Psychoacoustics of Cochlear Hearing Impairment and the Design of Hearing Aids

Brian C.J. Moore

Department of Experimental Psychology, University of Cambridge,
Downing Street, Cambridge CB2 3EB, England

Abstract: Cochlear hearing impairment is usually associated with damage to the hair cells within the cochlea. When the damage is restricted to the outer hair cells (OHCs), the main consequence is disruption of the "active" mechanism which normally enhances the response of the basilar membrane to weak sounds and which sharpens the tuning (frequency selectivity) of the basilar membrane. Psychoacoustically, damage to OHCs results in loss of sensitivity (elevated absolute thresholds), loudness recruitment and reduced frequency selectivity. Damage to the inner hair cells (IHCs) causes basilar membrane vibrations to be transduced less efficiently, so absolute thresholds are elevated, but it does not result in loudness recruitment or reduced frequency selectivity. Current hearing aids can partially compensate for the effects of loudness recruitment by using compression amplification, but there is no consensus about the "best" form of compression. The deleterious effects of reduced frequency selectivity on speech intelligibility in noise can be alleviated by various methods for improving the speech-to-noise ratio, although so far only directional microphones have given clear benefits.

PHYSIOLOGICAL CONSEQUENCES OF COCHLEAR DAMAGE

The functioning of the normal cochlea reflects the operation of an active mechanism that is dependent on the integrity of the outer hair cells (OHCs) within the cochlea. This mechanism plays an important role in producing the high sensitivity of the basilar membrane (BM) to weak sounds and the sharp tuning on the BM (1). The normal BM shows several nonlinearities (2), including compressive input-output functions (3,4); these nonlinearities also appear to depend on the operation of the active mechanism. Cochlear hearing loss often involves damage to the OHCs and inner hair cells (IHCs); the latter act as transducers to transform BM vibration into action potentials in the neurons of the auditory nerve. The OHCs are generally more vulnerable to damage than the IHCs. When OHCs are damaged, the active mechanism is reduced in effectiveness or lost altogether. As a result, several changes occur: the sensitivity to weak sounds is reduced, so sounds need to be more intense to produce a given magnitude of response on the BM; the tuning curves on the BM become much broader, and input-output functions become more nearly linear.

Schematic illustrations of input-output functions on the BM are given in Figure 1. Both scales are logarithmic (dB). The solid line shows the type of function that would be observed for a tone at the characteristic frequency (CF) of the place being studied. The ordinate is scaled so that, for the CF tone, there is a gain of 55 dB for a 0 dB input, roughly consistent with estimates of the gain provided by the active mechanism. For mid-range levels, the output grows by about 2 dB for each 10-dB increase in input level, indicating compression; the function becomes more nearly linear for very low and very high input levels. The long-dashed line shows the type of function that would be observed for a tone with frequency well above or below CF. In this case, the response grows in a linear manner. A linear response is observed for all frequencies when the OHCs are severely damaged or when their function is strongly impaired by drugs or metabolic disturbances.

FIGURE 1. Schematic BM input-output functions for a tone close to CF (solid line) and a tone well below CF (dashed line).
EFFECTS OF COCHLEAR HEARING LOSS ON ABSOLUTE THRESHOLDS

The most obvious sign of cochlear damage is reduced sensitivity to weak sounds; absolute thresholds are higher than normal. This can arise in two main ways. Firstly, damage to the OHCs results in reduced BM vibration for a given low sound level. Hence, the sound level has to be increased to give a just-detectable amount of vibration. Secondly, IHC damage results in reduced efficiency of transduction, so the amount of BM vibration needed to reach threshold is higher than normal. Damage to the neurons in the auditory nerve may have a similar effect. In principle, it is possible to partition the overall hearing loss at a given frequency into a component due to OHC damage and a component due to IHC (and neural) damage (5):

\[ HL_{\text{total}} = HL_{\text{ohc}} + HL_{\text{ihc}} \]  

where all quantities are in decibels. It is not possible to determine the balance between the two components from measures of absolute threshold alone. However, the balance can be estimated from measures of frequency selectivity or loudness growth (see below) or from forward masking (6).

EFFECTS OF COCHLEAR HEARING LOSS ON FREQUENCY SELECTIVITY

Frequency selectivity refers to the ability of the auditory system to resolve (to a limited extent) the components in a complex sound. It is often quantified by using masking experiments (7). The "auditory filter shape" derived from such data represents the frequency selectivity at a specific center frequency; it probably corresponds reasonably well to the filtering that takes place on the BM at the place with the same CF. Frequency selectivity as measured behaviorally is poorer than normal in people with cochlear hearing loss (8). The auditory filters of normally hearing subjects broaden on the low-frequency side with increasing level (9). This effect probably depends on the active mechanism in the cochlea, which plays a reduced role at very high sound levels. In ears with cochlear damage, changes in frequency selectivity with level are absent or much less pronounced (10,11). As a result, the differences between normal and hearing-impaired subjects tend to decrease at high sound levels. However, at levels where sounds are loud, but not uncomfortably so, hearing-impaired ears generally have broader auditory filters than normal ears (12).

For a given degree of hearing loss, the bandwidths of the auditory filters can vary markedly across individuals (8). This can probably be explained in terms of different relative amounts of OHC and IHC loss; OHC loss results in broadening of the auditory filters, whereas IHC loss does not (13).

LOUDNESS RECRUITMENT

Most, people with cochlear damage show loudness recruitment (14); when a sound is increased in level above the (elevated) absolute threshold, the rate of growth of loudness level with increasing sound level is greater than normal. When the level is sufficiently high, usually around 90 to 100 dB SPL, the loudness reaches its "normal" value. With further increases in sound level above 90-100 dB SPL, the loudness grows in an almost normal manner. On average, the higher the absolute threshold, the greater is the rate at which loudness level grows with increasing level (15,16). This is consistent with the idea that threshold elevation and loudness recruitment are both linked to the loss of the active mechanism in the cochlea. However, for a given hearing loss, considerable individual variability in the slopes of loudness growth functions also occurs. Part of this variability can be accounted for by different relative amounts of OHC loss and IHC loss (5).

A plausible explanation for loudness recruitment is that it arises mainly from a reduction in or loss of the compressive nonlinearity in the input-output function of the BM. If the input-output function on the BM is steeper (less compressive) than normal in an ear with cochlear damage, this would be expected to lead to an increased rate of growth of loudness with increasing sound level. However, at high sound levels, around 90-100 dB SPL, the input-output function becomes almost linear in both normal and impaired ears. The magnitude of the BM response at high sound levels is roughly the same in a normal and an impaired ear. This can explain why the loudness in an impaired ear usually "catches up" with that in a normal ear at sound levels around 90-100 dB SPL.

For sounds with inherent amplitude fluctuations, such as speech or music, recruitment results in an exaggeration of the perceived dynamic qualities (17). The sound appears to fluctuate in loudness more than it would for a
normally hearing person. When listening to music, the *forte* passages may be perceived at almost normal loudness, but the *piano* passages may be inaudible (18).

**SPEECH PERCEPTION BY PEOPLE WITH COCHLEAR DAMAGE**

One of the commonest complaints of people with cochlear hearing loss is difficulty understanding speech, especially in the presence of competing sounds. Plomp (19) reviewed several studies which measured the speech reception threshold (SRT) for sentences presented in a continuous speech-shaped noise. Even for high noise levels, people with cochlear loss had higher SRTs than normally hearing people. The increase in SRT varied from about 2.5 dB to 7 dB, depending on the nature and severity of the loss. An elevation in SRT of 2.5 dB is sufficient to create a substantial loss of intelligibility in difficult listening situations. The elevation in SRT can be much greater when a fluctuating background noise or a single competing talker is used instead of a steady noise. Normally hearing subjects are able to take advantage of temporal and spectral “dips” in the interfering sound to achieve much lower SRTs than when steady background noise is used. People with cochlear damage are less able to do this (20,21). Hence, when the background is a single talker, the SRT is 12 dB or more higher for people with cochlear loss than for normally hearing people. This represents a very large deficit.

Finally, people with cochlear loss are less able than normally hearing people to take advantage of spatial separation of the target speech and interfering sound(s). This can lead to a further elevation in SRT, relative to that found for normally hearing people, of about 7 dB (20).

In summary, in some common listening situations, such as trying to listen to one person when another person is talking, people with cochlear damage may require speech-to-background ratios 16 dB or more higher than normal. This represents a very substantial problem.

**APPLICATIONS TO HEARING-AID DESIGN**

The primary goal of most hearing aids is to restore audibility via frequency-selective amplification. It is well known that it is not practical to use linear amplification to compensate fully for the loss of audibility. The major factor preventing this is loudness recruitment. Say, for example, a person had a cochlear hearing loss of 60 dB at all frequencies. The highest comfortable level (HCL) for such a person would typically be around 90-100 dB HL. A hearing aid that fully compensated for the loss of audibility would apply a gain of 60 dB at all frequencies. However, that would mean that any sound with a level above about 40 dB HL would be amplified to a level exceeding the HCL. In practice, many sounds encountered in everyday life would become unpleasantly loud. Even when aids include output limiting, it is impractical to compensate fully for loss of audibility. Rather, various rules have been developed that prescribe a gain between one-third and one-half of the hearing loss.

It was suggested many years ago that problems associated with loudness recruitment could be alleviated by the use of automatic gain control (AGC) (14). With AGC, it is possible to amplify weak sounds more than stronger ones, with the result that the wide dynamic range of the input signal is compressed into a smaller dynamic range at the output. Hence AGC systems are also called “compressors.” Although this idea sounds simple, in practice there are many ways of implementing AGC, and there is still no clear consensus as to the “best” method, if there is such a thing.

AGC systems have been designed in many different forms, mostly on the basis of different rationales or design goals. Some systems are intended to adjust the gain automatically for different listening situations. The idea is to relieve the user of the need to adjust the volume control. Usually, such systems change their gain slowly with changes in sound level; this is achieved by making the recovery time of the AGC circuit rather long (greater than a few hundred milliseconds). These systems are often referred to as “automatic volume control” (AVC). Although it is generally accepted that AVC can be useful, relatively few commercial hearing aids incorporate AVC. One reason is that, following a brief intense sound, such as a door slamming, the gain drops and stays low for some time; the aid effectively goes “dead.” This problem can be alleviated by using an AGC circuit with dual time constants (22).

An alternative type of compressor, with lower compression ratios and lower compression thresholds, has been used in hearing aids in attempts to make the hearing-impaired person's perception of loudness more like that of a normal listener and to ensure that the weaker consonant sounds of speech will be audible without the more intense sounds (e.g. vowels) becoming uncomfortably loud. Such compressors usually have short time constants (typically 20-100 ms) and are often referred to as “syllabic compressors,” since the gain changes over times comparable to the durations of individual syllables (23). Often, syllabic compression is applied separately in two or more frequency
bands. Evaluations of such systems have given mixed results, but some studies have shown clear benefits (24); the commercial success of multi-band syllabic compression is beyond doubt.

It seems likely that impaired frequency selectivity is at least partly responsible for the reduced ability of people with cochlear hearing loss to understand speech in noise (25,26). Linear amplification and multi-band compression do not compensate for the effects of reduced frequency selectivity, although high-frequency emphasis can partially alleviate masking of middle and high frequencies by low frequencies. Many researchers have attempted to improve speech intelligibility using digital signal processing (DSP) techniques to enhance speech in background noise (8,27,28). Although these techniques have had only limited success, digital processing can be used to reduce interference from narrowband background sounds (29), and this possibility is now being exploited in commercial digital hearing aids. Substantial improvements in the intelligibility of speech in noise can be obtained using directional microphones (30), and these improvements may be enhanced still further by DSP (31).

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