips: A slim tip is an acrylic tip that is custom made from an ear mould impression to fit over the slim tube of open canal or the receiver of RIC hearing aids. It provides a larger fitting range than conventional domes. Acoustic parameters of slim tips as they fit into the ear canal are defined similarly to that of full ear moulds and are therefore no longer considered an open fitting, even though they are used with slim tubes attached to open-fit or RIC hearing aids. Venting might also be necessary (large vent when low frequency thresholds are 20 - 40dB and a medium vent when low frequency thresholds are between 40 and 60dB). ***Use slim tube and slim tips when low frequency thresholds are between 20 and 60dB and for sloping high frequency hearing loss from 1000Hz***.

3. Shell

The shell is the housing or 'ear mould' *of a custom-made hearing aid (Figure 14)*. The hearing aid and shell are one piece that is made to fit a specific ear. The style of the shell *i.e. Completely in canal (CIC) hearing aid*, *In the Canal (ITC)*, or *In the Ear (ITE) hearing aids (Figure 14)* depend on the strength of the custom-made hearing aid, the patient's needs and the ear anatomy.

Figure 14: Completely in the Canal (CIC) and In The Canal (ITC), and In the Ear (ITE) hearing aids

Vents are selected using the same principles as for BTE earmoulds. However, a different principle applies for choosing the canal length of the shell. If the low frequency thresholds in the audiogram are >60dB, select a long canal length as this prevents occlusion, as the canal of the hearing aid reaches the bony portion of the ear canal and reduces the occlusion effect. Choose a medium canal length when the low frequency thresholds are <60dB.

Types of Non-Invasive Hearing Devices

Hearing devices are classified as ***non-invasive*** and ***invasive*** hearing devices.

Non-invasive hearing devices are:

1. Body worn hearing aid
2. Behind-the-ear (BTE) hearing aid
3. Custom-made hearing aid *(Figure 14)*
4. Open-fitting hearing aid (Open canal/ RIC)
5. Bone conduction hearing aid
6. CROS and BiCROS hearing aid

1. Body worn hearing aid *(Figure 15)*

All the hearing aid components (microphone, battery, amplifier and telecoil) are contained in a large unit which is worn on the body from which leads an electric cord to the receiver worn in a custom earmould (through a ring-clip attachment).

Figure 15: Body-worn hearing aid

Body worn hearing aids are generally used for severe-to-profound hearing losses. However, they are seldom fitted nowadays. They might still be available in some developing countries, because of their robustness and because parts can more easily be replaced by the clinician.

Advantages: Body worn hearing aids provide more amplification than other hearing aids because the receiver is separated from the hearing aid by a cord. This reduces the risk of feedback, permitting more power to be utilised. The ear “probes” are available in standard sizes and are not customised. These aids are rugged, they use commonly available AA-size cells, or can used rechargeable batteries. In addition, the large controls are easy to handle for the very young/ old or the manually/visually disabled.

Disadvantages: Not commonly used, so repairs, clinician support and service can take longer. Cosmetically not good. The cord to the receiver is vulnerable. Very little amplification over 2500Hz, resulting in poor speech discrimination. "Clothes rub" noise. Unnatural microphone position.

2. Behind-the-ear (BTE) hearing aid *(Figure 16)*

Figure 16: Example of a Behind-the-ear (BTE) hearing aid

The body/housing aid fits behind the pinna, and sound is conducted to the ear canal via a plastic tube connected to an earmould.

BTE's are widely used and can be fitted for the majority of hearing losses.

Advantages: Cosmetically acceptable, robust, convenient, easy-to-handle, facilitates earmould hygiene. Wide variety of performance modifications possible by dispenser. Powerful amplification possible. Earmould modifications relatively easy. Provides access to auxiliary/educational equipment through audio input**.**

Disadvantages: Cosmetically less acceptable to some users. Fitting problems for some spectacle users and small/flat pinnae. Earmould tubing produces resonant peaks.

3. *Custom-made hearing aids*

These hearing aids are custom-made for each patient and are commonly used. Types of custom-made hearing aids include: *In-the-ear (ITE), In-the-canal (ITC)* and *Completely-in-the-Canal (CIC) (Figure 17)*

Figure 17: CIC, ITC and ITE custom-made hearing aids

The entire hearing aid is built into a custom-moulded shell, which either fits into the entrance of the ear (ITC), fills the concha (ITE) or fits completely into the canal (CIC). A variation of the concha model is the *"semi-concha"* or *"half concha"* model, in which the helix part (or most of it), is removed. A variation of the CIC model is the *"canal small"* (CS) or *"mini canal"* model, which is slightly bigger than the CIC, but smaller than the ITC. Unlike the CIC model, the CS model has room for user-operated controls. Canal type custom-made hearing aids, especially in their CIC format are the smallest type of hearing aid available. Currently an ever-smaller size custom-made hearing aid is available, namely the *Invisible-in-the-canal* (IIC) hearing aid. These are deep-fitting hearing aids which assist with relieving the occlusion effect experienced by patients with normal or near-normal low frequency thresholds.

Custom-made hearing aids are suited to a variety of hearing losses, but the more severe the hearing loss, the larger the circuit and battery required and thus the larger the hearing aid needs to be.

Advantages: Cosmetically appealing. Preserves the pinna-effect. Receiver output closer to the eardrum. Improved high frequency amplification resulting in better speech discrimination. Better hearing in noisy surroundings. Better resonance at 2000Hz. Facilitates telephone use.

Disadvantages: Less robust than the BTE – not suitable for users with dexterity/fine motor problems. Shorter life expectancy because of exposure to cerumen and moisture in the ear canal. Limited shell alterations are possible (especially CIC). Smaller custom-made hearing aids can be limited in their amplification, receiver output and battery life (smaller battery size). Occlusion effect can occur. Custom fitting often requires reshelling, because of changes in the ear canal size (especially with elderly clients). Not suitable for profound hearing loss.

4. *Open-fitting hearing aids (Open canal/ RIC)*

a. *Open canal hearing aids*

The open canal hearing aid keeps the ear canal open so that normal low frequency thresholds (which are found with sloping hearing losses) are not amplified by an earmould occluding the ear canal. It is commonly used for mild-moderate sloping hearing losses. It’s a type of BTE, but doesn’t use an ear-mould. It has a thin tube coming from the BTE, ending in an ear tip that is affixed in the ear canal *(Figure 18).*

Figure 18: Open canal hearing aid

Advantages: Cosmetically more discreet than traditional BTE. Less occlusion due to less sound pressure SPL at low frequencies in the ear canal. Ear’s natural resonance is maintained, therefore little insertion loss occurs. Improved high frequency amplification. Standard tube and tip sizes, thus less time spent on making and modifying ear-mould. Facilitates telephone use.

Disadvantages: Not suitable for all hearing losses (not appropriate for losses larger than moderate and lower frequency ranges). Feedback may be a bigger problem than with traditional BTE. Thin tube very small – not suitable for users with dexterity problems. Not suitable for people who struggle in noisy situations (open ear canal lets in noise).

***b. Receiver-in-the-canal (RIC) hearing aids** (Figure 19)*

RIC hearing aids are commonly used. The core components are mounted in the BTE housing, but the receiver is mounted on a soft tip or in a custom shell and is inserted via thin tubing into the ear canal. This thin tube contains wires that connect the BTE and “in the ear” (ITE) parts. It is also an open-fitting hearing aid, keeping the ear canal open, and is therefore suitable for mild-moderate sloping hearing losses.

Figure 19: Receiver-in-the-canal hearing aids

Advantages: Using an external receiver saves space in the BTE housing; thus, the hearing aid can be reduced in size. Less occlusion due to less SPL at the low frequencies in the ear canal. Ear canal’s natural resonance is maintained, thus little insertion loss occurs. Improved high frequency amplification. Standard tubes and tip sizes, thus less time spent on making or modifying an ear--mould. Facilitates telephone use.

Disadvantages: Not suited to all hearing losses; not appropriate for losses larger than moderate and for lower frequency ranges. Feedback may be a bigger problem than with traditional BTEs. Receiver and thin tube very small and not suitable for users with dexterity problems. External receiver is placed directly in the ear canal, exposing it to cerumen and moisture in the ear canal. Receiver and wires are handled daily, and these components are sometimes quite fragile and can easily be pulled apart. Not suitable for people who struggle in noisy situations as the open ear canal lets in noise.

5. *Bone conduction hearing aids*

A bone vibrator (receiver) is held in place on the mastoid bone behind the pinna by a headband or soft band (for children) providing adequate tension *(Figure 20)*. It is either connected to a BTE or body-worn hearing aid.

Figure 20: Bone conduction aid

Bone conduction hearing aids are suitable for individuals that are not candidates for traditional BTE or custom-made hearing aids *e.g.* with atretic ears and/or chronically infected ears. However, they are not that commonly used, as nowadays a candidate for a bone conduction hearing aid will rather be considered for a Bone-Anchored Hearing Aid (BAHA), whether it is through implantation or on softband (see Chapter on BAHA´s).

Advantages: Useful for conductive losses with good residual sensorineural hearing (when surgery is ruled out). Earmoulds not necessary (ideal for chronically infected ears and deformities such as partial or total atresia). Can be used for trial periods to determine candidacy for BAHA.

Disadvantages: Not commonly used, therefore repairs, clinician support and service can take longer. Cosmetically unacceptable. Headband often uncomfortable and painful when wearing for long periods. High frequency amplification not optimal.

6. *CROS and BiCROS hearing aids (Figure 21)*

Contralateral routing of signals (CROS) applications are used for unilateral hearing losses or single-sided deafness (SSD). The microphone (empty hearing aid case) is mounted on the side having the more severe hearing loss. The amplifier and receiver are mounted on the other ear (ear with normal hearing/mild hearing loss). The unit is placed behind or inside the poorer ear, and picks up sound and transmits it either via a cord or wirelessly to the better ear. The hearing in the good ear remains natural and completely unaffected.

Bilateral contralateral routing of signals (BiCROS) applications are used for asymmetrical hearing losses, such as a moderate hearing loss in one ear and a severe-to-profound hearing loss in the other. One unit with a microphone, amplifier and receiver and one unit with a microphone only are used to provide the user with an amplified signal from both sides. The unit with only the microphone is mounted on the poorer ear, while the unit with the microphone, amplifier and receiver is mounted on the ear with the moderate hearing loss. The unit placed behind or inside the poorer ear picks up sound and transmits it either via a cord or wirelessly to the better ear. At the same time, the hearing aid on the better ear also serves as an amplifier improving hearing in that ear.

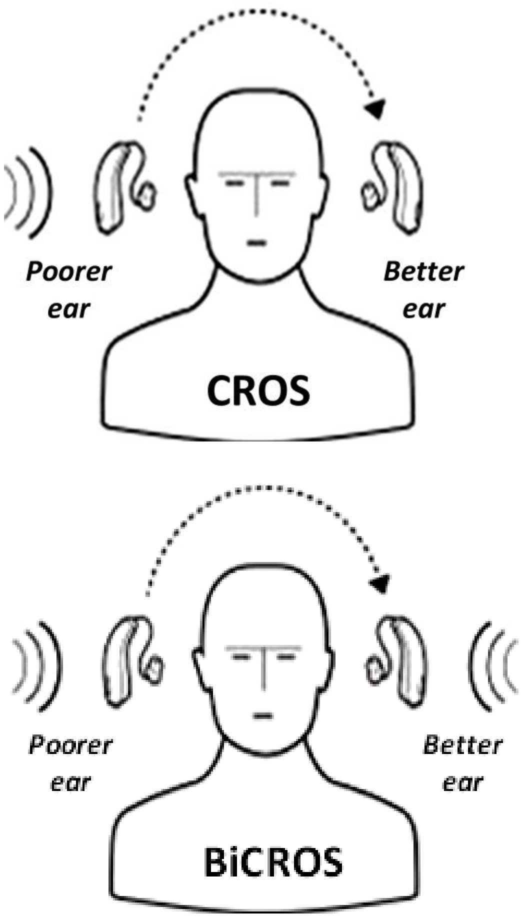


Figure 21: CROS and BiCROS

Controls and Functions of Hearing Aids

Sound delivered from a hearing aid can be controlled by adjusting controls which are set to ***determine the output, gain and frequency range*** that is effectively amplified. A substantial part of this adjustment is performed by the hearing aid fitter when fitting the hearing aid; these settings cannot be changed by the user. Some of the controls *e.g.* the volume control can be set by hand and thus be adjusted at the user's discretion.

The controls and functions are presented under the headings:

1. User operated controls
2. Dispenser operated controls

1. User operated controls

Volume control (VC) *(Figure 22)*

The VC can be analogue (round wheel) or digital (soft button or toggle). The patient uses the VC to set the hearing aid's volume in different listening environments or in accordance with personal preferences. However, not all hearing aids have a VC. The smaller the hearing aid, the less space is available for controls such as a VC. Hearing aids without a VC are usually equipped with preset automatic gain control (set by clinician during initial programming of hearing aid) that adjusts the volume automatically according to the incoming sound signal.

On/off switch

In older hearing aids, this is a tiny switch, mounted on the (BTE) hearing aid case – usually this is the M-T-O (Microphone-Telecoil-Off) switch found on the BTE hearing aid case. Newer generation hearing aids have the on/off switch integrated into the battery compartment. In other words, the hearing aid is switched on or off by opening or closing the battery door. If the hearing aid is equipped with a digital toggle, the toggle can also be programmed by the clinician to act as the on/off switch of the hearing aid, should the patient not prefer to use the toggle in another capacity *e.g.* as a VC or program selection switch.

Figure 22: Volume (VC) and program selection control (PS) of Behind-the-ear (BTE) and Custom-made hearing aids

Microphone-telecoil (M-T) switch

This is also known as the M-T-O switch. The microphone function is usually used, enabling the hearing aid to receive the signal from the microphone. Whenever the M-T switch is in the ***T-position***, the hearing aid receives the signal from a magnetic loop system (as used in some theatres, cinemas and churches). When the hearing aid is in the T-position, the microphone is usually disabled. However, some hearing aids have an ***M-T option*** where the microphone is enabled (either 25 or 50%) while the hearing aid is in the T-position (in digital hearing aids, the clinician can set the M-T function as such *e.g.* mT / MT). In this way the user can follow a conversation on the telephone via the telecoil, while still hearing others around him/her speak, the door bell or other important environmental noises.

With recent advances in hearing aids, the M-T-O switch has become outdated. The M-T switch is nowadays incorporated in dedicated programmes on hearing aids. Should a patient be in an environment where they can utilise the telecoil function, they can simply switch to that particular programme where the telecoil is activated. With newer generation hearing aids, should the telecoil function of the hearing aid be activated, the hearing aid will recognise if it is within a magnetic loop system and automatically switch to telecoil mode.

Program selection switch *(Figure 22)*

Certain multi-program hearing aids have a program selection button. This enables the user to select certain programmes according to their listing environment or preferences. These programmes are pre-set by the clinician and contain different combinations of acoustic parameter settings. These programmes can provide optimum listening for a particular user in specific listening situations.

Remote control *(Figure 23)*

In some cases, hearing aids have a remote control whereby the user can select either the volume or different programmes for various listening conditions. The transmission pathway from the remote control to the hearing aid is either based on infrared light, ultrasonic sound, radio waves or Bluetooth. By controlling the hearing aid with a remote control, a smaller and cosmetically more discreet hearing aid is possible. Also, patients with dexterity and visual problems are given access to larger controls. Some remote controls with screens can provide additional information to the user, such as battery status, current program selected and VC position. Recently hearing aid manufacturers have made available smartphone applications which can be downloaded on cellular telephones with which hearing aid settings can be adjusted.

Figure 23: Examples of remote controls

2. Dispenser operated controls

Most hearing aids have switches, trimmers and/or computer-operated digital memories which can be used by the service provider to adjust the hearing aid for the individual hearing loss. These controls are used to set the maximum output, to pre-set gain, compression (automatic gain control) and amplification of low or high tones. Dispenser operated controls include the following:

- Preset gain control
- Filters
- Peak clipping (PC)
- Output control
- Automatic gain control
- Wide dynamic range compression

Preset gain control

The preset gain is adjusted to a position to give the user the most suitable operating range for the volume control. It is especially useful in children and for adults who have difficulties when adjusting the volume control. Maximum gain is also limited to avoid feedback (whistling) in more powerful hearing aids. A hearing aid with a preset gain function can be adjusted to reduce the maximum gain by up to 20dB.

In a multiprogram hearing aid the preset gain control can also be used to equalise the balance for different programs. Binaural loudness balance is also created by means of the preset gain control for when the ears have different hearing losses or are fitted with different hearing aid models.

Output control

When used alone, the output control normally introduces some sort of distortion. Therefore, when output control is used to reduce the output of a hearing aid, it is normally used in conjunction with *Automatic Gain Control* (AGC) (see below) to minimise distortion. The combination of these two functions is considered the best way to reduce the output of a hearing aid.

Automatic gain control (AGC) (Figure 24)

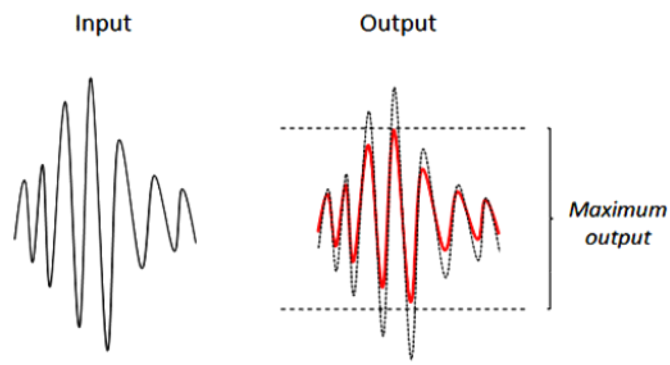


Figure 24: Automatic gain contol

This refers to compression. Originally compression was developed as a means to compensate for recruitment, by compressing the large amplitude variation of daily sounds into the more narrow dynamic range of an impaired ear. Compression is often referred to as automatic gain control (AGC), because it changes the gain of the hearing aid as the input intensity changes. AGC automatically adjusts the gain of the hearing aid to prevent the sound from being too soft or too loud. It is especially implemented in the presence of loud sounds, so that the patient's tolerance for loud sounds is not exceeded. By using compression, the hearing aid user is does not need to reduce gain (and make soft speech sound inaudible) in order to avoid a few intense sound impulses from becoming uncomfortably loud.

Up to a certain point (known as the ***knee-point of the input-output chart***), the gain is linear and an increase of 1dB input would result in a 1dB increase in output *(Figure 2).* Beyond the knee-point, the gain is non-linear *e.g.* a 1dB increase in input may only result in a 0.5dB increase in output. This would be a compression ratio of 2:1. Compression hearing aids have a variety of compression ratios, as illustrated below.

Wide Dynamic Range Compression (WDRC)

It is often the case that a person with a hearing loss has a faster-than-normal growth of loudness perception. A simple way to slow down the growth in loudness perception is to reduce gain on the instru-ment, as input increases. A hearing aid should provide enough gain so that the least intense "meaningful" sounds, are still audible. Therefore gain reduction should occur immediately above that level. Gain reduction will occur above the point (low compression threshold) at a rate (compression ratio) determined by the comfort level of the hearing impaired ear. With WDRC low level inputs (below 40 to 50dB SPL) are amplified more than high level inputs.

Other modern advances in hearing aid technology

Modern hearing aid technology also introduced other advances in hearing aids. These advances don't necessarily affect the way in which the incoming signal is processed by the digital hearing aid, although some of these advances may also affect the hearing aid's signal processing. Rather, many of these advances are implemented in hearing aids or hearing aid accessories for the convenience or benefit of the hearing aid user and/or clinician.

Open platform

Traditionally, digital signal processing (DSP) microchips in hearing aids are "hardwired" for a set of signal processing algorithms that are set before the hearing aid leaves the manufacturing facility. With open platform technology, however, the manufacturer or clinician can choose the software to be downloaded to the hearing aid. Should newer software or algorithms *e.g.* updated feedback cancellation algorithms, be available within a specific hearing aid brand, the hearing aid can be updated with the newer software/algorithm, without having to exchange the hearing aid for a newer model. This feature adds flexibility and convenience for clinicians when fitting hearing aids. Some manufacturers, on the other hand, choose to have a closed platform, meaning that if newer software or algorithm updates become available the patient must upgrade the hearing aids to newer models.

Rechargeability

In a technological world that demands plug-and-play functionality, the ability to "charge and go" has become a non-negotiable requirement, as it has with modern electronics such as cell phones, laptop computers, tablets, digital cameras and MP3 players. Rechargeability of hearing instruments has therefore become one of the most highly ranked requirements for hearing aid users, because of convenience and flexibility.

Two rechargeable options are currently available:

The first is where the ***entire hearing aid is placed in a charging case to recharge the battery*** *(Figure 25).*

Figure 25: Example of entire hearing aid unit placed in a charging case to recharge the battery

The hearing aid unit is typically placed in the charger to be recharged for a few hours overnight, allowing 15 to 18 hours of wear time the next day. The battery in these rechargeable hearing aids can last for up to 5 years, thus saving the hearing aid user the cost of disposable batteries over this time. However, the hearing aid user can still use disposable zinc air batteries in these hearing aids, should they choose to do so. Rechargeable hearing aids have the advantage of freeing people with dexterity problems from the need to change batteries. Other advantages include drying the hearing aid while charging (charging case is a charger and drying kit), as well as protecting the environment from discarded batteries.

Another rechargeable option for hearing aid users, are hearing aids that can operate with ***rechargeable batteries***. Only the batteries are recharged and not the entire hearing aid unit. A battery charger is used that can plug into a standard wall outlet, computer or even a car adaptor. Battery chargers are small enough to carry in a handbag or a pocket, making it convenient and travel friendly. An advantage of rechargeable batteries is that hearing aid users can still substitute conventional batteries if they lose or damage the rechargeable batteries. Like the batteries found in rechargeable hearing aid units, rechargeable batteries also offer a greener solution than conventional disposable batteries.

There are also now ***solar powered hearing aids*** or ***solar powered batteries*** for hearing aids. Solar powered hearing aids are provided with a case which includes solar cells *(Figure 26)*. Solar batteries are available that last 2-3 years and can be used in 80% of hearing aids on the market today. They can be charged by sunlight, household light, or a cell phone plug.

Figure 26: Example of a solar powered charger (Solar Ear)

Binaural hearing aid systems

Binaural hearing aid systems, better known as ***ear-to-ear communication*** or ***e2e***, allow real-time cooperation between the left and right hearing aids through a wireless link such as short-range radio waves. The e2e hearing aids analyse sounds in the environment, automatically share information, and switch modes and programs simultaneously when a change in environment is detected. The first binaural hearing aid systems only had e2e control, where a change made in the settings by a remote control or buttons on either hearing aid was simultaneously made to the other hearing aid. Nowadays binaural hearing aid systems have e2e processing, which means that all digital signal processing (DSP) operations, such as compression, noise reduction and directional beamforming happen simultaneously in the left and right hearing aids – thus all functions within the hearing aids are synchronised. A pair of hearing aids can therefore be considered as a single system, rather than two separate hearing aids.

E2e communication helps facilitate binaural hearing. Binaural hearing is hearing with two ears and then constructing one concept of what has been heard. This is advantageous – compared to listening with one ear only (monaural hearing) – especially when differences exist between the signals for the two ears. The binaural hearing advantages of e2e communication are greatest in complex and dynamic listening environments such as restaurants, cars and large groups.

Connectivity

Because wireless digital technology has become universal in consumer electronics, the introduction of wireless digital technology is expanding hearing aid fitting possibilities and the way patients can connect to external devices. Wireless digital technology is embedded in electronic products, making them easier to connect with hearing aids wirelessly. Bluetooth has become a standard that manufacturers have agreed to use when they digitally transmit their audio. This allows other products with a Bluetooth receiver to pick up the transmitted audio and play it without any specialised design requirements. A single Bluetooth receiver in or attached to a hearing aid can receive sound from a variety of sound sources, such as televisions, radios, cell phones, MP3 players and personal computers.

Bluetooth technology is currently too bulky to be incorporated in hearing aids. Advances in decreasing the chip size and power consumption of Bluetooth technology may allow for future Bluetooth receivers to be embedded in all hearing aids. Meanwhile, hearing aid manufacturers are creating Bluetooth accessories that plug into a BTE hearing aid direct audio input, or that one can communicate wirelessly with the hearing aid. These accessories can connect via Bluetooth with a variety of electronic devices, thus indirectly connecting these devices with the hearing aid.

Another application of Bluetooth technology in the hearing aid industry, is fitting and programming of hearing aids. Bluetooth is already being used to replace programming cables used to program hearing aids. This device uses Bluetooth technology and communicates to a Bluetooth receiver/ transmitter that is in the computer or attached to the computer via an external emulator. This allows the patient to walk or move around freely inside or even outside the clinician’s room to test the effectiveness of hearing aid programs, without having to disconnect the hearing aids from the programming module. If further changes need to be made to hearing aid settings, there is no need to reconnect the hearing aid as it is still connected to the programming module.

Water/dustproof hearing aids

A feature patients increasingly request is hearing aids that are water- and dustproof. For hearing aids to be classified as water-and/or dustproof, they need to adhere to the *Ingress Protection (IP) classification system*. Some hearing aids have an IP rating of IP68. These hearing aids are dust tight and waterproof, and are ideal for people who spend time working in a dusty environment, and for sporting activities, showering, swimming, working out in the gym *etc*.

Mobile applications

A recent development are mobile applications ("Apps") that focus on hearing loss and hearing aids. Many hearing aid manufacturers recently introduced or are currently working on applications that can be installed on smartphones with which hearing aid settings can be adjusted and even saved for a specific location using GPS function of the smartphone (geotagging). Mobile applications are another way in which modern technology is integrated with hearing aid technology, making hearing aids more convenient and flexible.

Suggested reading

Resource for hearing-aid technology suitable for low- and middle-income countries
http://apps.who.int/iris/bitstream/10665/258721/1/9789241512961-eng.pdf?ua=1

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