

NAL-NL1 Procedure for Fitting Nonlinear Hearing Aids: Characteristics and Comparisons with Other Procedures

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Abstract

A new procedure for fitting nonlinear hearing aids (National Acoustic Laboratories' nonlinear fitting procedure, version 1 [NAL-NL1]) is described. The rationale is to maximize speech intelligibility while constraining loudness to be normal or less. Speech intelligibility is predicted by the Speech Intelligibility Index (SII), which has been modified to account for the reduction in performance associated with increasing degrees of hearing loss, especially at high frequencies. Prescriptions are compared for the NAL-NL1, desired sensation level [input/output], FIG6, and a threshold version of the Independent Hearing Aid Fitting Forum procedures. For an average speech input level, the NAL-NL1 prescriptions are very similar to those of the well-established NAL-Revised, Profound procedure. Compared with the other procedures, NAL-NL1 prescribes less low-frequency gain for flat and upward sloping audiograms. It prescribes less high-frequency gain for steeply sloping high-frequency hearing losses. NAL-NL1 tends to prescribe less compression than the other procedures. All procedures differ considerably from one another for some audiograms.

Key Words: Hearing aid prescription, nonlinear amplification, speech intelligibility

Abbreviations: AI = Articulation Index, CR = compression ratio, CT = compression threshold; DSL[i/o] = desired sensation level [input/output], IHAFF = Independent Hearing Aid Fitting Forum, LGOB = loudness growth in 1/2-octave bands, NAL-NL1 = National Acoustic Laboratories' nonlinear fitting procedure, version 1, NAL-R = NAL Revised, NAL-RP = NAL-Revised, Profound, PLL = preferred listening level, POGO = prescription of gain and maximum output, RAB = Ricketts and Bentler, rms = root mean square, SII = Speech Intelligibility Index, WDRC = wide dynamic range compression

Over the past 50 to 60 years, and especially the last 25 years, there has been substantial research into the amplification needs of people with hearing impairments. This has led to the development of numerous hearing aid prescription procedures, including several that are supported, in varying degrees, by research (reviewed in Byrne, 1983, 1993; Skinner, 1988). The few well-established

procedures provide prescriptions only for linear amplification. This has become a serious limitation because most current hearing aids feature some form or forms of nonlinear amplification. Furthermore, although there is room for much debate about the specific benefits of different types of nonlinear amplification, it is widely accepted that compression amplification can be beneficial, at least in maintaining speech intelligibility and comfortable listening over a range of input conditions (Dillon, 1996). The use of compression only to provide low-distortion output limiting has minimal implications for hearing aid prescription. However, other forms of nonlinear amplification that are broadly designated wide dynamic range compression (WDRC) are now in common use. This has

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created an urgent need for procedures to prescribe compression characteristics and hence to specify how the gain-frequency response should vary with input level.

So far, two main approaches have been used for devising nonlinear amplification prescription procedures. First, as manufacturers of advanced hearing aids have been obliged to provide a fitting system, some manufacturers have developed their own prescription formulae, often in a form influenced by the features of a particular hearing aid. Some such methods are based on substantial research (Lunner et al, 1997a, b, c; Arlinger et al, 1998). Other methods may not be research based, or any such basis may not be published and available for scientific scrutiny. If all manufacturers adopted this approach, the likely result would be a proliferation of prescription methods of which some may be scientifically defensible but others may not. Among other possible problems, the person who is responsible for fitting a client may not be in control of the fitting process and may not even know what amplification is being provided. Furthermore, there is a dilemma if the audiologist believes that one manufacturer's device is most suitable but that the accompanying fitting procedure is not.

A second approach has been to develop a more generic prescription procedure, that is, one that is applicable to all types of aids or at least to a range of aids of broadly the same type. Over recent years, several such procedures have been developed and are completely "new" in the sense of having rationales that have little, if anything, in common with those of existing linear prescription procedures. The majority of the new procedures, such as loudness growth in $\frac{1}{2}$ -octave bands (LGOB) (Allen et al, 1990), Independent Hearing Aid Fitting Forum (IHAFF) (Cox, 1995), Ricketts and Bentler (RAB) (Ricketts, 1996) ScalAdapt (Kiessling et al, 1996), and FIG6 (Killion and Fikret-Pasa, 1993), have a loudness normalization rationale. There are two aspects to normalization, as it is applied in the new procedures. First, the overall loudness of sounds is normalized. Thus, sounds that would be soft or loud for a normally hearing person will be amplified to be soft or loud, respectively, to a person with a hearing impairment. Second, the relative loudness of different frequency components of complex sounds will be preserved. Thus, for example, the softer frequency components of speech will continue to be softer than other frequencies after amplification. Although the idea of loudness normalization is appealing intu-

tively, it has been argued that it may not be optimal (Byrne, 1996). Briefly, the argument is that normalization will not optimize the audibility and intelligibility of speech. For people with mild or moderate hearing loss, the evidence validating linear procedures supports a loudness equalization, rather than normalization, fitting rationale. By equalization, we mean that all frequency bands of speech will be amplified to contribute equally to the loudness of the speech.

Not all new procedures are based on loudness normalization. Moore et al (1998) have questioned whether normalization is an appropriate goal and have proposed a fitting procedure with the rationale of "giving good audibility for speech over a wide range of sound input levels while maintaining listening comfort" (p.178). The procedure is based on loudness and quality judgments of speech presented through a hearing aid. The gain in each band of a multiband hearing aid is adjusted so that speech of 85 dB SPL is judged to be "loud" and speech of 60 dB SPL is judged to be "quiet" and that speech at both levels is neither "tinny" nor "boomy." In the present classification, the status of the desired sensation level [input/output] (DSL[i/o]) procedure is ambiguous in that the formula originally presented (Cornelisse et al, 1995) normalized loudness, whereas it has been more recently described as a loudness equalization procedure but one that can be modified to provide normalization (Seewald et al, 1996).

Many aspects of any nonlinear procedures must be new because there is no significant research to indicate optimal strategies for amplifying low- or high-level inputs. However, the research supporting linear procedures does indicate appropriate strategies for an average speech input level. Therefore, a well-validated linear procedure can provide a good estimate of what should be prescribed by a nonlinear procedure for an average speech input level. This suggests a third possible approach for developing a nonlinear prescription procedure, namely, extending an established, validated procedure, rather than developing a completely new one. The advantage of doing this is that, provided that the original and extended procedures agree for an average input, the extended procedure can be considered to be validated with respect to the average level prescriptions. This is a substantial, and probably the single most important, part of the prescription as average speech levels are the most common input levels. Indeed, people tend to adopt strategies to receive average level inputs whenever possible (e.g., by adjusting the

TV volume or moving closer to or away from a soft or loud talker). Thus, a validated linear procedure can provide part of a nonlinear procedure or can be used to check the validity of an important part of a nonlinear procedure. There remains the question of deriving prescriptions for inputs that are significantly higher or lower than average. For the present, such prescriptions must be based mainly on logic as there is very limited evidence on which compression thresholds (CTs) and ratios (CRs) are best.

This article concerns a nonlinear procedure that may be viewed as an extension of the National Acoustic Laboratories' Revised (NAL-R) linear procedure (Byrne and Dillon, 1986), later modified for severe hearing losses to become NAL-Revised, Profound (Byrne et al, 1991). We present an overview of the features of the new nonlinear fitting procedure, designated NAL-NL1, describe and discuss some implications of the resulting prescriptions, and compare the prescriptions with ones derived from some other procedures. We conclude by discussing some validation issues that are critical for all procedures. The NAL-R procedure was considered to be a suitable basis for extending because it was derived from research (Byrne, 1986a, b; Byrne and Murray, 1986), was subsequently validated (Byrne and Cotton, 1988), and appears to be widely accepted and used (Martin et al, 1998). Similarly, the modifications leading to NAL-RP were based on research (Byrne et al, 1990), and the prescriptions for severe hearing losses have been supported by research (Snik et al, 1995; Ching et al, 1996). Furthermore, the main principles that are common to NAL-R and some other linear procedures, such as the half-gain rule and loudness equalization, are well supported by research (reviewed in Skinner, 1988; Byrne, 1993).

NAL HEARING AID PRESCRIPTION PROCEDURES

Principles of NAL Linear Procedures (NAL, NAL-R, NAL-RP)

It is pertinent to review the principles of NAL linear procedures because they also provide much of the theoretical basis for the new, nonlinear procedure. In the original NAL procedure (Byrne and Tonisson, 1976), the gain prescription was based on data (Byrne and Fifield, 1974) that verified the "half-gain rule" proposed by Lybarger (1944). Specifically, gain was increased at 0.46 times the rate that hear-

ing threshold level increased. The prescription of frequency response was based on the concept of maximizing the amount of audible signal and thereby maximizing the potential for understanding speech, as predicted from the Articulation Index (AI) (ANSI, 1969). It was reasoned that, when a hearing aid's volume was set at the preferred level, audibility would be maximized if all frequency bands of speech contributed equally to loudness. This loudness equalization concept may be best understood by considering the reverse situation. If loudness is determined predominantly by the levels in just one or a few frequency bands, and the hearing aid's volume is adjusted to maintain comfortable listening, then the levels in some other frequency bands are likely to be soft or even inaudible. Thus, equalizing loudness across frequency bands should, for any selected loudness level, approximately maximize the amount of audible signal averaged over a wide frequency range.

Research that evaluated the original NAL procedure (Byrne, 1986a, b) supported the loudness equalization principle but showed that the original formula did not achieve this aim. The formula was, therefore, revised on the basis of the evaluation data and that of a follow-up study (Byrne and Murray, 1986) to provide the NAL-R procedure (Byrne and Dillon, 1986). (The NAL-R designation was used first by Humes [1986] and came into general use.) Thus, NAL-R was a revised formula designed to achieve the aim of the original procedure, namely, loudness equalization. It also used the half-gain rule for prescribing average gain, but frequency response was varied according to a "third-slope" rule in place of the original "half-slope" rule (i.e., variations in audiogram slope are compensated for by about one-third as much variation in frequency response slope).

From the outset (Byrne and Tonisson, 1976), it was appreciated that a half-gain rule and the loudness equalization principle might not be optimal for severe hearing losses. A half-gain rule might not provide adequate audibility, and the equalization principle is logical only if it is assumed that useful hearing is available over a wide frequency range and that a given amount of audibility has a similar value at all frequencies. A study by Byrne et al (1990) confirmed that the NAL-R procedure needed to be modified for severe hearing losses. When hearing level exceeded about 60 dB, the gain rule needed to be changed to a "two-thirds" rule, and when hearing loss was profound at the high frequencies, the frequency response needed to have

more low-frequency emphasis than that prescribed by NAL-R. From these data, the procedure was further modified and is now designated NAL-RP. The aim of this procedure, like its predecessors, was to maximize speech intelligibility. For most hearing losses, that aim will be achieved with a frequency response that follows, approximately, the equalization principle. However, when hearing loss is profound at the high frequencies, maximal speech intelligibility will be obtained by amplifying those frequencies to contribute less to audibility and loudness than the other frequencies.

Principles of NAL Nonlinear Procedure (NAL-NL1)

The NAL nonlinear prescription procedure, NAL-NL1, has a similar rationale to previous procedures in that it aims to maximize speech intelligibility for a specified loudness level. However, if all speech inputs were amplified to the same loudness level, say the preferred listening level or the level that maximized intelligibility, it is highly probable that the speech quality would be unacceptable. That is, it seems assured that some variation in loudness levels is needed to preserve a natural speech quality. In the absence of any data to indicate what loudness variation is desirable, we have adopted the principle of amplifying speech to normal loudness or to a lower level if it provides greater speech intelligibility. Thus, loudness normalization is applied to overall speech levels except that high speech inputs will often be amplified to less than normal loudness because this should result in greater speech intelligibility. The NAL-NL1 procedure does not aim to normalize the relative levels of the different frequency components of speech, and it will be shown later that it does not do so. Unlike the NAL-R procedure, NAL-NL1 is not designed to equalize loudness across frequency, but it does tend to do so as a consequence of optimizing the predicted speech intelligibility for a specified loudness.

Derivation of NAL-NL1 Procedure

General Description

The NAL-NL1 procedure was derived by calculations that combined a loudness model (Moore and Glasberg, 1997) with a modified form of the Speech Intelligibility Index (SII) (ANSI, 1993). The SII includes a level distortion correction whereby the SII is proportionately

reduced as the speech level exceeds 73 dB SPL. However, this correction for listening at high levels, as hearing aid users must do, has been shown to be insufficient to account for the speech recognition difficulties of hearing-impaired people (Ching et al, 1998; Hogan and Turner, 1998). Therefore, we modified the SII by an effective audibility correction calculated from the data of Ching et al (1998). This correction encompasses the reduction in speech intelligibility arising from listening at high levels plus a further reduction associated with increasing degrees of hearing loss. This latter factor has been designated hearing loss desensitization (Studebaker and Sherbecoe, 1992) and possibly may be related to such factors as reduced temporal or frequency resolution. The effect of the effective audibility correction is that, for a given amount of speech audibility, the SII contribution is reduced as hearing level becomes greater. The correction is larger for the high than for the low frequencies and is larger for high sensation levels than for low sensation levels. The main implication for hearing aid fitting is that the frequency response required to optimize the SII for sloping audiograms will have less high-frequency emphasis than it would if the standard level distortion correction were the only correction used. The estimated optimal frequency response will have considerably less high-frequency emphasis than it would if calculated from one of the simplified AI procedures that include neither a hearing loss desensitization nor level distortion correction. The complex procedure of deriving our effective audibility correction will be described in a separate article (Ching et al), together with a general discussion of the relationship of audibility to speech intelligibility.

The derivation procedure involved calculating prescriptions for several input levels for 52 audiograms that represented all of the common variations in severity and configuration of hearing loss. For each input level, a program calculated the normal loudness level of speech for the international long-term average speech spectrum (Byrne et al, 1994). Then, for each input/audiogram combination, the program manipulated the gains in each $\frac{1}{3}$ -octave band until the SII was maximized and the loudness was constrained to be normal or to a lower loudness level if that achieved a higher SII. The procedure was very complex and involved various constraints, such as disregarding any frequency that could not make more than a minuscule contribution to the SII. (To do otherwise resulted in unrealistic prescriptions such

as recommending extremely high gain at 6000 or 8000 Hz.)

Example of Derivation Procedure

The calculations produced three types of output for each audiogram and input level. This is illustrated in Figure 1, which shows the data for the 65 dB SPL input for one audiogram. The top panel shows the insertion gain/frequency response curve that is optimal in the sense that the SII has been maximized while loudness has been constrained to be normal or less. Such curves may be regarded as the primary output from our computations in that they comprise the data used for calculating the NAL-NL1 insertion gain prescription formula. The audiogram and the NAL-RP prescription are also shown. A middle panel shows the specific loudness in each frequency band obtained with the optimized frequency response and the overall loudness adjusted to 23.43 sones, which is the calculated normal loudness for speech with a root mean square (rms) level of 65 dB SPL. Also shown is the specific loudness pattern of normal loudness for each frequency band of speech. The bottom panel shows three graphs in which the data are expressed as the contributions of each frequency band to the SII. The highest of the three graphs shows simple audibility, which is the difference between the speech peak levels and hearing threshold level. (In this context, “peak” refers to the maximum short-term rms levels, which are assumed to be 15 dB above the long-term rms levels.) A value of 1.0 would indicate that audibility in that band is sufficient to make a maximal contribution to intelligibility. Perfect speech intelligibility would be predicted if the value were 1 across all frequencies. A second graph shows effective audibility. The audibility contributions have been reduced to account for listening to amplified speech at a level exceeding 73 dB SPL and to account for the reduced capacity to use audible information that results from a hearing loss. Except for frequencies below 500 Hz, effective audibility is less than simple audibility. The third graph shows effective audibility times the importance function for average speech. These values have been multiplied by 10 to fit conveniently on the same figure. The values shown are for critical bandwidths, and the SII is the sum of the values for all critical bands, divided by 10. A hearing aid prescription was derived by combining the primary graphs for several input levels. The second and third types of graphs proved to be very useful for under-

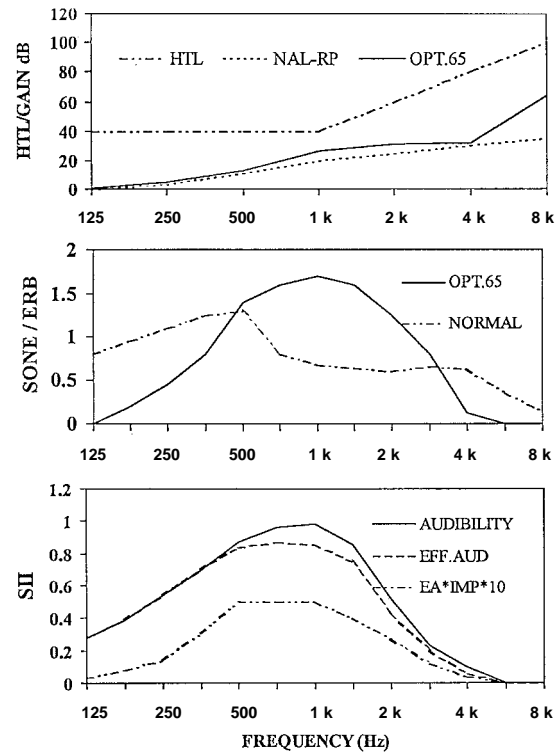


Figure 1 Example of the outputs obtained for one audiogram and one input level during the derivation of the NAL-NL1 procedure. The top panel shows the audiogram (HTL), the optimized gain/frequency response for a 65 dB SPL speech input (OPT.65), and the gain/frequency response prescribed by the NAL-RP procedure. The center panel shows the specific loudness pattern, for a person with this audiogram, of speech amplified by the optimized gain/frequency response. Also shown is the specific loudness pattern of unamplified speech for a person with normal hearing. The bottom panel shows the audibility of speech, for the above audiogram and the optimized amplification, expressed as the contribution of each frequency band (in quarter equivalent rectangular bands) to the Speech Intelligibility Index. The graphs show (a) simple audibility, depending only on sensation level (40 dB SL = 1); (b) effective audibility (audibility reduced to allow for level distortion and hearing loss desensitization); and (c) effective audibility times the importance function for average speech, scaled by 10.

standing the implications of the calculation procedure and for detecting anomalies that required correction.

The graphs shown in Figure 1 illustrate some interesting characteristics of the NAL-NL1 procedure. The graph in the middle panel is typical of such graphs for all of our audiograms in that it shows a range where the specific loudness is approximately equal across frequencies. This range is centered around 1000 Hz and becomes wider as input level increases. It bears

repeating that the calculations were not designed to equalize specific loudness, but rather this is the result of optimizing the SII while constraining the overall loudness to a particular level. Thus, this result confirms the loudness equalization rationale that has been the basis of the linear NAL procedures, apart from the modifications for severe hearing losses. The NAL-NL1 calculations do not support the idea of normalizing loudness across frequencies. That would require a different specific loudness pattern, as is also shown on the figure. The bottom panel shows simple audibility, effective audibility, and effective audibility times the importance function, at each frequency. The highest and lowest frequencies make little, if any, contribution to the SII. It can be seen (middle panel) that those extreme frequencies are also making little contribution to loudness. In our final calculations, we excluded frequencies that were making less than a 0.0015 (shown as 0.015 on the figure) contribution to the SII. The practical implication of these data is that the gain at the extreme frequencies could be increased or decreased substantially without making any difference to either loudness or speech intelligibility. In this example, we would disregard the gain prescription for frequencies above 4000 Hz. Needless to say, this figure presents just one example. The range of frequencies that contribute to the SII will vary for other audiograms and other input levels.

NAL-NL1 Insertion Gain Prescription Formula

The procedure described above is far too laborious to be practical for clinical use. Therefore, we took the resulting prescriptions and applied a curve fitting process to derive a usable prescription formula. That formula, which will not be made public, is too complex to be used manually. It has been implemented in a computer program and will be made available to manufacturers who wish to use it in their fitting or measurement software. The factors encompassed by the formula, for calculating insertion gain at each frequency, are hearing level and air-bone gap at that frequency, three-frequency average hearing level, and the overall speech input level. It may be noted from Figure 1 (top panel) that the NAL-NL1 prescription (before simplification and final adjustments) for an average speech level (65–70 dB) agrees closely with the NAL-RP prescription that is also shown on the figure. Approximate agreement was

achieved for the whole set of audiograms used in the derivation process. Nonetheless, as we shall illustrate later (Table 1), there were small discrepancies between the prescriptions derived from the two formulae. This is to be expected, considering that the formulae provided completely independent estimates of the gain and frequency response required for an average input level for each audiogram. We considered that both of these estimates had good credibility, and that, therefore, the final NAL-NL1 procedure should be calculated to be an average of the two estimates. In other words, for an average input level, NAL-NL1 was adjusted by half of the difference between its original prescriptions and the NAL-RP prescriptions. Prescriptions for other input levels were adjusted by the same amount as prescriptions for the 70-dB input level. If, for example, for a particular audiogram, the original prescription at 3000 Hz for a 70-dB input level was 6 dB higher than the NAL-RP prescription, prescriptions at 3000 Hz for all input levels were reduced by 3 dB. This adjustment was carried out prior to the final curve fitting process.

Implementation of NAL-NL1

The insertion gain prescription formula, derived in the manner described above, has been implemented in a more comprehensive hearing aid fitting program. The software has screens for recording client data; for entering the audiogram; for specifying the type of hearing aid, number of hearing aids (unilateral or bilateral), and number of channels (one to four); and for displaying the prescription. The “target” screen permits the prescriptions to be displayed in several forms that include real-ear insertion gain, real-ear aided gain, real-ear aided threshold, several forms of coupler gain, input/output curves, and an aided speech spectrum display. In addition to the graphs, the target screen provides prescriptions in the form of crossover frequencies and, for each channel, CT, CR, and gain for input levels of 50, 65, and 80 dB SPL.

The NAL-NL1 formula prescribes gain/frequency curves for a series of input levels. The complete prescription, as described above, requires additional formulae and calculations. The default compression threshold (CT) values are calculated so that a speech input of 52 dB SPL will just activate the compression. This value is a compromise. It was chosen because NAL research (Dillon et al, 1998; Barker and Dillon, 1999) has indicated that, for single-channel

hearing aids with fast-acting compressors, the majority of hearing aid wearers prefer a CT in excess of 60 dB SPL rather than the lower values that are often advocated. The default CT for pure tones will depend on the number of hearing aid channels. For a one-channel hearing aid, the default CT will vary from 61 dB SPL at 400 Hz to 44 dB SPL at 4000 Hz. There is an option for the audiologist to set the CT to any desired speech input level, and the pure-tone CT can be changed for any channel. The software calculates the CR prescriptions by fitting a straight line to the input/output curve above the CT.

The selection of number of channels is left to the hearing aid fitter to decide. Presumably, this will depend on the model of hearing aid that is being considered. The crossover frequencies, and hence the frequency ranges of each channel, are based on the audiogram in such a way that hearing threshold varies by the smallest degree possible within each channel.

COMPARISONS OF NAL-NL1 PRESCRIPTIONS WITH OTHER PROCEDURES

Comparison Method

NAL-NL1 prescriptions were calculated for 13 audiograms representing various degrees of flat, gently sloping, steeply sloping, and reverse sloping configurations. Similar calculations were made for the NAL-RP, FIG6, and DSL[i/o] procedures. We also included a threshold version of the loudness-scaling-based procedure of Cox (1995). That procedure seems most commonly known as the IHAFF protocol (Valente and Van Vliet, 1997). The DSL[i/o] prescriptions were expressed as insertion gain by subtracting the eardrum to free field transfer function (Bentler and Pavlovic, 1989) from the DSL[i/o] real-ear aided gain prescription for a speech-weighted input. The CT was set at 50 dB SPL to make the prescriptions most comparable to the NAL prescriptions. The DSL prescriptions are for soft, average, and loud speech. The other prescriptions are for input levels of 50, 65, and 80 dB SPL. The purpose of this exercise was to indicate the range of prescriptions provided by NAL-NL1 and to ascertain how they compared with the prescriptions of other available procedures.

Before presenting the comparisons, it is necessary to explain three characteristics of the NAL-NL1 graphs. First, the gain/frequency response prescriptions for pure-tone inputs vary

depending on whether a single-channel or a multichannel aid is selected. At each frequency and input level, NAL-NL1 prescribes a certain gain for broadband input signals such as speech, irrespective of the number of channels. In any multichannel nonlinear hearing aid, however, the power falling into any channel is less than the total power of the input signal, particularly for high-frequency channels. When a pure-tone signal is input, all of its power falls into a single channel at any one time. Consequently, if the channel is in compression, the hearing aid will apply a lower gain for a pure tone than it would for a broadband signal at the same total level. The gain difference increases as the channel bandwidth decreases and increases as the CR increases. The gain difference, typically 5 dB at the most affected frequencies, mostly occurs when changing from one to two channels, but smaller differences may occur when changing from two to three or three to four channels. As the number of channels is not considered specifically in the FIG6, IHAFF, or DSL procedures, it is not clear which form of the NAL-NL1 prescription is most appropriate for comparison. We calculated NAL-NL1 prescriptions for each number of channels. Fortunately, the rather general conclusions that will be stated are not affected by which form of the NAL-NL1 prescription we use.

Second, the gains prescribed by NAL-NL1 at different frequencies are generally lower for a bilateral fitting relative to a unilateral fitting to take account of loudness summation effects. Because other prescriptions do not include considerations for the number of hearing aids fitted, the NAL-NL1 prescriptions used in the comparisons are based on averaging gain required for a unilateral and a bilateral fitting.

Third, in some NAL-NL1 graphs, no prescription is provided at some of the highest and/or lowest frequencies. The reason is that these frequencies cannot contribute significantly to the predicted speech intelligibility regardless of how much gain is provided. Our recommendation is that the gain should be equal to or less than that at adjacent frequencies. The actual amount may be determined by practical considerations such as avoiding acoustic feedback or providing what is easiest to achieve when the prescription has been met at other frequencies.

In the following sections, we present examples of the prescriptions of NAL-NL1 (for a three-channel aid) and the comparison procedures for each of five audiograms, together with

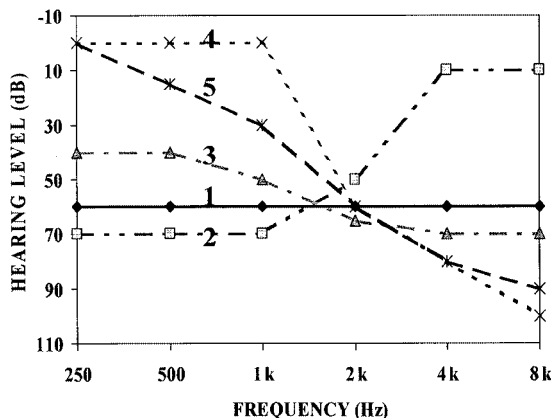


Figure 2 Examples of audiograms used for comparing prescriptive procedures, as shown in Figures 3 to 7.

some observations based on inspection of the full set of 13 audiograms. Before considering the nonlinear procedures, we shall show how NAL-RP prescriptions compare with the NAL-NL1 prescriptions for an average input level (65 dB SPL).

Results of Comparisons

NAL-NL1 versus NAL-RP

Figure 2 shows five sample audiograms. The prescriptions that follow assume that all of the hearing losses are sensorineural. (The NAL-NL1 program prescribes additional gain for conductive or mixed hearing losses.) Table 1 shows how the NAL-NL1 prescriptions for 65 dB SPL input compare with NAL-RP prescriptions.

Flat Audiograms

Figure 3 shows the prescriptions (insertion gain curves) for a flat 60 dB HTL. The NAL and IHAFF prescriptions are shown in the left panel, and the FIG6 and DSL[i/o] prescriptions are shown in the right panel.

The three NAL curves are relatively flat above 1000 Hz. Below 1000 Hz, there is a low-frequency cut that is greatest for the lowest input level. At the low frequencies (below 1000 Hz), there is not much difference in the gain prescribed for low and high inputs, thus indicating that there is not much compression. At the higher frequencies, the gain difference is about 15 dB, which would indicate about 2:1 compression if applied over the whole range of inputs from 50 to 80 dB. The prescribed CRs for a three-channel aid, with the CT at the default set-

Table 1 Differences Between Insertion Gain Prescribed by NAL-NL1, for 65 dB SPL Input, and NAL-RP Procedures for the Five Sample Audiograms Shown in Figure 2

Audiogram	Frequency (kHz)						rms
	0.25	0.5	1	2	4	6	
1	0.5	-1	0	1	2	2	1.3
2	0	-2	0.5	0	-1.5	0	1.0
3	1	-3	0	1	2		1.7
4	0	0	2.5	0	0		1.1
5	0	0	-0.5	0.5	1.5		0.7

The values are NAL-NL1 gain minus NAL-RP gain. The differences are shown for six frequencies together with the root mean square (rms) difference.

ting of 52 dB SPL for speech, were 1.23 at 315 Hz (pure-tone CT = 55 dB), 1.53 at 630 Hz (CT = 57 dB), and 2.23 at 2500 Hz (CT = 44 dB).

The IHAFF prescription is very different from NAL in that it is a low-frequency emphasis response. Although the gain prescriptions of the two procedures are broadly similar above 1000 Hz, IHAFF prescribes far more gain at the low frequencies. The differences between the three IHAFF curves indicate that the procedure prescribes somewhat more than 2:1 compression for all frequencies. The FIG6 procedure prescribes a flat frequency response, for all input levels, for a flat audiogram. For this 60 dB HTL, the CR appears to be 2.6. (The FIG6 program actually prescribes a CR of 2.9 for 40- to 65-dB input levels and a CR of 2.3 for 65- to 95-dB input levels.) FIG6 and DSL both prescribe more low-frequency gain than the NAL but less than the IHAFF.

In this example and in the following figures, the DSL[i/o] prescription is almost the same for the soft and average speech inputs. This reflects the selection of a relatively high CT (50 dB SPL). In other words, nearly all input levels up to the

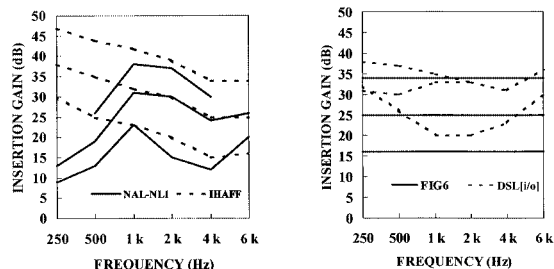


Figure 3 Prescriptions for flat audiogram (1), for inputs of 50, 65, and 80 dB SPL, of NAL-NL1, IHAFF (threshold version), FIG6, and DSL[i/o] procedures.

average level are amplified with the same gain (i.e., linearly). If the CT is set lower, the soft speech input will be given more gain than the average input. This does not happen to the same extent for NAL-NL1 because CT is varied for each channel of a multichannel aid and, as shown above and in the following examples, the CT at the higher frequencies is less than 50 dB SPL.

Reverse Slope Audiogram

Figure 4 shows the prescriptions for the reverse slope audiogram. NAL-NL1 prescribes most gain at the mid frequencies, with less at the low frequencies (500 Hz and lower) and least at the high frequencies (above 3000 Hz). The prescribed CRs for a three-channel aid are 1.47, 2.24, and 1.38 for the low, mid, and high frequencies, respectively. The three comparison procedures prescribe similar gain to NAL-NL1 at the mid frequencies (1000 Hz and 2000 Hz) but a little less than NAL-NL1 at the high frequencies and considerably more at the low frequencies. As for the flat audiogram, the IHAFF prescribes the most low-frequency gain. The comparison procedures prescribe the most compression at the low frequencies. The CRs at 500 Hz range from about 1.5 for DSL[i/o] to about 3 for the IHAFF. For DSL[i/o], the gain for low and average levels is the same at frequencies above 1000 Hz (i.e., amplification is linear for all below-average inputs).

Moderately Sloping High-Frequency Hearing Loss

Figure 5 shows the prescriptions for the moderately sloping audiogram. NAL-NL1 prescribes a moderate degree of high-frequency emphasis with little gain and little compression at frequencies of 500 Hz and below where the hearing loss is mild. At higher frequencies, the prescribed CRs are 2.0 and 2.18 at 1600 and 4000 Hz, respec-

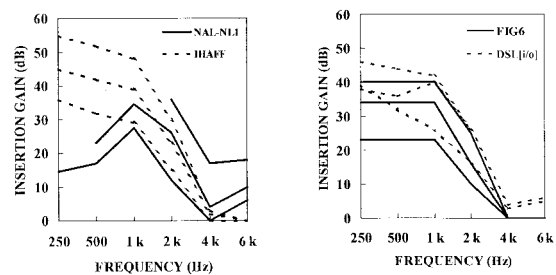


Figure 4 Prescriptions for reverse slope audiogram (2), for inputs of 50, 65, and 80 dB SPL, of NAL-NL1, IHAFF (threshold version), FIG6, and DSL[i/o] procedures.

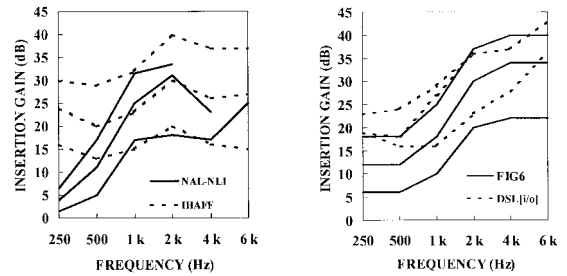


Figure 5 Prescriptions for moderately sloping audiogram (3), for inputs of 50, 65, and 80 dB SPL, of NAL-NL1, IHAFF (threshold version), FIG6, and DSL[i/o] procedures.

tively. The comparison procedures prescribe similar gain to NAL at the mid frequencies (1000–2000 Hz). At the low frequencies, they prescribe more gain than NAL-NL1 and a significant degree of compression. At frequencies at and above 4000 Hz, FIG6 and DSL[i/o] prescribe more gain than NAL.

Steeply Sloping High-Frequency Hearing Losses

Figures 6 and 7 show the prescriptions for the two steeply sloping audiograms. NAL-NL1 provides a substantial degree of high-frequency emphasis with no gain at the low frequencies, which have normal or near-normal hearing. At 1600 and 4000 Hz, respectively, the prescribed CRs are 1.48 and 1.86 for audiogram 4 and 1.67 and 2.06 for audiogram 5. The comparison procedures prescribe more high-frequency emphasis than NAL-NL1. The IHAFF and FIG6 also prescribe more compression at the high frequencies. The differences in frequency response are most evident from the gain at 4000 Hz or by comparing the response slopes from 1000 to 4000 Hz. For example, for the 65-dB input for audiogram 4, the slopes (4000 Hz gain minus

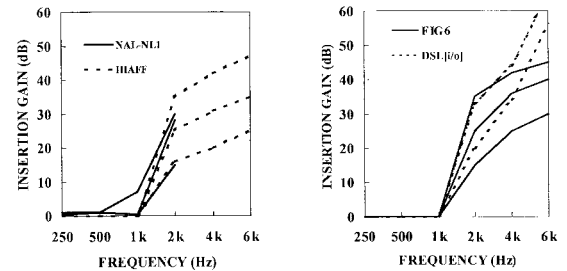


Figure 6 Prescriptions for steeply sloping audiogram (4), for inputs of 50, 65, and 80 dB SPL, of NAL-NL1, IHAFF (threshold version), FIG6, and DSL[i/o] procedures.

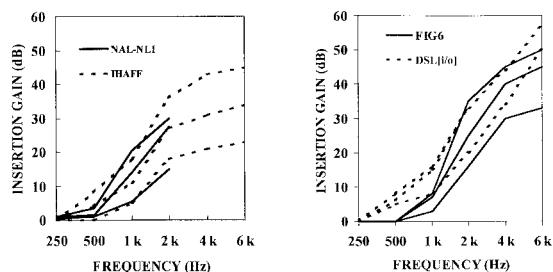


Figure 7 Prescriptions for steeply sloping audiogram (5), for inputs of 50, 65, and 80 dB SPL, of NAL-NL1, IHAFF (threshold version), FIG6, and DSL[i/o] procedures.

1000 Hz gain) are 19 dB for NAL-NL1, 30 dB for IHAFF, 35 dB for FIG6, and 44 dB for DSL[i/o]. If we consider a variation of audiogram 4 in which the hearing threshold levels at 2000 and 4000 Hz are increased to 85 and 105 dB, respectively, then NAL-NL1 will not provide a prescription for frequencies above 2500 Hz. Thus, although the comparison procedures would prescribe considerably more gain at 4000 than at 2500 Hz, NAL-NL1 predicts that the gain at the higher frequencies will not make any difference to speech intelligibility and, therefore, recommends gain that is equal to or less than the gain at 2500 Hz.

DISCUSSION

Characteristics of NAL-NL1 Prescriptions

For an average speech input level (65 or 70 dB SPL), NAL-NL1 prescriptions agree closely with NAL-RP prescriptions. This agreement is partly because the final NAL-NL1 prescriptions are averages of those obtained from the NAL-NL1 derivation procedure and those of NAL-RP. However, the agreement is still relatively good if we consider the NAL-NL1 prescriptions as originally derived. Examples of such prescriptions can be deduced from Table 1 as they simply differ from NAL-RP by twice as much as the NAL-NL1 prescriptions that are shown.

The gain prescribed for various input levels, for each channel, is greatest for the lowest inputs and least for the highest inputs (i.e., compression). The amount of compression varies with frequency and hearing loss, tending to be greatest at the highest frequencies and the larger hearing losses. At frequencies where there is sufficient hearing loss to require amplification, CRs are usually in the range from 1.3 to 2.3:1.

For sloping audiograms, the frequencies with the greatest hearing loss will usually be associated with the most reduction in dynamic range and will, thereby, tend to need the most compression. When the degree of compression is frequency dependent, the frequency response prescriptions for a nonlinear aid will be level dependent. This is true for the NAL-NL1 prescriptions but less so than might be expected from considering loudness perception data. For example, we might expect that the frequency response curves for a sloping hearing loss would become flatter as input increases because equal loudness curves become flatter at higher levels. However, this does not consistently happen to the degree expected on the basis of loudness normalization. An explanation is apparent from examining specific loudness and weighted audibility graphs of the type shown in Figure 1. When the hearing loss at the low frequencies is only moderate, relatively little low-frequency gain is required to maximize the SII contribution of the low frequencies for an average, or even soft, input level. Consequently, when the input is increased, there may be no advantage in increasing the low-frequency output level; therefore, the frequency response required to maximize speech intelligibility may steepen rather than flatten. Of course, this is directly the result of using a calculation method that maximizes predicted speech intelligibility. There may be other reasons, perhaps related to speech quality or the detection and localization of sounds, that argue against too much limitation of low-frequency signal.

A distinctive feature of NAL-NL1 is that it may not provide a prescription at the most extreme frequencies. This is especially likely to occur at the high frequencies if hearing loss is severe. The reason is that amplified signal at those frequencies can make no more than a minimal contribution to predicted speech intelligibility. This is partly because of limited capacity to use high-frequency information (i.e., hearing loss desensitization) and partly because even the maximal contribution of those frequencies to the SII is small.

As illustrated in Figure 1, NAL-NL1 tends to equalize loudness across frequencies for mild and moderate hearing losses, except at the most extreme frequencies. The range of frequencies over which loudness is equalized widens as input level increases. This is a consequence of striving to maximize speech intelligibility while constraining overall loudness. It is interesting and reassuring that this occurs as it agrees with

the rationale of the NAL-R linear procedures, which was to equalize loudness except for the modifications for severe hearing losses. As also noted here (Fig. 1) and by Moore and Glasberg (1998), a different specific loudness pattern would be required to normalize loudness across frequencies.

Comparisons with Other Prescriptions

Figures 3 to 7 show that NAL-NL1 prescriptions differ from the prescriptions of all of the comparison procedures. NAL-NL1 prescribes relatively less low-frequency gain for flat audiograms and relatively less high-frequency gain for steeply sloping audiograms. It also tends to prescribe less compression than the other procedures.

The differences between NAL and the comparison procedures can be explained largely by the operation of two factors. First, the other procedures are based on loudness normalization, whereas NAL is an intelligibility maximization procedure. If the aim is to normalize loudness, then the speech spectrum will be amplified so that the different frequency bands will retain their normal relative loudness; consequently, some frequencies, mainly the low frequencies, will be louder than others. A procedure that maximizes intelligibility will first tend to equalize specific loudness by flattening the speech spectrum. Second, it will give least gain to those frequencies that are least important for intelligibility. Both of these processes will lead to least gain for low-frequency sounds. Thus, for a flat audiogram, NAL-NL1 will prescribe a low-cut frequency below 1000 Hz, whereas FIG6 will prescribe a flat frequency response. The IHAFf threshold procedure, which is designed to approximate the original IHAFf procedure based on loudness judgments, prescribes a low-frequency emphasis response for a flat audiogram.

The second factor is the slope rule. Implicit in all threshold-based prescription procedures is a rule that describes how variations in audiogram slopes are compensated for by varying the frequency response slopes. Several linear prescription procedures have been based on a half-gain rule, which, if applied independently at each of a number of frequencies, as in some procedures (Byrne and Tonisson, 1976; McCandless and Lyregaard, 1983; Moore and Glasberg, 1998), translates into a half-slope rule. For example, if the audiogram slope between two frequencies becomes greater by 10 dB, then the frequency response slope will be increased by 5

dB. In the DSL (linear) procedure (Seewald et al, 1991), the implied slope rule is approximately a two-thirds slope rule, and in the NAL-R procedure, there is a one-third slope rule. In the non-linear procedures, the slope rules are more difficult to discern and are level dependent. Nonetheless, it is clear that the slope rules (i.e., the change in response slope for a given change in audiogram slope) differ for the various procedures. For an average level input, NAL-NL1, like NAL-R, embodies approximately a one-third slope rule, whereas the rules of the other procedures would be from one-half to two-thirds slope. The explanation of why NAL-NL1 has a less steep slope rule is partly related to the inclusion of the hearing loss desensitization correction.

The differences in slope rules are the reason why the NAL-NL1 prescriptions show less high-frequency emphasis for the steeply sloping audiograms than do the other prescriptions. The slope rule differences do not have any effect on flat audiograms, and the differences in the prescriptions arise because the equalization procedure (NAL-NL1) includes speech spectrum adjustments, whereas the normalization procedures do not. For moderately sloping audiograms, the effects of the speech spectrum adjustments and the slope rule differences are approximately equal but opposite in direction; hence, there is reasonable agreement between NAL-NL1 and the other prescriptions. The rationale behind the DSL[i/o] includes a variation from conventional loudness normalization: an extended dynamic range, rather than the normal dynamic range, is mapped onto the hearing-impaired dynamic range. It is of interest to note that the DSL[i/o] prescriptions are nevertheless similar to the normalization prescriptions. In fact, when expressed as insertion gain, DSL[i/o] prescriptions are usually similar to the FIG6 prescriptions. There are, however, differences between the three comparison procedures even though IHAFf and FIG6 have the same rationale.

The IHAFf procedure used in these comparisons is a threshold version rather than the original and better-known version based on loudness measurements (Cox, 1995). However, as part of another study, loudness-based IHAFf prescriptions have been calculated and compared with NAL-NL1 prescriptions. The broad conclusions about differences between procedures would be the same regardless of which version of the IHAFf is used. For the individual, the reported differences could be greater or less when the loudness-based IHAFf is used because

the prescriptions may vary for different individuals having the same audiogram.

In this article, we have not reported any comparisons of NAL-NL1 with any of the linear fitting procedures. However, some inferences can be drawn from previous reports comparing NAL-RP with other procedures (Humes, 1986; Byrne, 1987, 1992; Byrne et al, 1997). In general, compared with NAL-RP, the more popular other procedures, such as prescription of gain and maximum output (POGO) or POGO II (Schwartz et al, 1988) and DSL (Seewald et al, 1996), prescribe more high-frequency emphasis for sloping high-frequency hearing losses and more gain for severe hearing losses. The same would be true if these procedures were compared with the average input prescriptions of NAL-NL1 as these are similar to NAL-RP. The recently proposed Cambridge formula (Moore and Glasberg, 1998) may be of particular interest because it was derived in a similar fashion to NAL-NL1. The basis of the formula is to equalize specific loudness across the frequency range above 500 Hz. It is argued that this should maximize the AI, and data are presented to show that it does so (Moore and Glasberg, 1998). Note that the Cambridge formula aims to equalize loudness and that the tendency to maximize the AI is a consequence of this. By contrast, NAL-NL1 aims to maximize the SII, and a consequence is that, within certain limits, loudness tends to be equalized. Some idea of how the Cambridge and NAL-NL1 prescriptions will compare may be gained by appreciating that the Cambridge formula is almost identical to the original POGO formula (McCandless and Lyregaard, 1983), which is rather similar to the original NAL formula (Byrne and Tonisson, 1976). The main respect in which Cambridge differs from NAL-RP, and hence NAL-NL1, is that it embodies a one-half slope rather than one-third slope rule. Therefore, for sloping audiograms, Cambridge will prescribe more high-frequency emphasis than NAL.

It may seem surprising that two procedures, NAL-NL1 and Cambridge, that were derived in a similar manner and that both apparently maximize the AI or SII, can result in different prescriptions. The explanation is that, unlike NAL-NL1, the Cambridge formula, and the AI calculations that are reported to support it, do not take account of hearing loss desensitization or even the level distortion correction that is incorporated into the SII calculations. Consideration of hearing loss desensitization is unique to NAL-NL1 and its predecessors and is the reason for using a different slope rule that results

in less high-frequency emphasis, for sloping high-frequency audiograms, than is prescribed by most other procedures. Failure to consider hearing loss desensitization or level distortion is also the reason why calculations based on simplified AI schemes can, and frequently will, lead to wrong conclusions about the relative effectiveness of different frequency responses (Byrne, 1992).

Validation Issues

The NAL-NL1 procedure, like several other recently developed procedures, provides a prescription of the amplification characteristics for nonlinear hearing aids. The prescription is generic in that it can be applied to any type of nonlinear aid, although the derivation assumes the level distribution of uncompressed speech. That is, its prescriptions strictly apply only to hearing aids with attack and release times longer than the duration of speech phonemes. However, given the small effect of compression on the intelligibility of audible speech and the suitability of the SII for predicting the intelligibility of compressed speech (Souza and Turner, 1999), the NAL-NL1 procedure may also have application to hearing aids with fast attack and release times. Although NAL-NL1 has a plausible rationale, the critical question for any procedure is whether it really works in the sense of prescribing the best amplification characteristics for each individual. We consider NAL-NL1 to be partly validated because the prescriptions for an average speech input agree closely with those of the NAL-RP procedure that is supported by considerable research. The agreement was reasonable even before the final adjustment of averaging the original NAL-NL1 and NAL-RP prescriptions. The graphs presented earlier (see Fig. 1) confirm that the rationale of optimizing predicted speech intelligibility does tend to equalize loudness across frequencies. This degree of validation is reassuring and, we believe, an advantage of NAL-NL1 over completely new procedures that have no empirical support. However, there is no research to support the NAL-NL1 or any other prescriptions for high- and for low-level inputs. Even the average-level prescriptions (i.e., those equivalent to NAL-RP prescriptions) have been validated only against the criteria of perceived speech intelligibility and pleasantness (Byrne and Cotton, 1988).

To conduct a comprehensive validation of any prescription procedure, we need to consider alternative fitting rationales and a range

of validation criteria. The NAL-NL1 procedure has the rationale of optimizing speech intelligibility while presenting speech with normal overall loudness or at a lower level if that would improve speech intelligibility. There is no evidence that normalizing overall loudness corresponds to hearing aid wearers' preferences or is, in any sense, optimal. Consider, for example, some alternative possibilities for amplifying high- and low-level inputs. If we assume that average speech (65–70 dB SPL) will be amplified to the preferred listening level (PLL), then higher level inputs will be amplified to fall between the PLL and the hearing aid's limiting level, which presumably will be set at or below the aid wearer's loudness discomfort level. One possible fitting rationale would be to apply a high degree of compression to high-level inputs so that most would be amplified to levels not much above PLL. Fitting on this basis should result in greater comfort than using less compression, which would permit a greater proportion of sounds to be amplified to levels approaching or reaching limiting. However, a high degree of compression could result in unacceptable sound quality. There is little information on which to judge how much compression of high-level sounds is needed to maximize comfort or how much can be used before sound quality is perceived as being degraded. Certainly, there is no basis for assuming that the amount that normalizes loudness will be optimal or, indeed, that the preferred amount is strongly correlated with loudness. In a similar vein, there is no strong argument that very soft sounds should be amplified to normal loudness. Other rationales could be advanced and at least one, based on audibility, has been (Moore et al, 1998).

The NAL-NL1 procedure, like its predecessors and most other procedures, is strongly based on the idea of maximizing speech intelligibility. This priority is understandable but limiting in that it may be important, for some or all individuals, to consider other aspects of auditory functioning. Indeed, research suggests that sound quality is an important determinant of satisfaction with amplification (Humes, 1999). Furthermore, it seems that speech intelligibility may be little affected by a considerable variation in amplification characteristics (Van Buuren et al, 1995), at least for speech presented over a restricted range of overall levels. Consequently, such differences in speech intelligibility as may occur could well be less important than other effects of moderate variations in frequency response or compression characteristics. Indi-

rectly, and to a limited extent, NAL-NL1 takes account of some quality considerations in that NAL-R was validated partly on the basis of pleasantness judgments. Furthermore, the wide acceptance of NAL-R for over a decade suggests that its prescriptions do not lead to notably poor sound quality. Nonetheless, there are many questions to be answered about the effects of amplification variations on the various attributes of quality and of the importance of these for individuals.

Variations in amplification could be expected to affect the detection and localization of sounds. Byrne and Noble (1998) have discussed some implications of localization research for hearing aid fitting. There is little information on the detection of environmental sounds by people with hearing impairments, although they do report reduced ability to hear at a distance (Noble et al, 1995). Considering that localization, in the horizontal plane, is most highly correlated with low-frequency hearing and that many environmental sounds have most energy in the low frequencies, we would expect that localization and detection would suffer if a hearing aid did not provide sufficient low-frequency amplification. It is possible that the frequency response that is optimal for speech intelligibility may not be best for localizing and detecting sounds.

The general point of the above discussion is that it is a complex issue to determine what is optimal amplification or, indeed, to judge what is the best basis for making such a decision. Consequently, it is extremely difficult to perform a comprehensive validation of a prescriptive procedure. Nonetheless, we urge that validation research should take a broad view of possible fitting objectives and should try to consider speech intelligibility, under various conditions, listening comfort, sound quality, the detection of environmental sounds, and spatial aspects of hearing (localization and externalization). As some important factors may not be readily measured, and some listening conditions may not be readily simulated, it is important to supplement laboratory studies with field trials and some global measures of the success of different amplification strategies.

SUMMARY

This article has presented an overview of a new procedure for prescribing nonlinear amplification (NAL-NL1). The rationale of the procedure is to maximize predicted speech intelligibility while constraining loudness to be nor-

mal or less. Speech intelligibility is predicted by a version of the SII that has been modified to account for the reduced ability to use audible information associated with listening at high levels and with increasing degrees of hearing loss. A series of examples has illustrated the main characteristics of NAL-NL1 prescriptions and has shown how they differ from the prescriptions of other procedures. The NAL-NL1 prescriptions for an average-level input agree closely with those of the well-established NAL-RP procedure. Such prescriptions may be accepted with considerable confidence because of the supporting research and wide acceptance of the NAL-RP procedure. However, the prescriptions for high- and low-level inputs are derived purely from logic, and the rationale adopted requires validation. It is acknowledged that other plausible rationales could be proposed and that validation is a complex and difficult issue.

The NAL-NL1 prescriptions have been compared with those provided by the two most popular threshold-based nonlinear fitting procedures, FIG6 and DSL[i/o], and with a threshold version of the IHAF procedure. In general, all procedures give similar prescriptions for audiograms sloping to a moderate degree from low to high frequencies and having normal hearing at the lowest frequencies. If there is a mild hearing loss at the low frequencies, the comparison procedures may prescribe significant low-frequency gain, whereas NAL-NL1 may not. The NAL-NL1 prescriptions usually differ substantially from those of the other procedures for flat audiograms, reverse slope audiograms, and for steeply sloping high-frequency hearing losses. The three comparison procedures also differ from each other for many audiograms.

Acknowledgments. We are most grateful to Robyn Cox for providing data from which we calculated a threshold formula that provided, on average, prescriptions equivalent to those based on her contour test. We are also indebted to Richard Seewald for advice on which options of the DSL[i/o] software should be used to generate prescriptions most comparable with those of NAL-NL1 applied with the default CT setting.

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