Electronic aids to hearing

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Despite many scientific advances in the biology of hearing, there remain no wide-spread medical or surgical interventions for listeners with sensorineural hearing impairments. The provision of amplification and associated rehabilitation remains the only effective intervention available for sensorineural hearing loss. It is also effective for conductive hearing loss when surgical intervention to improve hearing (and medical intervention to eradicate pathology) is either not appropriate or not available. There is a danger when concentrating on ‘advances and developments’ to place too great a focus on advances in the technological content of amplification devices at the expense of the rehabilitative context within which those devices are embedded. In addition to describing technical advances, this chapter identifies important aspects of candidature for hearing aids and some issues of service delivery. Here ‘electronic aids to hearing’ includes assistive listening devices and communicators as well as head- or ear-worn personal amplifiers (hearing aids) whether they be of a conventional air-conduction, bone-conduction or implantable configuration. Cochlear implants are covered elsewhere (see Ramsden, this volume).

Hearing aids may overcome some, though not all, of the deficits associated with a hearing loss. Some sounds are inaudible, while others can be detected because part of their spectrum is audible, but may not be correctly identified because other parts of their spectrum (typically the high-frequency parts) remain inaudible. The dynamic range between the weakest sound that can be heard and the threshold of discomfort is less for a person with sensorineural hearing loss than for a normal-hearing person. To compensate for this, a hearing aid would have to amplify quiet sounds more than 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. A hearing-impaired person also has decreased ability to hear a signal that rapidly...
follows, or is rapidly followed by, a different signal. This decreased frequency and temporal resolution makes it more likely that speech understanding will be disrupted in adverse listening environments, and is discussed in detail elsewhere in this volume.

Hearing aids are often classified according to where they are worn. In order of decreasing size, these categories are: body, spectacle, behind-the-ear, in-the-ear, in-the-canal and completely-in-the-canal. Decreasing size has been a driving force during the history of the development of the hearing aid, but it is important to recognise that size and style are not exclusively related to cosmetic appearance. Some years ago, listeners who opted for smaller in-the-ear or in-the-canal devices paid a definite penalty in terms of processing capability, sound quality, and battery life. Technical advances in circuitry and battery technology have largely eradicated that penalty, although the choice or recommendation of a hearing aid style still does interact with the features in a hearing aid. For each style there are advantages relating to ease of insertion, ease of manipulation, visibility, amount of gain, sensitivity to wind noise, directivity, reliability, telephone compatibility, processing flexibility, ease of cleaning, and avoidance of occlusion and feed-back. The need for specific features such as a volume control, tele-coil, direct audio input and directional microphone have to be determined on an individual basis and will influence professional recommendation and client choice, almost independent of cosmetic factors.

Much hearing aid research and promotional literature from manufacturers concentrates on the signal processing contained within a hearing aid. However, the first piece of technology encountered by a sound entering a hearing aid is the microphone, and there can still be occasions where the performance of a hearing aid is limited, not by the electronics, but by this component. Modern miniature electrical microphones provide high sound quality, with only minor imperfections associated with internal noise and sensitivity to vibration. Directional microphones, which have two entry ports, are more sensitive to frontal sound than to sound arriving from other directions. The benefits of directionality are based on the ecologically reasonable assumption that listeners will orientate themselves to face a sound source of interest, and that interfering sound sources are likely to be at other locations in space. High directionality in hearing aids might compromise access to new sound sources of definite interest in those with the cognitive capacity to benefit. However, the trade-off between such a restriction and improved selectivity for wanted sound has yet to be quantified for a range of listeners. Directional microphones enable hearing aids to improve the signal-to-noise ratio by 3–5 dB relative to their omni-directional counterparts, and hence improve the intelligibility of speech in noise when speech and noise do not come from the same source angle. Dual-microphone hearing aids can be
switched by the users to be either directional, or omni-directional, as required in different listening situations. Although dual microphone hearing aids impose stringent requirements regarding matching and stability on their constituent components, they do offer listeners the opportunity to select the microphone sensitivity mode most appropriate for any given listening circumstance. Hearing aids are now in the market-place which attempt to identify the location in space of an interfering noise source and to adapt their directional pattern to suppress optimally the interfering source (which is always assumed to be other than straight ahead from the listener). Data on the effectiveness of such schemes are only beginning to emerge.

The use of a remote microphone located near the source of sound is effective, but often socially unpractical. Apart from this, multi-microphone directional arrays (including directional microphones) are the most effective way to improve intelligibility in noisy environments. Until recently, directional microphones used in hearing aids have been fixed arrays, meaning that they have the same directional pattern (represented by their polar response) in all situations. These fixed arrays use processing in which the signals from two microphones, or the sounds entering the two inlet ports of a single microphone, are subtracted to form a difference signal. Although microphone arrays offer attractive theoretical possibilities and laboratory results can be encouraging, it is a formidable challenge to deliver such processing schemes in real products. The products have to give advantages to hearing-impaired listeners in circumstances amenable to the processing without complementary disadvantages in other circumstances. Single-microphone schemes for noise reduction are not very effective. They can improve sound comfort, and the overall signal-to-noise ratio, but as conventionally and simply measured they do not improve the crucial signal-to-noise ratio for the frequency bands carrying the important information over any short time period. Consequently, they do not significantly improve intelligibility, except for highly unusual background noises.

Hearing aids can be classified by their technology into analogue, digitally programmable analogue, and fully digital types. Digitally programmable hearing aids employ conventional analogue circuits for processing the sound, but use a digital control circuit to alter the characteristics of the analogue elements. This enables the circuit, and hence the sound, to be more flexibly altered than is possible with fully analogue devices. The digital programming circuit also enables the user to switch between listening programmes in different situations. Fully digital circuits may be constructed to perform any arithmetic operation, in which case the type of processing they do depends on the software that is loaded into them. They can thus process sounds in ways specific to each device. Some manipulations of sound are performed more efficiently with digital processing, and some complex operations are only feasible with digital processing. At the time of
writing, the hearing-aid industry is in a transition period from reliance on analogue and digitally-controlled analogue technology to fully digital products, and the cost penalties of fully digital implementation relative to a similarly featured analogue counterpart (where that is possible) are gradually disappearing. The ‘benefits of digital hearing aids’ was always a misleading issue, but it will soon become totally irrelevant. The scientifically valid issue of the benefits of different features that may be incorporated into a hearing aid rationale and fitting can then return to the fore.

The performance of hearing aids is most conveniently measured when the hearing aid is connected to an acoustic coupler. While test boxes provide a convenient way to get sound into the hearing aid in a controlled manner, they are an imperfect means to an end. That end is the performance of the hearing aid in an individual patient’s ear. This performance can be directly measured using a soft, thin probe-tube inserted in the ear canal. A singular development in recent years has been the gradual incorporation of real-ear measures of hearing aid performance into both the fitting, fine-tuning and evaluation of hearing aids. The increasing complexities of hearing aid processing have placed increasing demands upon the signals, equipment and procedures for such measures.

Feedback (‘whistling’) is a major problem in hearing aids. It occurs when the amplification from the microphone to the receiver is greater than the attenuation of sound leaking from the output back to the input. Feedback can be made less likely by several means. One simple technique is to decrease the gain only for those frequencies and input levels at which oscillation is likely. A second technique involves adding a controlled internal feedback path that has the gain and phase response needed to cancel the accidental leakage around the ear-mould or shell. These techniques are already available in advanced hearing aids. Feedback has been one of the predominant problems with hearing aid fitting and a significant bar to acceptance both on the part of hearing-impaired listeners themselves, but also their family and significant others. The advent of flexible feedback management and suppression algorithms, though as yet by no means perfect, has led to significant advances in the degrees and forms of amplification provided and the overall acceptability of fittings. Even where a feedback suppression or management regimen leads to no overall change in the acoustical characteristics of the amplification delivered, but simply results in the ability to employ an ear-mould delivery system which leads to significantly less occlusion, there will be a material benefit to listeners. Such a fitting will result in increased use and comfort of the hearing aid, with a resultant increase in satisfaction.

The ear-mould is designed to fit an individual’s ear and retains the hearing aid on the head. It also provides the soundpath from the receiver to the ear canal. In many cases, the ear-mould provides a second
sound path, referred to as a vent, between the air outside the head and the ear canal. One unwanted consequence of an ear-mould can be the occlusion effect, in which the aid wearer’s own voice is excessively amplified by bone-conducted sound. At present, most occlusion management techniques are based around ear-mould alterations. The acoustical, as opposed to the discomfort, aspects of occlusion are still poorly understood, though preliminary experiments using acoustical cancelling techniques to offset, or at least alleviate, the acoustical elements of occlusion are underway.

Because of the non-linear elements of SNHL, many hearing aid rationales employ amplitude compression. Compression’s major role is to match the range of sound levels in the environment to the dynamic range of a hearing-impaired person better. The compressor may be most active at low, mid or high sound levels. Alternatively, it may vary its gain across a wide range of sound levels, in which case it is known as a wide dynamic range compressor. Compressors can react to a change in input levels within a few milliseconds, or they can take many tens of seconds to react fully. Simple compression systems can be classified as input controlled, where the compressor is controlled by a signal prior to the hearing aid’s volume control, or as output controlled, where the compressor is controlled by a signal subsequent to the volume control. This classification is irrelevant for hearing aids with no volume control. Compression systems have been used to achieve various specific aims and different compression parameters are needed for each rationale. Output-controlled compression limiting can prevent the output from ever causing loudness discomfort. Fast-acting compression with a low compression thresholds can be used to increase the audibility of the softer syllables of speech, whereas slow-acting compression will leave the relative intensities unchanged, but will alter the overall level of a speech signal. Compression applied with a medium compression threshold will make hearing aids more comfortable to wear in noisy places, without the advantages or disadvantages that occur when lower level sounds are compressed. Multichannel compression can be used to enable a hearing-impaired person to hear sounds at the same loudness as a normal-hearing person listening to the same sounds. Alternatively, it can be used to maximize intelligibility, while making the overall loudness of sounds normal (rather than normalizing the loudness at each frequency). Compression can be used to decrease the disturbing effects of background noise by reducing gain at those frequencies where the signal-to-noise ratio is poorest. Gain reduction of this type increases listening comfort and, with some unusual noises, may also increase intelligibility. Finally, compression can be applied by using the combination of compression parameters that patients are believed to prefer, irrespective of whether there is a theoretical rationale guiding the application.
Despite some complexity, the benefits of compression demonstrated in clinical trials can be summarized as follows. Compression can make low-level speech more intelligible, by increasing gain, and hence audibility. Compression can make high-level sounds more comfortable and less distorted. In mid-level environments, compression offers little advantage relative to a well-fitted linear aid. Once the input level goes up, of course, the advantages of compression become evident. Major disadvantages of compression include greater likelihood of feedback oscillation, and excessive amplification of unwanted lower level background noises. These considerations of compression give some indications of how the choices might interact with aspects of candidature and rehabilitation. Although the research base is still small, it does appear logical that those implementations of compression designed to function well across wide ranges of auditory environment are likely to be most beneficial to listeners who do experience those conditions. On the other hand, compression regimens which are optimally configured to overcome the restrictions in dynamic range, masking and frequency and temporal resolution are more likely to be most beneficial to listeners who suffer most from those deficits.

The most complex forms of amplification, which are not yet widely available, involve enhancing speech in ways that vary from one speech sound to the next. These methods include exaggerating the peaks and troughs in the spectrum of a speech sound, lengthening and shortening the duration of particular sounds, and increasing the amount of amplification whenever a consonant occurs. On the evidence available so far, however, none of these techniques will produce a large increase in intelligibility compared to conventional amplification.

Many hearing-aid fittings need to be fine-tuned, either electronically or physically, after the patient has had sufficient listening experience. In those cases where it is not clear which control should be adjusted, or by how much it should be adjusted, a systematic fine-tuning can be performed using one of two general methods. The first of these is paired comparisons, in which the patient is asked to choose between two amplification characteristics presented in quick succession. Multiple characteristics can be compared by arranging them in pairs. Paired comparisons can be used to adaptively fine-tune a hearing aid control if the settings compared in each trial are based on the patient’s preference in the preceding trial. Such techniques can also be used as part of the initial fitting process. The second general method for fine-tuning relies on the patient making an absolute rating of sound quality. The best amplification characteristic (out of those compared) is simply the characteristic that is given the highest rating by the patient. The absolute rating method can also be used to alter adaptively a chosen hearing aid control. This is achieved by deciding on a target rating (e.g. just right) and adjusting a control in the direction indicated by the patient’s rating.
(e.g. too shrill, or too dull). The paired comparisons and absolute rating methods are best carried out while the patient listens to continuous discourse speech material. Depending on the complaint being investigated, this can be supplemented with recordings of commonly encountered background noises.

A notable development in audiological practice throughout the world is the increasing commitment to formalised outcome measures as part of both an evaluation and a patient centred optimisation process. Because of time constraints, these are often by simple self-report rather than performance measurement. Systematic measurement of outcomes helps inform clinicians which of the practices, procedures and devices are achieving the intended aims. Appropriate outcome measures can also help determine how the rehabilitation for individual patients should be structured and when they might be ended or delivered in some other way. Self-report measures that assess benefit can be grouped into various classes. First, patients can be asked to make a direct assessment of the benefit of rehabilitation. Alternatively, patients' views of their disability can be assessed both before and after the rehabilitation programme. The change in score provides a measure of the effects of rehabilitation. Measures obtained both before and after rehabilitation provide a more complete view of disability or handicap status and change. These difference measures probably assess change less accurately than those that directly assess benefit because they involve subtracting two scores. The second way in which self-report measures differ is the extent to which the items are the same for all patients or are determined individually for each patient. Results can more easily be compared across patients if a standard set of items is used for all patients. When the items are individually selected for each patient, however, the questionnaires become shorter and can more easily be incorporated within interviews with the patient. Self-report measures are the only viable way to assess hearing aid use and satisfaction. Some measures contain questions that address only one dimension (benefit, use, or satisfaction) whereas others address more than one dimension. While outcomes can be assessed any time after hearing aid fitting, the extent of benefit does not appear to stabilise until about 6 weeks after fitting. Hearing aid use is associated with general improvements in health-related and quality-of-life. However, generic measures of health outcome are not all efficient means to assess the outcomes of rehabilitation, because they are sensitive to too many other variables.

Sensing sounds in two ears (binaural hearing) makes it possible for a person to locate the source of sound and increases speech intelligibility in noisy situations. Wearing two hearing aids (a bilateral fitting) instead of one hearing aid (a unilateral fitting) increases the range of sound levels for which binaural hearing is possible. Bilateral fitting is thus increasingly important as hearing loss increases. Bilateral fitting of
hearing aids has several other advantages. These include improved sound quality, suppression of tinnitus in both ears, and greater convenience when one hearing aid breaks down. In addition, a unilateral fitting can lead to decreased speech processing ability in the unaided ear if this ear is deprived of auditory stimulation for too long. Although bilateral fitting of devices has long been held to be an appropriate goal to aim at (two aidable ears deserve two hearing aids), the evidence base for cost-effectiveness in providing the second aid has yet to be established. Particular processing strategies which specifically implement or enhance binaural processing capabilities have been investigated in laboratory settings though have yet to reach the commercial market.

Hitherto this section has discussed conventional air conduction hearing aids. Bone-conduction devices output a mechanical vibration instead of an air-borne sound wave. They are most suited to people who (usually for medical reasons) cannot wear a hearing aid that includes the ear in any way. For patients with sensorineural hearing loss, bone-conduction hearing aids do not stimulate the cochlea as effectively as air-conduction devices due to the relative inefficiency of the bone-conduction route, but can for patients with substantial conductive hearing losses. Bone-conduction hearing aids require mechanical coupling to the head usually via a head band, though occasionally via spectacles. Such devices have limited cosmetic appeal and patient acceptability. An established alternative form of bone-conduction aid is the bone-anchored hearing aid, in which the vibrations are transmitted to the skull via an embedded titanium screw. Numerous clinical trials have demonstrated the effectiveness and acceptability of this implementation for specific patient groups. Benefits of bilateral provision are beginning to be developed. At an experimental level, devices can also enable vibrations to be transmitted directly to the tympanic membrane, the ossicular chain or to the round window. Clinical trials are under way concerning the effectiveness of and candidature for such devices, though at present the potential impact would appear to be limited to certain specific patient sub-groups.

Apart from directional microphones, success for signal processing schemes to improve actively the intelligibility of speech in noise remains elusive. The most effective way to make speech more intelligible is to locate the microphone nearer the person talking. This decreases interfering noise and reverberation, but does require a means of transmitting the signal from the microphone to the hearing aid at a remote distance. Methods currently include magnetic induction to a small telecoil inside the hearing aid, radio and infrared transmission, each of which has advantages and disadvantages. Although not the subject of dramatic technological improvements (with the possible exception of the miniaturisation of coupling systems to acceptable dimensions), there is an increasing realisation and use of such remote
coupling particularly in circumstances where the orientation of speakers and listeners is relatively fixed, such as in classrooms, meeting rooms and residential care facilities. A broad approach to technical capabilities can deliver significant benefits to patients.

Finally the term ‘electronic aids to hearing’ does not have to be hearing aids that are worn entirely or on the head or body of the hearing impaired person. These are usually classified as assistive listening devices and include the remote transmission systems described above, as well as devices that are specific to particular pieces of instrumentation (such as television or telephone amplifiers) and those that convert signals into another modality (such as smoke detectors or doorbells that cause a light to flash or provide a vibratory sensation). Technological advances in this domain are relatively limited, though all benefits of miniaturisation that have accompanied developments in the electronic industry do flow almost automatically. A major step forward in services for hearing impaired people is the growing realisation that a sensible and coherent coupling of the technical capabilities and features in the acoustical processing features of personal hearing aids with the listening and life-style demands of patients in the context of remote and assistive listening devices when delivered as part of a comprehensive rehabilitation programme is the optimal way of delivering new developments to the benefit of patients.

References

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