Determining amplification requirements for people with hearing impairments is vital for the design and fitting of hearing aids. Although substantial advances have been made, the challenge is as great as ever because new hearing aid technology has greatly increased amplification options. Considerable effort is being directed towards the development of new hearing aid fitting procedures and systems, as well as new types of hearing aids. I shall argue, however, that some current directions give cause for concern and that there is a need for some reorientation of thinking and research effort.

This paper discusses the broad philosophical and theoretical issues relating to the fitting of new types of hearing aids. The discussion will be preceded by outlining the history and current trends in hearing aid selection, the major characteristics of new types of hearing aids and their implications for fitting practices, and some current design and fitting rationales for nonlinear amplification. I shall conclude by summarizing some concerns about current directions and suggesting some other possible directions and approaches. This paper challenges certain dominant ideas that tend to be taken to be self-evident, particularly the uncritical acceptance of loudness normalization as the only prescriptive rationale worthy of consideration. I shall argue that new fitting procedures should build on current knowledge and procedures and that a variety of fitting rationales should be evaluated with a view to developing validated prescriptive procedures.

**TRENDS IN HEARING AID PRESCRIPTION**

**Present Situation**

Over the past 20 or so years, the subject of hearing aid selection has received considerable attention, following a long period of comparative neglect (Studebaker, 1982). This interest has included the development of several new formulae for prescribing the gain and frequency response of a hearing aid (Crouch and Pendry, 1990).
Journal of the American Academy of Audiology/ Volume 7, Number 6, December 1996

1975a, b; Byrne and Tonisson, 1976; Berger et al, 1977; Cox, 1983, 1988; McCandless and Lyregaard, 1983; Seewald et al, 1985; Byrne and Dillon, 1986; Schwartz et al, 1988; Skinner, 1988; Byrne et al, 1991). Such formulae have been supported by varying degrees of validation research (reviewed in Byrne, 1983, 1993; Skinner, 1988). The selection of maximum power output (MPO) has received less attention. Nonetheless, useful recommendations, together with a limited amount of validation evidence, are available (Dillon et al, 1984, 1994; Hawkins et al, 1987).

Recently, there has been a renewed interest in procedures for evaluating hearing aid fittings. These include paired-comparison judgments, or magnitude estimations, of speech quality or intelligibility (e.g., Punch and Parker, 1981; Studebaker et al, 1982; Levitt et al, 1987; Purdy and Pavlovic, 1992) and other techniques such as cued listening (Jerger et al, 1994). In some research (Neuman et al, 1987; Byrne and Cotton, 1988), hearing aid selection has been achieved by comparing frequency response characteristics representing systematic variations from a response derived from a prescriptive procedure. Clinical procedures along these lines have also been suggested (Byrne and Cotton, 1988; Kuk, 1994).

At present, no single procedure is universally accepted as the best way to select a hearing aid. Nonetheless, most audiologists would agree that, as a result of substantial research from many laboratories, scientific bases exist for selecting gain, frequency response, and MPO by using one of the better-validated prescriptive procedures or a combination of such a procedure with an evaluation method. It is, therefore, disconcerting to find that methods proposed for fitting nonlinear hearing aids (discussed later) mostly ignore the principles established for selecting linear amplification. Indeed, there seems to be an increasingly common view (e.g., Brunved, 1994) that current hearing aid selection methods have no application to new types of hearing aids.

The Future?

What, then, is the future for hearing aid selection? One possible scenario is that virtually all new types of hearing aids will be fitted by using a manufacturer-specific fitting system and that such a system will include proprietary formulae for calculating amplification requirements, as well as methods for adjusting the hearing aid parameters. This is not necessarily the way that all manufacturers would wish to go but it may be unavoidable if scientists and clinicians fail to develop properly researched selection methods that are applicable to new types of hearing aids. The scenario described raises concerns, both scientific and philosophical. Scientifically, the concern is that amplification may become prescribed by a wide variety of proprietary formulae of which few, if any, are validated by published research. A possible philosophical problem is that control of the fitting process is taken away from the fitter who is responsible for care of the client. This concern has already been expressed in relation to the common practice of “selecting” custom in-the-ear aids by simply sending an audiogram to the manufacturer (Bratt and Sammeth, 1991). It may be argued that it does not matter who controls the fitting process, provided that it is done effectively. However, at the least, the fitter should understand the fitting procedure and be assured that it is appropriate for his or her client. Another concern is that the choice of a particular type of hearing aid would obligate the fitter to use that manufacturer’s fitting formula.

The trend towards manufacturer-specific fitting formulae is not universal. Some general prescriptive formulae, applicable to nonlinear as well as linear amplification, have been suggested, of which the IHAF protocol (Cox, 1995) is a good example. Such formulae, however, have not been validated and most are based on the same rationale, loudness normalization, which is acknowledged to be an “intuitive, though as yet unproven, notion” (Mueller, 1995).

In view of the above concerns, it seems desirable to examine the hearing aid selection and fitting process in terms of how it applies to current and future hearing aids. What are the major issues that need to be resolved in order to develop validated fitting procedures? To what extent are existing methods applicable (i.e., do we really need to start all over again)? What are appropriate roles for researchers, manufacturers, and clinicians in the process?

NEED FOR NEW HEARING AID FITTING PROCEDURES

New hearing aid fitting procedures are needed because new types of amplification have recently become available. We need to decide what type of amplification system is best for an individual and, for any particular type, we may need to prescribe values for the various
amplification parameters. The major complication is that most recently developed hearing aids are nonlinear amplification systems, of which there are several types. A smaller complication is that many current aids provide multiple memories that enable the user to select different types of amplification. Both of these developments stem from the belief that there is no single set of amplification characteristics (e.g., combination of overall gain, frequency response, compression characteristics, and MPO) that will be optimal for an individual at all times. Nonlinear systems vary amplification depending on changes in acoustic input. Multiple memory aids can provide variations, in linear or nonlinear amplification, that may be chosen either to accommodate changes in acoustic input or changing preferences in sound quality. Multiple memories complicate hearing aid selection in that two or more sets of amplification characteristics need to be selected. Such selection has been discussed by Keidser et al. (1995, 1996). Dillon (1996) has reviewed the various types of nonlinear amplification systems and the evidence evaluating each type. Such a review will not be attempted here but it is necessary to outline the major characteristics of compression systems in order to indicate their implications for hearing aid selection issues.

Characteristics of Nonlinear Amplification Systems

Figure 1 illustrates three variations in nonlinear amplification expressed as input/output (I/O) functions. In Panel a, compression is used simply for limiting. In addition to gain and frequency response, the required descriptive parameters are the kneepoint at which limiting begins (K lim) and the compression ratio (CR) of the function above K lim, CR lim.

Panel b illustrates whole range compression. Starting from a low input level, gain decreases as input increases, with the same CR until the limiting level is reached. If the I/O function is independent of frequency, the required descriptive parameters are gain and frequency response for a typical input level (e.g., 70 dB SPL), the low kneepoint (K Lo), CR-wide range (CR WR), K lim, and CR lim. If the I/O function varies with frequency, the hearing aid’s performance can be described either by obtaining I/O functions at different frequencies or by obtaining multiple frequency responses with different input levels. (Here, and later, it is assumed that frequency response is measured with a stationary broadband signal. However, such measurements may not accurately indicate the effect of compression on the spectra of speech signals that have a spectral shape that varies with time.)

Panel c shows a system that may be designated as low level compression (Dillon, 1996). Compression occurs over most of the input range but amplification becomes linear (and may provide zero gain) for high-level inputs. It now becomes necessary to specify three CRs (of which CR Hi may be unity) and three kneepoints. A further complication occurs with compression systems that produce a curvilinear I/O function. Although these may require complex equations to be described precisely, they may be approximated by straight-line I/O functions with one or more kneepoints. The kneepoints of compression systems can be specified as either input or output levels. Logically, the choice should depend on fitting rationale; output level would be appropriate for a kneepoint prescription derived from a hearing loss characteristic, whereas input level would be appropriate if the kneepoint is not prescribed. For example, the kneepoint for limiting should be specified as an output level if it is intended to correspond to the individual’s loudness discomfort level (LDL). On the other hand, a kneepoint could be specified as an input level if compression is intended for noise reduction and is not varied for individuals.

Compression systems may also be classified on the basis of whether their time constants, attack and release times, are relatively fast or slow. Fast-acting systems (release time less than 150 msec) are usually called “syllabic” compression, whereas slow-acting systems are called automatic volume control (AVC) (Walker and Dillon, 1982). In most systems, the time
Implications of Nonlinear Amplification for Hearing Aid Selection

The hearing aid selection and fitting process has been conceptualized as having four stages (Byrne, 1979). The first stage is prescribing amplification characteristics to suit the client. The second stage is matching the prescription by finding a suitable combination of hearing aid, settings, and attachments. The third stage is verifying that the required amplification has been provided in the ear of the individual. The fourth stage is evaluating how the client hears with the fitted hearing aid and, where indicated, readjusting ("finetuning") the hearing aid fitting.

The use of nonlinear amplification (and/or multiple memories) complicates all stages of the process. The verification and evaluation stages require a greater number of test signals and various problems may be encountered in selecting appropriate signals for the system concerned. The matching stage has been affected by the advent of programmable aids in that it may be a matter of programming the appropriate settings into a single, flexible aid rather than choosing among different instruments. (The audiologist should not, however, overlook the possible value of acoustic modifications rather than relying exclusively on electronic variations.)

Although the use of nonlinear hearing aids affects all stages of the selection process, its implications are greatest for prescription. This may involve three steps. The first is determining what type of compression system is best for the individual. (If multiple memories are available, it may be appropriate to select two or more types.) This step presupposes that no single compression system is best for all people. Whether that is true remains to be established, although there is some indication that different systems may be best under different conditions (Keidser, 1995) and that some systems are most suitable for certain degrees or types of hearing loss (Killion, 1993).

The second step involves determining which parameters of the chosen system need to be individually selected. This issue, which cannot be resolved until the validity of different prescription rationales has been tested, will be discussed later. The third step is prescribing values for the prescriptive parameters. Possible prescription parameters are outlined in the following discussion and are summarized in Table 1.

Gain and frequency response are individual prescription parameters. They can be varied extensively, are currently prescribed, and have strong theoretical and validated rationales. The use of compression should not change gain and frequency response requirements for a typical input level (e.g., speech with an overall rms level of 65–70 dB SPL).

$K_{lim}$ is an individual prescription parameter. It is equivalent to MPO and the same prescription principles apply. Nearly all aids provide

### Table 1 Possible Prescriptive Parameters for Nonlinear Hearing Aids

<table>
<thead>
<tr>
<th>Amplification Parameter</th>
<th>Need for Prescription</th>
<th>Measurement Requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gain</td>
<td>Yes</td>
<td>HTL or MCL</td>
</tr>
<tr>
<td>Frequency response</td>
<td>Yes</td>
<td>HTL or MCL</td>
</tr>
<tr>
<td>Maximum output or</td>
<td>Yes</td>
<td>LDL &amp;/or HTL</td>
</tr>
<tr>
<td>limiting kneepoint (K__lim)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Compression ratio,</td>
<td>Yes</td>
<td>Dynamic range or loudness scaling</td>
</tr>
<tr>
<td>wide range (CR__WR)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low-level kneepoint (K_Lo)</td>
<td>Yes</td>
<td>HTL?</td>
</tr>
<tr>
<td>High-level kneepoint (K_Hi)</td>
<td>Yes</td>
<td>HTL or loudness scaling</td>
</tr>
<tr>
<td>Attack time (Ta)</td>
<td>Maybe</td>
<td>??</td>
</tr>
<tr>
<td>Release time (Tr)</td>
<td>Maybe</td>
<td>??</td>
</tr>
<tr>
<td>Compression ratio,</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>limiting (CR_lim)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Compression ratio,</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>high level (CR_Hi)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
scope to vary this parameter, although usually not on a frequency by frequency basis. Good rationales exist for prescribing MPO or K lim.

CR WR is usually treated as a prescription parameter although an exception may be when compression is regarded purely as a noise reduction system (see below). Prescription rationales (discussed later) are based broadly on the idea of compensating for a hearing-impaired person's reduced dynamic range.

In some hearing aids, “K Lo” (compression threshold) is variable. The undesirability of applying compression to sounds that are inaudible could lead to prescriptive formulae for appropriate combinations of gain and compression threshold. Furthermore, Killion (1993) has suggested that compression threshold may sometimes need to be set at a higher level than is usual for the K-Amp, to avoid complaints of circuit noise.

K Hi is intended to represent the level at which recruitment is complete or at which the loudness growth function asymptotes and assume a normal shape. As this level does not vary greatly for people with mild and moderate hearing losses (Lyregaard, 1988), it may be reasonable to use the same value for all such people. However, K Hi will certainly need to be varied if this type of system is used for people with severe hearing losses.

The choice of “Ta” and “Tr” define whether the compression system is of the syllabic or AVC type. They are not currently treated as prescription parameters. However, there may be possibilities for developing prescription rationales based on individual differences in temporal masking or on information concerning the listening environments most commonly encountered by the hearing aid wearer.

For various reasons, the other parameters shown on Figure 1 are probably not prescription parameters. CR lim will always need to be high to serve its limiting function and there is no reason to think that it should be varied. CR Hi will always be unity (or close to unity) as the rationale of low-level compression systems is to provide linear amplification above the level at which the loudness growth function becomes normal.

DESIGN AND FITTING RATIONALES FOR NONLINEAR HEARING AIDS

There are several rationales for using nonlinear amplification. The simplest, which will not be discussed further, is using compression to provide low-distortion limiting (Walker and Dillon, 1982). Four additional rationales are to reduce noise, to improve audibility for soft sounds, to normalize loudness perceptions, and to minimize the need for volume control adjustments. These four key concepts are illustrated and discussed by presenting an overview of some system designs and fitting procedures. However, it is not intended to describe fully or to classify particular devices or fitting procedures. In fact, any such classification would be arbitrary as some devices and procedures incorporate two or more of the concepts.

Noise Reduction

The earliest examples of the new wave of nonlinear hearing aids were designed as noise reduction systems. For low-level inputs, these aids provide their broadest and flattest frequency response while, for higher inputs, the bass response is progressively cut (i.e., the response has more high-frequency emphasis). The rationale is that high inputs are presumed to include high levels of noise and many noises are predominantly low frequencies. Reducing the low-frequency amplification will reduce the noise but also the low-frequency components of speech. Nonetheless, there could theoretically be some advantage in speech intelligibility through a reduction in upward spread of masking, and/or some advantages in listening comfort and decreased distortion because the reduced gain for high-intensity low-frequency inputs would reduce the likelihood of saturation.

A recent variation of this type of system (i.e., one in which compression affects mainly the low frequencies) is the MultiFocus hearing aid (Brunved, 1994). This is a two-band hearing aid with wide range (low-level) compression in the low-frequency band only. The compression ratio is varied in a manner designed to compensate for the average loudness growth functions of persons with various degrees of sensorineural hearing loss. Thus, with respect to the low-frequency band, amplification is prescribed to compensate for the individual's abnormal loudness growth function, as predicted from hearing level. The high-frequency band has compression limiting only (although capable of being set at a relatively low level) because it is reported that the use of dynamic range compression in both bands resulted in reduced speech intelligibility in noise, presumed to arise from a reduction in spectral contrasts.
Improving Audibility

Most nonlinear hearing aid fitting procedures or design rationales include the concept of normalizing loudness. Some rationales also emphasize using compression to improve audibility for low-intensity speech sounds. Such rationales may be distinguished from others that are unconcerned with audibility or that simply assume (wrongly) that normalizing loudness will ensure optimal audibility. (Normalization does not, in itself, optimize audibility because some components of speech may be inaudible when the speech is soft or when masking occurs.) A rationale that emphasizes audibility, as well as normalization, is that of the K-Amp amplifier in its level-dependent frequency response configuration (Killion, 1993). For sloping high-frequency hearing losses, this provides a treble boost, as well as more gain, for low-level inputs. The rationale is that, when voice levels are low, additional high-frequency amplification is needed to provide audibility of the low-intensity high-frequency components of speech. Very pertinently, Killion (1993, p. 60) points out that recruitment should be viewed as “an abnormal loss of sensitivity for quiet sounds.” In keeping with this view, the K-Amp provides the most gain for low-level inputs in order to restore audibility. (The fitting procedure, Fig. 6, proposed by Killion [1994] prescribes gain for low-level inputs to be equal to HTL -20 dB for hearing losses 20 to 60 dB HTL.) The gain decreases for higher level inputs up to about 90 dB SPL, where the system becomes linear and gain becomes zero (or relatively little) because people with mild and moderate sensorineural hearing losses are considered to have no loss (or little loss) of loudness for high-level sounds. The gain for mid-level inputs is based on the principle of gradually reducing the gain from what is required for low levels to that required for high levels (possibly zero) where the system becomes linear. The complex compression system of Moore and colleagues (Laurence et al, 1983; Moore et al 1985; Moore and Glasberg, 1986; 1988; Moore, 1987) may be considered under the audibility rationale, although it also has strong elements of the AVC, as well as the loudness normalization, rationales. This approach combines slow-acting (AVC) and fast-acting (syllabic) types of compression. An AGC amplifier at the front of the system is usually triggered by a moderate input (about 63 dB SPL) and operates with long time constants (several hundred msec) to reduce the variations in long-term speech levels. It can, however, also be triggered by higher level sounds to operate as a fast-acting limiter. The signal is then split into two bands and is processed by a syllabic compressor to reduce the short-term variations in speech sounds. In the latest version of the system, the syllabic compression is applied to the high-frequency band only. It is reported that “the use of dual front-end AGC eliminates the need for compression in the low-frequency band” and that “this reduces spurious spectral and temporal distortions introduced by the syllabic compression” (Moore and Glasberg, 1988, p. 103). The need for a two-band system is argued on the grounds that recruitment often varies across frequency and that “relatively weak high-frequency components in speech... are often accompanied by, or follow rapidly after, relatively intense low-frequency components. The use of fast-acting AGC in two or more separate bands can ensure that these weak high-frequency components are always audible” (Moore, 1993, p. 152). This conclusion contrasts with the MultiFocus rationale that speech intelligibility will be optimized with a system that uses wide-range compression in the low-frequency band only. The use of two or more types of compression complicates fitting considerations. With the Moore and Glasberg system, the AVC characteristics are the same for everyone but the syllabic compression is adjusted to suit individual hearing losses, partly on an empirical basis rather than strictly according to a prescriptive procedure.

Loudness Normalization (Recruitment Compensation)

Loudness normalization is a prominent feature of the K-amp rationale and, to a lesser extent, the Moore rationale. However, those rationales also emphasize audibility and it is a major consideration in their system designs. By contrast, there are some suggested fitting procedures in which loudness normalization is certainly the primary aim and it is presumed that normalizing loudness will ensure an optimal fitting. An example is the loudness growth in half-octave bands (LGOB) method recommended for fitting the ReSound hearing aids. Loudness growth functions are measured with 1/2-octave bands of noise (Pluvinage, 1989) and the compression characteristics are selected to restore normal loudness. In practice, this involves selecting the crossover frequency for a two-band
compression system and prescribing the gain for 50 dB SPL and 80 dB SPL inputs for each band (Johnson et al, 1989). For most clients with sloping high-frequency losses, this aid would provide most compression in the high frequencies because a higher compression ratio would be required in the high band than in the low band to restore normal loudness.

For fitting a research system, Kollmeier et al (1993) used a recruitment compensation procedure based on loudness scaling measurements with narrow bands of noise. The dynamic range is defined by measuring the levels required at each frequency to elicit loudness impressions of "very soft," "comfortable," and "very loud." Gain is provided to compensate for the differences between the measured levels of a hearing-impaired subject and the corresponding levels for a normal-hearing person.

A recent example of loudness normalization is the IHAFF protocol. According to Mueller (1995), this procedure is based on the "notion that when hearing aid processing is matched to the patient’s loudness growth function across frequencies, greatest user benefit will result" (p. 10). Cox (1995) states that "amplification should normalize the relationships between environmental sounds and loudness perception. This means that a sound that appears soft to a normal-hearing listener should be audible, but soft, after amplification, to the hearing-impaired person. Similarly, sounds that are comfortable or loud to a normal-hearing listener should be comfortable or loud, respectively, after amplification..." (p. 10). The procedure is based on measuring loudness growth functions by determining the levels of pulsed warble tones that correspond to seven loudness categories. In principle, measurements could be made at several frequencies but, for clinical use, Cox suggests that two frequencies should be sufficient. The prescription formula calculates the gain required at each frequency to amplify soft, average, and loud speech to the levels required for them to be perceived normally. The formula was derived using data showing the relationship between loudness perceptions of warble tones and speech. The computerized selection procedure, VIOLA, uses the loudness scaling data to calculate target levels, for two or more frequency bands, for soft, average, and loud speech inputs. These define an I/O function that can be compared with the I/O functions of one or more hearing aids to determine their suitability. Cox stresses that the formula is provisional and may change after evaluation of its underlying assumptions.

**Automatic Volume Control**

A major element of some fitting rationales is that compression minimizes the need for volume adjustments by the user and thereby makes aid usage easier and more comfortable. A notable example is the MultiFocus type of hearing aid, which does not have a volume control because it is considered unnecessary. The slow-acting AVC of the Moore system is also claimed to minimize the need for volume adjustments. Similar statements have been made by some Australian Hearing Services’ clinicians with regard to some single-band, whole-range compression hearing aids. Furthermore, after reviewing the evidence for different types of compression systems, Dillon (1996) has concluded that the main advantage demonstrated for compression, whatever type, is that it reduces the long-term level variations of speech and thereby tends to maintain auditory favor for soft speech, together with comfort for loud sounds, without much need for volume control adjustments.

**Evidence for Fitting Rationales**

The evidence supporting the various types of compression amplification systems has been reviewed by Dillon (1996). In that such evidence is, indirectly and in varying degrees, evidence for different fitting rationales, it will be briefly reviewed here. Several evaluation studies of the older noise reduction systems have generally found little, if any, advantage over a single-band, whole-range compression hearing aids. Furthermore, after reviewing the evidence for different fitting rationales, it will be briefly reviewed here. Several evaluation studies of the older noise reduction systems have generally found little, if any, advantage over an optimally fitted linear system (Dillon and Lovegrove, 1993). The MultiFocus rationale is supported by a series of in-house studies in which field trials showed this type of amplification to be preferred to linear amplification or to a system with wide-range compression in both the low and high bands (Lundh, 1981, 1983; Lundh and Nielsen, 1992). Biering-Sorensen et al (1995) evaluated the MultiFocus hearing aids and concluded that, compared with linear hearing aids, they did not provide any better speech intelligibility in noise but were preferred by the majority of clients. The nonlinear aid was rated as superior for listening in quiet, for brightness of sound, and for reducing the annoyance of traffic noise.

The various studies by Moore and colleagues (Laurence et al, 1983; Moore et al, 1985; Moore, 1987) have shown that their system can provide improved intelligibility for soft speech (when volume control adjustment is not permitted) and improved understanding of speech in noise.
Moore et al (1992) found similar, but much smaller, advantages for the ReSound hearing aid, which differs from the Moore system in various respects, notably that it does not have slow-acting compression preceding the syllabic compression. There seems to be no commercial hearing aid with slow-acting compression only but, in experiments with a master hearing aid, Neuman et al (1994) found slow-acting compression, with a CR of 1.5 to 2, to be beneficial for listening in noise for people with small dynamic ranges.

Apart from the above-mentioned studies, the support for currently available compression systems seems to be mainly anecdotal or based on comparisons with the clients' own hearing aids, which are often of unspecified condition, quality, or suitability. Taken together, the various case study reports (e.g., Killion and Villchur, 1993) provide general support for the value of compression but no conclusive evidence for the superiority of any specific compression system or fitting rationale.

CRITICAL FITTING ISSUES

In the available evidence, it is not possible to decide which of the various design and fitting rationales is most valid. Yet, different rationales would have very different implications for selecting amplification and for determining what types of measurements and prescription formulae are necessary. Therefore, the most basic research need is a thorough evaluation of fitting rationales before proceeding to develop any particular rationale into a fitting procedure. Such research should consider the following issues.

Loudness Considerations

Virtually all hearing aid selection rationales are concerned with loudness in that it is generally agreed that speech should be amplified to audible and comfortable levels and that no sounds should reach uncomfortable levels. Furthermore, many procedures, either explicitly or implicitly, aim to deliver the various frequency bands of speech with a particular loudness relationship (e.g., Byrne and Tonisson, 1976; Cox, 1983, 1988; Seewald et al, 1985; Byrne and Dillon, 1986; Tyler, 1986; Skinner, 1988). Consideration of loudness relationships has received even greater prominence in procedures for fitting nonlinear hearing aids (e.g., Cox, 1995). It is, therefore, pertinent to ask: How important is it to amplify speech to provide some specified loudness relationship between different frequency bands? I shall argue that, in one sense, it is critically important but that, in another sense, it may not be important at all.

Unimportance of Loudness Relationships

Van Tasell (1993) has observed that "there is no conclusive evidence that loudness relationships among the various frequency regions of speech are important for their intelligibility, as long as the regions are sufficiently audible and not uncomfortably loud" (p. 237). In the present context, the relationship of most interest is loudness normalization, as this concept is a major element of most fitting rationales for nonlinear hearing aids. Not only is there no evidence that loudness normalization will optimize speech intelligibility or quality, but there are arguments why it may be unimportant or even detrimental under some circumstances. Normal-hearing people experience a wide range of loudness levels depending on the intensity of sound at the source, its distance from the listener, and various acoustic conditions. The long-term spectrum of speech, and the short-term spectra of particular sounds, will also vary considerably for different talkers and depending on reflection and baffle effects. Variations in loudness and spectra do not cause any problems provided that they remain within the range that is both audible and comfortable. Why then should it matter whether a hearing-impaired person experiences exactly the same loudness sensation that a normal-hearing person would in the same situation? Research has confirmed that a wide range of speech spectra can provide equivalent speech intelligibility (Horwitz et al, 1991; Van Buuren et al, 1995).

Inherent in the loudness normalization rationale is the assumption that normal is best. Yet, under some difficult listening conditions, such as in many moderate to high noise levels, speech intelligibility would be improved for normal-hearing people by providing amplification with high-frequency emphasis. If we accept the unprovable, philosophical position that what is normal must be best, we might surmise that the unimpaired human auditory system provides loudness sensations that constitute the best compromise among somewhat conflicting requirements of auditory functioning that include understanding speech, enjoying the quality of sounds, and detecting and locating sounds. However, such a compromise might not be
optimal for a hearing-impaired listener who has difficulty understanding speech in a greater range of situations than a normal-hearing listener. It may well be that something different from normal loudness sensations will provide the best speech recognition or a better compromise for intelligibility, detection, quality, and localization. Indeed, restoring normality to some aspect of audition (e.g., recruitment compensation) could be counterproductive if other aspects (e.g., frequency resolution) remain abnormal.

**Importance of Loudness Relationships**

Although there is no evidence that any particular loudness relationship is intrinsically important, the achievement of a certain relationship may be essential to meet other objectives, notably to maximize audibility consistent with comfort. This is explicit in the rationale of the original (Byrne and Tonisson, 1976) and revised (Byrne and Dillon, 1986) National Acoustic Laboratories' (NAL) procedures. Specifically, it is hypothesized that, with volume adjusted for comfortable listening, the audibility of speech averaged across frequencies will be maximized if all frequency bands are equally loud. Conversely, if some frequencies, say the low frequencies, were amplified to higher loudness levels than other frequencies, then the overall level required for comfortable listening (presumably reflected in the preferred hearing aid volume control setting) would be determined mainly by the level of the louder frequencies while the other frequencies could be at an inadequate, or even inaudible, level.

Figure 2 illustrates how audibility is affected by the choice of frequency response. The data, in addition to the threshold and discomfort levels of a particular client, are the peak (rms + 12 dB) levels of speech amplified with three frequency responses and with gain adjusted for comfortable listening. Response 1 provides the most signal at frequencies below about 800 Hz but the least signal at frequencies above 1600 Hz. Similarly, the other two responses each provide the most signal at some frequencies but the least signal at other frequencies. Thus, the choice of frequency response affects the audibility of speech in different frequency regions and the crux of the selection problem is to find the best trade-off between greater audibility in some regions at the expense of less audibility in others.

The selection problem has been quantified by Studebaker (1992), who has combined the Articulation Index (Weighted Audibility Index) with a loudness model to calculate how audibility of speech is affected by changes in frequency response when a constant loudness level is maintained. An example calculated by this program (Studebaker and Sherbecoe, 1992) is shown in Figure 3.

The calculations are based on the frequency responses prescribed by four popular procedures for a person with a steeply sloping high-frequency hearing loss. The data points on the “0” vertical line show the Weighted Audibility Index for each procedure with the overall gain adjusted to provide the same loudness as the NAL prescription. The data points to the left and right of the line indicate how the index would change with variations in the overall slope of the frequency response. The significance of these data, to this discussion, is that they show that the choice of frequency response (i.e., the provision of a particular loudness relationship) can make a considerable difference to the Weighted Audibility Index, that is, to potential for understanding speech. Studebaker (1992) commented that “...when loudness was held constant, maximizing weighted audibility produced frequency-gain prescriptions that agreed with the NAL-R.
prescription to a surprising extent” (p. 118). This appears to confirm that the loudness relationship provided by the NAL procedure, namely, equal loudness across frequencies, does tend to achieve its aim of maximizing audibility at a comfortable level.

The above discussion has referred to frequency responses prescribed for linear amplification. However, nonlinear systems could also be considered in terms of what loudness relationship is best, for a particular listening condition or over a range of conditions, for maximizing some objective such as audibility and/or comfort and/or sound quality. This orientation may be more productive than trying to restore normal loudness or to compensate specifically for some other hearing loss characteristic.

What Bandwidths Should Be Normalized or Equalized?

A methodological problem when trying to normalize, or equalize, loudness across frequency is deciding what bandwidths to consider. Equalizing loudness for narrow bands, say 1/6 or 1/3-octave bands, may require different amplification from equalizing loudness for broader bands (Byrne, 1986). There is no obvious simple way of deciding what bandwidth is most appropriate, especially as it probably varies (as critical bandwidths do) across individuals. This issue needs clarification before any loudness rationales can be evaluated with confidence. It is also possible that there may be less difference between equal loudness and normal loudness if it is appropriate to consider broad rather than narrow bands.

Are Loudness Measurements Always Valid?

Research has demonstrated acceptable reliability for loudness scaling measurements and that such measurements produce similar loudness growth functions for nearly all normal-hearing listeners (Elberling and Nielsen, 1993; Hohmann and Kollmeier, 1995; Kiessling, 1995). However, this is not sufficient to show that loudness scaling always gives a valid indication of amplification requirements for hearing-impaired listeners. The justification for using loudness scaling, rather than simply measuring threshold or threshold and loudness discomfort level, is that some individuals will show loudness growth functions that are not predictable from other measurements. However, there is an unanswered question of whether, for such individuals, the loudness scaling data are the best indication of amplification requirements. It is possible that such “aberrant” scaling results (i.e., ones that are greatly different from those of other people with similar hearing losses) reflect differences in using the loudness labels, rather than or in addition to differences in loudness perception. Procedures based on loudness scaling assume that the difference between two labels (e.g., “very soft” and “very loud”) corresponds to a constant loudness difference across people, and we cannot be sure that this is entirely true. This poses a methodological problem for validation research and for the application of loudness scaling based fitting procedures. A research need is to investigate whether fittings based on unusual loudness data are better or poorer than ones that assume average loudness growth functions.

Is One Fitting Rationale Sufficient?

Even for linear amplification, a single fitting rationale is not sufficient for all degrees of hearing loss. Studies by Schwartz et al (1988) and Byrne et al (1990a) have indicated that fitting procedures need to be modified substantially when hearing losses exceed about 60 dB HTL. Theoretical reasons for this have been discussed by Van Tasell (1993), among others. Byrne et al (1990b) have shown that the revised NAL procedure achieved its aim of amplifying all speech regions to most comfortable loudness level (MCL) but that this rationale did not provide optimal amplification for some people with severe or profound hearing losses. Particular types of compression systems are usually designed for a
certain range of hearing losses and sometimes it is specifically acknowledged that other types of systems may be required for other degrees of hearing loss (e.g., Killion, 1993).

A further issue is whether a single fitting rationale, such as amplifying all speech bands to MCL, is appropriate for all listening conditions? Data from studies of multiple memory hearing aids (Keidser et al, 1996) suggest not. Keidser (1995) found that, under one condition, one type of compression was best, whereas a different type was best under another condition. Furthermore, both types of compression were inferior to linear amplification for some conditions. Specifically, high-frequency compression was best for understanding a dialogue between two voices that varied substantially (by 10 dB) in overall level; low-frequency compression was best for minimizing the annoyance of traffic noise; linear amplification with the NAL frequency response was best for listening to speech in quiet or in speech spectrum shaped noise; linear amplification with a low cut, relative to the NAL response, was best for understanding speech in traffic noise. These findings suggest that an adequate rationale for fitting compression amplification may need to consider differences in listening conditions as well as hearing loss characteristics. Such a rationale could lead to prescribing two or more types of compression, possibly including linear amplification, to be provided by a multiple memory hearing aid. Indeed, the same hearing aid may be fitted by different strategies (choices of which parameters are prescribed and on what basis), depending on what is considered to be the purpose of using compression (Dreschler, 1992).

Consistency with Current Fitting Rationales

With just a few exceptions (e.g., Kiessling and Steffens, 1991; Fabry, 1993; Cornelisse et al, 1995), the procedures suggested for fitting non-linear hearing aids start from "scratch" rather than attempting to build on existing procedures. Loudness normalization is, in fact, contrary to the rationale of most currently popular procedures for prescribing the frequency response of linear hearing aids. The NAL (Byrne and Dillon, 1986), Desirable Sensation Level (Seewald et al, 1985, 1991), and Memphis State University (Cox, 1983, 1988) are based on the rationale of amplifying all speech bands to MCL (or something equivalent), and the general idea is that this will maximize the potential for understanding speech when listening at a comfortable level. This means that the procedure is intended to compensate for interfrequency differences in the long-term speech spectrum as well as interfrequency differences in preferred listening levels. Some other procedures (e.g., Berger et al, 1977; McCandless and Lyregaard, 1983) have similar adjustments that result in prescribing less gain, for a given hearing level, at the low frequencies than at the mid and high frequencies. A considerable body of research (reviewed in Skinner, 1988; Byrne, 1993) supports the rationale of amplifying speech bands to MCL or similar rationales. That research supports "equal" rather than "normal" loudness as being the optimal relationship among the various frequency bands of speech. Furthermore, for listening in low-frequency weighted noise, such as traffic noise, the best frequency response may have less low frequencies than the NAL response (Keidser et al, 1996). Such a response would be further removed than the NAL response from what would be required to normalize loudness.

Comparisons of Fitting Rationales and Procedures

What differences will result from using different fitting rationales, as implemented in the various fitting procedures? An example comparing the loudness normalization and loudness equalization rationales is presented in Figure 4. This shows the gain and frequency response prescribed by the NAL and Fig. 6 procedures, for an average speech level, for 50 dB HTL across all frequencies.

The main difference between the procedures is that Fig. 6 prescribes a flat frequency response, whereas NAL prescribes a low-cut response, specifically less gain at the frequencies below 1000 Hz than at the mid and high frequencies. The main reason for the difference between prescriptions is that, in order to equalize loudness across frequencies, it is necessary to "flatten" the long-term average speech spectrum (LTASS) by varying the gain across frequency to compensate for the intensity differences of the different frequency bands of speech. The figure also shows the LTASS for speech, spoken with normal vocal effort (Byrne et al, 1994). Note that the LTASS and NAL response curves are approximately mirror images of each other in that the 8 dB higher speech level at 500 Hz compared with 1000 Hz is closely matched by the reduction in gain at 500 Hz. Therefore, when speech is amplified with the NAL response, the 500-Hz band will be about equal in intensity to the 1000-Hz band,
which will correspond (approximately) to equal loudness. By contrast, when speech is amplified with the Fig. 6 response, the normal intensity and loudness differences among different speech bands will be retained, that is, the low frequencies will be louder than the mid and high frequencies.

For flat audiograms (of 95 dB HTL or less), the frequency responses (but not absolute gain values) for NAL and Fig. 6 will always be the same as shown in Figure 4. Of greater interest is how the difference between loudness normalization and loudness equalization will vary for different input levels. Figure 4 shows the prescriptions of Fig. 6 for low and high, as well as for average, speech inputs. Although gain varies with input, the frequency response is flat for all levels. Although the NAL procedure does not provide prescriptions for low or high inputs, we might deduce that the NAL frequency response shown probably would not equalize loudness for all input levels. The procedure is, in effect, attempting to overlay the amplified LTASS on an equal loudness contour and the shape of such contours may vary with level. However, the calculation of equalization, or normalization, responses for various speech levels raises the complex and unresolved issue of what bandwidths to consider (see previous discussion) and the further complication, which is considered in the IHAFF procedure, that the LTASS varies with vocal effort.

A further illustration of the main difference between normalization and equalization, for an average input, is shown in Figure 5. For this client, whose audiogram slopes gently from 30 dB HTL at 500 Hz to 55 dB HTL at 6000 Hz, prescriptions were calculated according to two equalization procedures (NAL and DSL) and three normalization procedures (Fig. 6, LGOB, and IHAFF). Loudness scaling data were obtained for the LGOB procedure and these were also used, with some interpolation, to approximate the IHAFF procedure. The most obvious difference between the equalization and normalization response is that the former have a low cut below 1000 Hz, again demonstrating that equalization requires flattening of the LTASS, whereas normalization does not.

The five procedures were compared for seven clients, selected to present a wide variety of audiograms. In the example shown (see Fig. 5), the two equalization procedures prescribe responses that are similar (but certainly not identical) to each other, as do the three normalization procedures. However, this is not so for all clients. For steeply sloping high-frequency audiograms, DSL will prescribe far more high-frequency emphasis than NAL. This is because variations in audiogram slope are matched by about one-third as much variation in the frequency response slope for NAL but by about two-thirds as much variation for DSL. Thus, although the two procedures have essentially the same rationale, which is to amplify all speech bands to MCL, a characteristic of the calculation procedure (the slope rule) will result in considerably different prescriptions for some clients.
audiograms. A similar situation exists for the normalization procedures. Although the LGOB and IHAFF procedures have similar rationales, and the calculations used the same loudness scaling data, the prescribed responses (and overall gain) were considerably different in some instances. For example, for one client, for an average input level, LGOB prescribed a 1 dB/octave rising response between 500 Hz and 2000 Hz, whereas IHAFF prescribed a 5 dB/octave falling response. For this client, Fig. 6 prescribed a 6 dB/octave falling response and was, thus, very similar to IHAFF but, in other instances, Fig. 6 and IHAFF differed substantially. Such differences may result from differences in the calculation methods of the two procedures and/or because one procedure was based on loudness data and the other on HTLs.

It is evident from these comparisons that procedures based on the same rationale can result in substantially different prescriptions because of differences in how the rationale is implemented, that is, differences in the calculation methods. It is also true that the effects of differences in calculation methods can, coincidentally, tend to offset the effects of differences in rationale. This can mean that, for some people, basically different procedures can happen to provide similar prescriptions. For example, for moderately sloping high-frequency losses, NAL and Fig. 6 may give similar prescriptions despite the differences in rationales, which will lead to substantially different prescriptions for other audiogram configurations. A challenge for research is to evaluate different rationales without being misled by the effects of procedural differences that are incidental to those rationales.

Is Prescription Necessary for Compression Parameters?

Earlier (see Table 1), a list of possible prescriptive parameters was presented. However, do all of these parameters really need to be prescribed, that is, calculated in a relatively precise fashion from individually measured hearing loss characteristics? The answer will depend on what fitting rationale is adopted. Advocates of loudness normalization (e.g., Pluvinage, 1989; Cox, 1995) often suggest deriving a loudness growth function from measurements at several levels and at two or more frequencies. This information is used to calculate the required CRs in different bands and, possibly, the point at which compression reverts to linear amplification, if such a system is used. Such a procedure is only justified if one believes that it is important to achieve a close match between compression characteristics and loudness growth functions. If less precision is acceptable, then compression characteristics could be calculated from a more simple set of measurements. Loudness growth functions can be estimated reasonably well from dynamic range (LDL-HTL) (Elberling and Nielsen, 1993) or even from thresholds only (Hellman and Meiselman, 1990), although it appears that the accuracy of such prediction decreases as HTL becomes greater (Kiessling, 1995).

If the rationale for using compression is to reduce long-term variations in speech levels, then a slow-acting system could be used and there would seem to be little justification for precise selection of compression parameters. It may be reasonable to use the same compression for everyone or to use just two or three variations in parameter values, selected for clients grouped broadly according to dynamic ranges or hearing levels.

At present, it is not clear whether, or how much, the use of compression complicates the hearing aid selection process because it is uncertain to what extent compression parameters need to be prescribed. Resolving this question is important for developing effective and efficient selection procedures.

STAGED APPROACH FOR FITTING NONLINEAR HEARING AIDS

The demonstrated or hypothesized advantages of compression amplification have been indicated above. However, many authors have suggested that some types of compression could also be detrimental. The main problem is associated with fast-acting (syllabic) compression that reduces intensity differences between successive speech sounds and, if multiband compression is used, between simultaneously occurring components such as the vowel formants. This reduction in intensity differences, together with possible distortions of temporal information, may reduce important cues for speech perception (Boothroyd et al, 1988; Plomp, 1988; Moore, 1993; Van Tasell, 1993). Indeed, in a study with a master hearing aid system in which long-term variations in speech level were minimized and the output was delivered at the highest comfortable level, Boothroyd et al (1988) found that the addition of syllabic compression resulted in a decrement in speech perception for the majority of their profoundly hearing-
impaired subjects. Compression may also increase noise during the gaps between speech and may increase the likelihood of acoustic feedback, especially when it involves applying high gain to low-intensity, high-frequency sounds (Dillon, 1996).

The problem of using compression optimally can be viewed as finding ways to maximize the potentially beneficial effects while minimizing the potentially detrimental effects. The Moore system reduces the need for syllabic compression by preceding it with slow-acting compression to reduce the long-term variations in speech levels. It now seems widely believed that, to avoid excessive reduction of spectral contrasts in complex stimuli, multiband systems should use just two or three bands rather than a large number. Moore (1993) recommends that the bands of a compression system should be broad compared with auditory filters to avoid adding to speech perception problems arising from reduced frequency selectivity. Despite this rather general view, recent research by Crain and Yund (1995) suggests that it may not necessarily be detrimental to use as many as 31 bands in compression systems when accompanied by individual fitting.

In line with the suggestions of others, notably Boothroyd et al (1988) and Van Tasell (1993), a logical approach to using nonlinear amplification (or any other form of signal processing) would be to define an objective (e.g., maximizing audibility at a comfortable level), seek to achieve the objective to the greatest extent with the most simple means, and then use more complex processing only if it is advantageous and only to the extent necessary.

In the present context, application of the above approach would be to optimize linear amplification, then (if necessary) use slow-acting compression (which is mostly free of the above-mentioned detrimental effects), and finally to use syllabic compression only to the extent required.

A staged approach to providing speech audibility, starting with the least drastic “medicine,” is illustrated in Figures 6 and 7. The left panel of Figure 6 shows the LTASS for speech with an overall level of 70 dB SPL, relative to a flat hearing loss of 40 dB HTL. The greater part of the speech signal is audible, even without amplification, but the less intense components are not. Obviously, if the voice level drops below 70 dB SPL, a greater amount of speech will become inaudible. The right panel shows the LTASS amplified according to the NAL procedure for prescribing gain and frequency response. Except for very low frequencies, all of the speech signal is audible and would remain so even if the voice level dropped by 5 dB. A person with such a hearing loss should hear relatively well with linear amplification with suitable frequency shaping. However, the addition of compression might be helpful to cope with particularly low voice levels and to minimize the need for volume adjustments. These requirements could be met by a slow-acting system.

Figure 7 shows the situation for a person with a moderate low-frequency hearing loss sloping to a severe high-frequency hearing loss. In the unaided condition (left panel), only the low frequencies of speech are audible. If aided with a flat frequency response (right panel), audibility is improved for the mid frequencies but a large proportion of the signal above 1000 Hz is still inaudible. When aided with the NAL response, there is a further improvement but much of the high-frequency signal is still inaudible. What are the options for improving audibility of the high frequencies? One recurring suggestion is to provide whatever high-frequency emphasis is needed to maximize the AI (e.g., Dugal et al, 1980; Humes, 1986; Rancovic, 1991). However, providing more high-frequency gain will result in increased loudness, which will lead to a reduction in overall gain to maintain the preferred listening level. When the preferred loudness level is maintained, high-frequency emphasis in excess of that prescribed by the NAL procedure usually will not increase the AI when an appropriate hearing loss desensitization correction is made (Studebaker, 1992). This agrees with experimental findings that the extreme high-frequency emphasis indicated by

Figure 6 The long-term average (5-octave band) speech spectrum (broken lines show peak levels and minima) for an overall level of 70 dB SPL, shown in relation to a moderate flat hearing loss, without amplification (left panel) and amplified according to the NAL prescription.
higher CR would be required to provide a given degree of audibility.

The above analysis of when and what type of compression is needed is consistent with the findings of Moore and Glasberg (1993) who examined the effects of amplification on simulated hearing losses with recruitment. They concluded that linear amplification with the NAL frequency response was effective for listening to speech in quiet at an average level, but that an AVC system, or manual volume adjustments, would be required to maintain audibility for low-level inputs and comfort for high-level inputs. For listening in noise, consisting of a single talker, they concluded that syllabic compression at the high frequencies would be desirable for a sloping hearing loss similar to that illustrated in Figure 7. They suggest that, for such a case, the most likely explanation for the poor performance of linear amplification was that "the amount of high frequency amplification was not sufficient to restore audibility to all the important high-frequency components in speech" (p. 2060).

Although the approach outlined in this section is logical, it must be admitted that there is little solid evidence that syllabic compression systems can be detrimental (Dillon, 1996). It may be that a variety of fast-acting and slow-acting systems will have a similar beneficial effect in improving audibility and comfort for a wide range of input levels and with minimal use of volume adjustments.

CONCLUSIONS AND RECOMMENDATIONS

I have discussed some basic issues concerning the fitting of advanced hearing aids. Primarily, these relate to the selection of compression characteristics, together with the further complication that some aids also have multiple memories. In part, this article has been prompted by three concerns about current trends in fitting advanced hearing aids. First is a concern that, with the increasing development of proprietary fitting systems, there may be a proliferation of manufacturer-specific fitting formulae that may not be validated and, indeed, may not even be open to scrutiny. A related concern is that the clinician may finish up with little control over, or understanding of, the fitting process. A second concern is that nearly all current attempts to devise fitting procedures are based, to a greater or lesser extent, on a single rationale, namely, loudness normalization. Associated
with this is a lack of interest in critically evaluating that rationale or in considering other possible fitting rationales. Although loudness normalization is intuitively appealing, there are reasons to suspect that it may not be an optimal fitting rationale. A third concern is that most proposed procedures ignore the results of years of research into the amplification requirements of hearing-impaired people. With these concerns in mind, the following principles are suggested for approaching the development of fitting procedures for advanced hearing aids.

First, methods for prescribing advanced hearing aids should be based on current prescriptive principles and methods. Although the new hearing aids add complexities, there are common points of reference. For all hearing aids, we need to prescribe limiting and, for any given input, the amount of amplification (overall gain) and the frequency response shaping. For nonlinear aids, we need a series of different gain and frequency response prescriptions for different input levels and spectra. Most research underlying prescriptive procedures has been conducted with sensorineural listeners with, presumably, typical auditory characteristics such as loudness growth functions and dynamic range. To the extent that prescriptive procedures have been validated, the prescriptions may be considered appropriate for clients with the specified degree of hearing loss when receiving a typical hearing aid input. Typical overall speech input levels appear to be about 70 dB SPL for clients with moderate hearing losses (Martin et al, 1976; Walden et al, 1977; Farrell et al, 1979) and a few dB higher for clients with severe hearing losses (Byrne and Cotton, 1987; Parkinson et al, 1989). For a typical input level, the amplification requirements defined by research, using linear hearing aids, should be approximately correct for nonlinear hearing aids as well. Therefore, the better-validated current prescriptive procedures can provide a prescription for one input level for nonlinear hearing aids and this may provide a useful reference from which to calculate the variations in prescriptions required for other input levels. This seems preferable to developing completely new procedures that ignore the results of years of research. It should be stressed that the potential advantages of compression apply only to low inputs (improved audibility, no need to turn up volume) and to high inputs (greater comfort and/or reduction of masking, no need to turn down volume). There is little reason to suppose that the use of compression will change amplification requirements for moderate input levels. As moderate input levels are more common than either very low or very high levels, it would seem especially important to get this aspect of the prescription right.

In a similar vein, current prescriptive procedures provide the logical starting point for deriving a set of amplification prescriptions for multiple memory hearing aids. The prescription will be the best estimate of what is required for the most typical listening conditions and research will indicate how this needs to be varied to suit other acoustic conditions or listening needs. The research of Keidser et al (1996) supports this position in that the NAL prescription was usually effective for listening to speech in quiet or in noises with speech-like long-term spectra, whereas certain other frequency responses or compression conditions were better for some other listening conditions.

Second, research is essential to develop validated procedures for prescribing nonlinear amplification. Such procedures need to be supported by experimental evidence rather than logic alone or anecdotes. This is a substantial task that will probably require the efforts of many scientists from various academic and commercial settings. With a few exceptions (e.g., Lundh, 1981, 1983), there seems a regrettable little interest in tackling such basic questions as whether there is any value in attempting to normalize loudness growth functions. On the contrary, there is often a distressing tendency to assume that what seems right must be right even though some “right-sounding” theories are mutually contradictory. Preferably, research should elucidate the principles relevant to prescribing amplification rather than simply comparing two or more available systems. While it may be of some value to know that system A works better than system B, it is much more valuable to understand the relevant principles and thereby permit inferences about the likely effect of any of a wide range of systems. Indeed, this provides the basis for developing better systems. Research should include independent scientists and clinicians and should produce prescriptive procedures that can be applied generally rather than being specific to a particular brand of hearing aid (The IHAFF, Fig. 6, and DSL [i/o] are examples of such procedures). Research findings must be published in scientific journals so that they can undergo rigorous scrutiny and, hopefully, lead to independent confirmation. This process may be slow but the alternative would be that each type of advanced hearing aid will be fitted according to a different prescriptive formula supported by
little (if any) published research. Among other problems, that situation would make it difficult to evaluate the effectiveness of fitting formulae and the systems with which they are used without confounding one with the other.

Finally, this article is based on the common assumption that compression systems can be beneficial. Although compression reduces the need for manual volume adjustments, other benefits largely remain to be demonstrated (Dillon, 1996). The extent to which research can demonstrate such benefits, and their specific nature, should be a major consideration in developing fitting procedures.

Acknowledgment. I am very grateful to two anonymous reviewers and to the following people for their comments on an earlier draft of this manuscript: Arthur Boothroyd, Robyn Cox, Harvey Dillon, Donald Dirks, Klaus Elberling, Gitte Keidser, and Richard Tyler.

REFERENCES


