Overview and Rationale for Prescriptive Formulas for Linear and Nonlinear Hearing Aids

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Historical Perspective

As early as 1940, researchers and audiologists were experimenting with selective amplification. In selective amplification, an attempt is made to prescribe a frequency response(s) that is specific to a particular patient’s configuration and degree of hearing loss. Watson and Knudsen (1940) proposed a suprathreshold method for determining required gain and frequency response based on the patient’s most comfortable loudness (MCL) levels across frequencies. Lybarger (1944) proposed the original -gain rule, indicating that approximately half of the hearing loss resulted in the appropriate amount of gain at each frequency in order for conversational speech to be audible and comfortable. Work on developing prescriptive hearing aid fitting methods ended abruptly in 1946 when the Harvard Report (Davis et al., 1946) was published. This document stated that most patients performed best with the same frequency response (a flat or 6 dB/octave rising response measured in the 2-cc coupler between 300 and 4000 Hz).

Because of the belief that frequency/gain characteristics were not important for optimizing speech intelligibility, audiologists turned to a comparative approach for hearing aid selection. Schwartz and Walden (1980) appeared to further support this notion when their study revealed that hearing aids with similar electroacoustic characteristics differed less than 8% in the majority of comparisons using monosyllabic word recognition lists. With the same group of subjects, scores on successive tests with the same hearing aids differed as much or more than the comparisons between hearing aids.

Until the early 1980s, the primary method used by audiologists for choosing appropriate hearing aids for patients was the comparative hearing aid evaluation (Humes, 1996). In a classic article, Carhart (1946) described the comparative procedure in which the patient is tested with several hearing aids using a variety of speech recognition tasks. The patient would ultimately be fitted with the hearing aid(s) that yielded the highest performance. This method, or a variation thereof, was popular for several decades (Humes, 1996).

In 1983, Walden et al conducted a study that evaluated key assumptions of the comparative hearing aid evaluation procedure. These included issues related to sensitivity of testing material, test-retest reliability, and relationship between relative performance in the sound booth and preference in real-
world environments. The authors found that unless hearing aids with very dissimilar frequency responses were employed (which was unlikely in clinical practice), the assumptions of this procedure were not met.

In 1975, Pascoe published an article that refuted the earlier findings of the Harvard Report (Davis et al, 1946). His research, along with that of others, indicated that the frequency-gain characteristics of hearing aids are important for optimizing speech intelligibility in patients with sensorineural hearing loss. The majority of subjects in the Harvard Report had conductive or mixed hearing loss. At the same time, audiologists were starting to appreciate the difference between coupler measurements of hearing aid output and real-ear measurements, including the impact of earmolds on the frequency-gain response (Killion, 1981). All of the data in the Harvard Report were collected through coupler measurement. Schwartz and Walden’s (1980) findings could be explained by data reported in 1978 by Thornton and Raffin that demonstrated that the Northwestern University (NU)-6 word recognition task had very poor test-retest reliability. One could expect the variability of this measure to obscure real differences that might exist between hearing aids. The careful work of these individuals as well as the introduction of custom products, led away from the comparative approach and back to the development of prescriptive hearing aid formulas that Lybarger (1944) and Watson and Knudsen (1940) had started 40 years earlier.

Introduction to Prescriptive Fitting Strategies

The term fitting strategy is analogous to a prescription. Simply put, a fitting strategy yields amplification settings that are appropriate for a patient based on his or her audiometric characteristics. The reason to have a fitting prescription is to generate a target (or targets) of gain as a function of frequency that can be used to select, set, or verify the hearing aid fitting in either a coupler or real ear. Fitting strategies can be characterized on several dimensions including type of signal processing for which they are designed [e.g., linear, wide dynamic range compression (WDRC)], amount and type of audiometric information required (e.g., audiometric thresholds, dynamic range measures), and underlying theoretical rationale (e.g., loudness equalization, loudness normalization) (see rationale section of Table 1–1). With a loudness equalization rationale, the goal is to amplify speech sounds so that they are perceived as equally loud. With a loudness normalization rationale, the goal is to amplify speech sounds so that normal interfrequency loudness relations are maintained (e.g., vowels are more intense than consonants). These rationales are discussed in more detail in subsequent sections.

Despite differences on one or more of these dimensions, most fitting strategies have, at their core, several basic assumptions. First and foremost is the recognition that audibility of speech sounds is critical. This can only be accomplished via a frequency-gain response that has a wide enough bandwidth to amplify critical high-frequency speech sounds and accounts for the degree and configuration of the hearing aid user’s hearing loss. In a series of investigations, Skinner and colleagues demonstrated the necessity of a wide frequency response for maximizing aided speech recognition ability (Skinner, 1980; Skinner and Miller, 1983).

Restoration of audibility, however, takes place within the constraints of the patient’s dynamic range and sound quality perceptions. Dynamic range is the area between just audible sounds (threshold) and sounds that are judged to be uncomfortable. There is a need to recognize the functional limitations imposed by the dynamic range of the listener when prescribing amplification characteristics. See Chapter 2 for a comprehensive overview on measuring loudness discomfort level (LDL) and for selecting/verifying the appropriate output of the hearing aid based on LDL data. As a general rule, the amplified signal should not exceed the patient’s LDL. With regard to sound quality, it is evident that certain frequency-gain responses, although appropriate for restoring audibility, may re-
## Table 1–1. Comparison among the Wide Dynamic Range Compression (WDRC) Fitting Strategies Discussed in This Chapter

<table>
<thead>
<tr>
<th>Fitting Strategy</th>
<th>NAL-NL1 (National Acoustic Laboratories Nonlinear Version 1)</th>
<th>DSL [i/o] ( Desired Sensation Level [Input/Output])</th>
<th>FIG6</th>
<th>IHAFF (Independent Hearing Aid Fitting Forum)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rationale:</td>
<td>LE or LN**</td>
<td>LN</td>
<td>LN</td>
<td>Loudness contours or threshold data with contour data predicted</td>
</tr>
<tr>
<td>Audiometric information that can be used</td>
<td>LE or LN** Threshold data*, LDLs, loudness contour data</td>
<td>LN Threshold data</td>
<td>LN</td>
<td>Loudness contours or threshold data with contour data predicted</td>
</tr>
<tr>
<td>Fitting information provided</td>
<td>Coupler targets, real-ear aided targets, real-ear gain targets, real-ear insertion gain, aided thresholds, Speech-O-Gram, HA parameters (e.g., CT, CF, CR)</td>
<td>Coupler targets, real-ear aided targets, real-ear gain targets, real-ear insertion gain targets, aided thresholds, SPL-O-gram, HA parameters (e.g., CT, CF, CR)</td>
<td>Coupler targets, real-ear gain targets HA parameters (e.g., CT, CF, CR)</td>
<td>i/o curves, HA parameters (e.g., CT, CF, CR)</td>
</tr>
<tr>
<td>Channels</td>
<td>User chooses between 1 and 4 channels</td>
<td>Provides information for 9 channels</td>
<td>Assumes 2 channels</td>
<td>Assumes 2 channels, but user can get info from every contour frequency (up to 6 frequencies)</td>
</tr>
<tr>
<td>Individualized HA fitting data that can be entered:</td>
<td>RECD, REUG, HA style, CT, earmold options, output limiting characteristics</td>
<td>RECD, REUG, REDD, HA style, earmold options, CT, compression type</td>
<td>None</td>
<td>None</td>
</tr>
<tr>
<td>Adjustment for binaural fitting?</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Adjustment for vent and tubing choices?</td>
<td>Yes (provides comments related to choices)</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Age-related adjustments for RECD?</td>
<td>Yes, can enter birth date</td>
<td>Yes, must enter birth date</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Adjustment for conductive loss?</td>
<td>Yes</td>
<td>No, but targets accurate if the individual’s LDLs are entered</td>
<td>No</td>
<td>No, but targets accurate if loudness contour data entered</td>
</tr>
</tbody>
</table>

* Obtained under headphones, insert earphones, or in sound field.
** See text.

LDL, loudness discomfort level; RECD, real-ear-to-coupler difference; REUG, real-ear-unaided-gain; REDD, real-ear-to-dial-difference; CT, compression threshold; CR, compression ratio; LE, loudness equalization; LN, loudness normalization; CF, crossover frequency; i/o, input/output; HA, hearing aid
result in sound quality perceptions that are unacceptable. As demonstrated by Skinner et al. (1982a), for example, this is a possibility when a sharply rising frequency-gain response is prescribed. Work by Hogan and Turner (1998) and Ching et al. (1998) indicates that high-frequency amplification actually may be detrimental in terms of speech intelligibility for some users depending on the degree and site of lesion of the hearing loss. As such, sound quality and distortion must be considered when determining appropriate fitting targets. The prescription generated must reflect a balance among audibility, loudness, and sound quality (Byrne, 1992). Within the framework outlined above, the best method for determining appropriate amplification characteristics remains unclear. Based on the large number of fitting strategies available to the audiologist today, it is evident that a consensus has not been reached, and empirical support for any particular approach(es) is lacking.

**Practical Considerations**

In choosing a fitting strategy, the audiologist may want to consider the following:

1. How much audiometric and related information will be employed within the prescriptive procedure in generating the fitting targets?
2. Does the prescriptive procedure use age-specific corrections if individual data are not available?
3. What types of transducers can be used to obtain the audiometric data?
4. What are the resulting targets that are provided for selection, presetting, and verification?

Table 1–1 compares four prescriptive strategies with regard to the practical considerations described below.

**Audiometric Information That Can Be Used**

The audiologist may want to work with a fitting strategy that requires minimum audiometric data (i.e., thresholds only; see Table 1–1, audiometric information that can be used). This implies that the fitting program will estimate LDL, MCL, and/or loudness contour data. The research available regarding the relationship between threshold and MCL and LDL indicates that the relationship is not strong (Kamm et al., 1978; Cox and Bisset, 1982), and that at least 25% of patients will deviate substantially from average in terms of LDLs (Pascoe, 1990). Using a threshold-based formula implies that the audiologist is making a choice as to where to spend time in the fitting process and is using flexible (programmable) technology that can be manipulated during the fitting process. Time can be spent in measuring MCL and LDL and including this in a fitting strategy prior to hearing aid fitting, or time can be spent during the fitting to fine-tune the hearing aids to account for any patient differences that were not considered in the audiometric testing. If the latter is chosen, the hearing aids must be flexible enough to change based on verification results, and the patient must be able to provide subjective feedback that can be used in determining appropriate manipulations of programmable parameters.

**Individualized Hearing Aid and Earmold Fitting Data That Can Be Entered**

The audiologist working with infants and children may wish to use a fitting protocol that accounts for as much individual data as possible [e.g., real-ear-to-coupler difference (RECD); see Chapter 3 for a full description of real-ear measures] because a young child cannot provide subjective feedback for fine-tuning purposes. Age-specific corrections may be useful with a pediatric population as well. In other words, if the RECD cannot be measured, does the fitting protocol provide estimates of this measure based on the age of the child who will be receiving the hearing aids? The audiologist may want to work with a fitting strategy that allows audiometric data to come from a variety of transducers (e.g., sound field, insert earphones, headphones, etc.). This is important when working with a pediatric population, as we cannot always assess children in a manner similar to that for adults (Table 1–1, age-related adjustments for RECD).
Entry of data related to the style of the earmolds and/or circuitry type of the hearing aids that will be employed can further individualize the fitting. The impact of style and venting characteristics can be incorporated when determining appropriate coupler settings that should yield real-ear measures that will closely approximate the prescriptive target(s) with minimal adjustment. Compression characteristics available on the particular hearing aids [e.g., compression threshold (CT), compression ratio (CR)] can be considered a priori in deriving appropriate fitting targets. If this information cannot be entered, compromises may need to be made when trying to meet the targets. Table 1–1 (individualized HA fitting data that can be entered) describes the user’s ability to use individual data in each fitting formula.

Fitting Information Provided

The audiologist may select a fitting strategy based on what verification methods are provided. If the audiologist prefers to verify the hearing aid fitting with real-ear measurements, a protocol that provides real-ear insertion gain (REIG), real-ear aided response (REAR), or real-ear aided gain (REAG) targets may be preferred. See Chapter 3 for details related to real-ear measures. The audiologist may want coupler gain or output targets to select conventional hearing aids based on matrix data or to preset programmable hearing aids prior to real-ear verification (Table 1–1, fitting information provided).

Channels

Prescriptive strategies can differ on the number of channels for which compression characteristics are prescribed. With multichannel hearing aids, the gain, CR, and CT can be manipulated individually in each channel. As such, with increasing circuitry sophistication, greater prescriptive data are needed (Table 1–1, channels).

Adjustments for Binaural Fitting

When prescribing targets for a binaural versus a monaural fitting, the impact of binaural summation should be considered. With a binaural fitting, the audiologist can expect a 3- to 6-dB reduction in the amount of gain necessary to achieve a given loudness when compared with a monaural fitting. With some prescriptive strategies, this reduction is automatically incorporated when a binaural fitting is chosen. With others, the audiologist must decide whether or not to reduce the amount of gain and to what degree (Table 1–1, adjustment for binaural fitting?).

Adjustments for Conductive Loss

With a purely conductive hearing loss, there is no reduction in the patient’s dynamic range. Therefore, a linear processing scheme may be more appropriate as a constant amount of gain is needed as a function of increasing input level. With sensorineural hearing loss, the greatest amount of gain is required for soft input levels and progressively less gain is needed with increasing input level. When fitting a conductive or mixed hearing loss, use of a prescriptive strategy that accounts for any conductive component is warranted (Table 1–1, adjustment for conductive loss?).

Theoretical Considerations

In reviewing the underlying theory and methods for implementing various prescriptive strategies, it is evident that these prescriptive strategies differ on primarily one or two dimensions. The first dimension relates to how the frequency bands within an amplified signal should relate with regard to overall loudness (Byrne, 1996). A second dimension relates to how the fitting strategy is incorporated within a fitting protocol (Lindley et al, 2001). These issues are discussed in more detail in the following sections.

Loudness Normalization (LN) versus Loudness Equalization (LE)

The underlying theory behind most prescriptive strategies can be described as a loudness normalization (LN) rationale or a loudness equalization (LE) rationale. With an LN rationale, the overall goal is to restore normal
loudness perception for the patient wearing hearing aids. For example, the speech presentation levels judged to be “soft,” “comfortable,” and “loud” by normal hearing individuals also should be judged “soft,” “comfortable,” and “loud” by the hearing aid wearer. In addition, the normal relative loudness across frequency bands in a complex signal should be maintained. With a speech signal, for example, this means that at a given presentation level, the lower frequencies will be perceived at a greater loudness than the higher frequencies (i.e., vowels have more acoustic power than consonants). The LN rationale is based on the assumption that restoration of normal loudness perception will lead to a more successful fitting and greater acceptance by the hearing aid user. Relatively greater weight is placed on loudness and sound quality as opposed to maximizing speech intelligibility.

With an LE rationale, the goal is to equalize loudness across frequency bands. This occurs while normalizing overall loudness. Thus, the patient should perceive the overall speech levels in a manner similar to that of individuals with normal hearing. It is the relation between frequency bands within the signal that differ. For a conversational input level [i.e., 65 dB sound pressure level (SPL)], for example, the various frequency bands would be perceived as being equally loud. The development of the National Acoustic Laboratories’ (NAL) fitting procedure has stimulated considerable research, the results of which suggest that hearing aid settings that equalize perceived loudness across frequency bands are preferred by many patients with hearing loss (Byrne, 1986). One assumption of this rationale is that speech recognition will be higher than that obtained with an LN rationale.

Incorporation of a Fitting Strategy within the Fitting Protocol

Regardless of what fitting strategy is employed in deriving an initial prescription, it is important to remember that the fitting strategy is only part of the whole fitting process. Employment of a fitting strategy results in a prescription for how the hearing aids should function when the output or gain of the hearing aids are measured in a coupler or in the user’s ear canal. What data are employed in deriving the initial targets and how far one initially deviates from this prescription when fitting hearing aids depends on what type of fitting protocol is employed.

At one extreme, an audiologist-driven (AD) protocol may be employed (Lindley et al, 2001). With an AD protocol, only threshold data are used with the fitting strategy in deriving a prescription. On the day of the fitting, the audiologist attempts to meet the target(s) as closely as possible. Further adjustments are not made to the hearing aids based on initial subjective perceptions provided by the hearing aid user. Rather, the assumption is that the prescription employed represents the best compromise between speech recognition and sound quality. The hearing aid user is provided with the opportunity to adapt to these hearing aid settings over a given period of time before any changes are considered. With this protocol, speech recognition is given higher priority than initial perceptions of sound quality or loudness.

In contrast to the AD protocol, a patient-driven (PD) protocol requires significant input regarding initial perceptions of loudness and sound quality from the patient being fitted with hearing aids (Lindley et al, 2001). The patient provides input at two stages of the fitting process. In stage 1, audiometric information such as thresholds, loudness contours, and/or LDLs are measured to determine the appropriate hearing aid settings. In stage 2, loudness judgments and formal or informal sound quality ratings are obtained on the day of the fitting with the patient wearing the hearing aids. This information is employed to verify that the original fitting goals have been met. If loudness normalization is the goal, the judgments obtained from the patient can be compared with normative data to ensure that normal loudness perception has been restored. With a PD protocol, initial percep-
tions of sound quality and/or loudness are given higher priority than maximization of speech recognition.

In clinical settings, it is likely that a combination of the above protocols is employed. That is, adjustments are often made on the day of the fitting to increase sound comfort yet maintain adequate, if not ideal, audibility levels. The use of adaptation managers within some manufacturers’ fitting software facilitates a gradual introduction to amplification, especially in first-time users. Hearing aid settings also can be adjusted based on the amount of hearing aid experience of the user. Over time, the amount of amplification prescribed, and hence audibility, is increased in an effort to improve speech recognition ability while providing acceptable loudness and sound quality. In this type of protocol, the targets provided by a given fitting strategy might serve as an ultimate goal, rather than an initial setting.

**Device-Independent versus Proprietary Fitting Strategies**

Device-independent fitting strategies imply that the prescriptive formula is not hearing aid dependent. The audiologist enters the required patient data and is presented with coupler or real-ear target(s) that can be applied to any hearing aid. The target(s) may include gain as a function of frequency, gain as a function of input level (for nonlinear technology), desired CT(s), and CR(s). The CT is the input level at which the signal is processed in a nonlinear, as opposed to linear, manner. In Figure 1–1 this occurs at 40-dB SPL for the WDRC example. The CR represents the degree of compression that is applied to the incoming signal and is calculated by determining how much of an increase in the amplified signal occurs when an increase in the input signal occurs. In the WDRC example from Figure 1–1, as the input level is increased from 40- to 70-dB SPL, the amplified signal increases 10 dB, resulting in a CR of 3:1 [i.e., change in input (30) divided by change in output (10)].

Proprietary fitting strategies are related to a particular circuit/technology. Individual patient data are entered (threshold, LDL, etc.), and a proprietary fitting algorithm programs all of the signal processing features of the hearing aids. This may include compression characteristics (threshold, ratio, attack and release times) in each channel as well as frequency-gain response and output as a function of changes in the overall input level. A variety of manufacturers have de-

![Figure 1-1. Input/output graphs for linear and wide dynamic range compression (WDRC) signal processing. SPL, sound pressure level.](image-url)
rived their own fitting algorithms as they moved toward digital signal processing (DSP). The rationale is that there is virtually infinite flexibility in DSP, and therefore the manufacturer must constrain some of the programmability. At a minimum, the audiologist needed a starting point with these technologies and did not desire a truly open platform technology where all aspects of signal processing could be manipulated by the audiologist. Rather a closed DSP platform is employed with the audiologist able to have programmable control only over specific signal processing characteristics. The advanced use of WDRC in achieving audibility throughout the dynamic range and reducing noise interference also pointed toward proprietary algorithms that set the compression time constants. None of the device-independent fitting strategies provides guidelines as to how to control the compression time constants across the various channels of the hearing aid.

A few manufacturers have provided software that represents a compromise between proprietary fitting algorithms and generally accepted independent fitting strategies. For example, the software for the Siemens Signia allows the audiologist to choose between a desired sensation level (DSL) input-output (i/o)-based fitting (emphasis on audibility) and an NAL nonlinear version 1 (NL1)-based fitting (emphasis on speech intelligibility within the constraints of loudness, sound quality, and degree of hearing loss) (Cornelisse et al, 1995; Byrne et al, 2001). Within the independent strategies, proprietary programming of the instrument is carried out related to compression characteristics (e.g., attack and release times, CT in each channel, etc.). The software for the Qualitone programming screen allows choices among a variety of the well-known fitting algorithms [FIG6, visual input-output locator algorithm (VIOLA), etc.] so as to leave the final rationale to the audiologist while setting some parameters in a proprietary manner (Gitles and Niquette, 1995; Cox and Flamme, 1998). Many manufacturers also provide the audiologist with the option of choosing among two or more levels of programming flexibility (i.e., number of parameters that can be manipulated) when adjusting the hearing aids. Audiologists can work at the programming level at which they are most comfortable.

Regardless of which type of prescriptive strategy (i.e., proprietary versus independent) and the degree to which the audiologist can control various signal processing characteristics, verification that fitting objectives have been met is critical. Real-ear measures related to the patient’s dynamic range, for example, are a powerful tool that can be used to document that audibility has been restored and the patient’s LDL has not been exceeded. The methodology used to reach the final amplification settings is secondary to achieving the desired results.

**Linear and Nonlinear Device Independent Fitting Strategies**

A linear hearing aid fitting is two-dimensional. Gain varies as a function of frequency. Gain, however, does not vary as a function of input level; therefore, a single frequency-gain target is produced by the fitting formula. The gain will remain the same regardless of input level until the hearing aids reach saturation. The input/output function for this type of signal processing will reveal a straight line at 45 degrees where a change in input results in an identical change in output (a one-to-one ratio; see Figure 1-1). The audiologist is aware that regardless of meeting prescriptive targets, the user of linear amplification can choose to use less or more gain as a function of the user-manipulated volume control wheel.

A hearing aid fitting that includes compression signal processing in the dynamic range (e.g., WDRC), on the other hand, is three-dimensional. Gain varies as a function of frequency and input level. Prescriptive fitting formulas for this type of signal processing will produce at least three targets, typically for soft (e.g., 45-dB SPL), moderate (e.g., 65-dB SPL), and loud (e.g., 85-dB SPL)
input levels. The gain generated for soft input levels would be greater than the gain generated for moderate or loud inputs levels. Many of these instruments are dispensed without a volume control because the one consistent advantage of WDRC is the automatic nature of the instrument (alleviating the user of the need to increase the gain for soft sounds and decrease the gain for loud sounds). The input/output function for this type of signal processing will reveal a linear response up to the compression threshold (kneepoint) and then changes in input will not produce identical changes in output. From Figure 1–1, it is evident that more of the aided signal falls within the patient’s dynamic range (shaded region represents the auditory area between threshold and LDL) with WDRC processing as opposed to linear processing. Alternatively, expansion (providing a decreasing amount of gain with decreasing input level) can be employed below the compression threshold in an attempt to reduce the annoyance of low-level ambient noises.

Examples of Fitting Strategies Designed for Linear Signal Processing

Of the many prescriptive formulas proposed for linear amplification over the years, only a few are in general use, and those will be reviewed in the following section. The formulas for these fitting strategies are listed in Table 1–2 and include National Acoustic Laboratories-Revised (NAL-R; Byrne and Dillon, 1986), prescription of gain and output (POGO; McCandless and Lyregaard, 1983), Libby one-third gain (Libby, 1986), and Berger (Berger et al, 1989). The desired sensation level (DSL, Seewald, 1992, 1994, Seewald et al, 1995) also provides a fitting strategy for linear amplification. The DSL procedure is not a simple multiplication based on magnitude of hearing loss. Thresholds in dB hearing level (HL) are converted to dB SPL using the measured or predicted RECD, and a speech spectrum (adult or child) chosen by the user is used to create the final target levels for the amplified speech spectrum.

The Berger et al (1989) procedure is based on the assumption that amplification should increase the input levels toward average conversational speech levels (65-dB SPL) and that amplification at 250 to 500 Hz should be reduced slightly because of their potential detrimental masking effect on speech recognition. The formula promoted by Libby (1986) is based on the finding that patients with mild hearing loss use very little gain in real-life listening situations. He concluded that a prescription should reflect the amount of gain actually used by the subjects in his study. The general rule of the NAL-R (Byrne and Dillon, 1986) is to provide sufficient gain at each frequency to amplify average conversational speech to the patient’s MCL. The NAL-R approach attempts to control for excessive gain in cases with steeply sloping hearing loss by providing slope gain modifications by multiplying the HL at each frequency by 0.31. The POGO

<table>
<thead>
<tr>
<th>250 Hz</th>
<th>500 Hz</th>
<th>1000 Hz</th>
<th>2000 Hz</th>
<th>3000 Hz</th>
<th>4000 Hz</th>
<th>6000 Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td>NAL-R*</td>
<td>0.31 (−17)</td>
<td>0.31 (−8)</td>
<td>0.31 (+1)</td>
<td>0.31 (−1)</td>
<td>0.31 (−2)</td>
<td>0.31 (−2)</td>
</tr>
<tr>
<td>POGO</td>
<td>0.5 (−10)</td>
<td>0.5 (−5)</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Libby 1/3</td>
<td>0.33 (−5)</td>
<td>0.33 (−3)</td>
<td>0.33</td>
<td>0.33</td>
<td>0.33</td>
<td>0.33</td>
</tr>
<tr>
<td>Berger</td>
<td>—</td>
<td>0.30**</td>
<td>0.63</td>
<td>0.67</td>
<td>0.59</td>
<td>0.53</td>
</tr>
</tbody>
</table>

* Plus 0.05 of hearing level at 500 + 1000 + 2000 Hz (addition for overall gain).
**0.50 for a 50-dB hearing loss.

NAL-R, National Acoustic Laboratories-Revised; POGO, prescription of gain and output.
procedure (McCandless and Lyregaard, 1983) is based on the assumption that frequency-gain response and saturation sound pressure level (SSPL) limiting are essential characteristics in a basic prescriptive fitting. Similar to the other strategies, POGO’s goal is to create audible, comfortable conversation level inputs. It is worth noting that maximum output specification is essential to the Berger, Libby, and POGO formulas.

Figure 1–2 illustrates the coupler gain targets generated for a mild (25 dB HL at 250 Hz) to severe (90 dB HL at 6000 Hz) sloping hearing loss from the DSL, NAL-R, POGO, Berger, and Libby fitting strategies. It is evident that the POGO and DSL fitting algorithms prescribe more gain in the middle to high frequencies. Whether these amplification levels can be obtained without feedback and with user satisfaction is a worthwhile concern, but the goal is to provide audible signals across a wide frequency range. Several of the fitting programs were modified in later years to provide slight variations for more profound hearing losses (e.g., NAL-RP, Byrne et al, 1990; POGO II, Schwartz et al, 1988; Libby two-thirds gain rule, Libby, 1986). Also, DSL and NAL prescriptive formulas now provide advanced fitting programs for nonlinear technology (NAL-NL1, Byrne et al, 2001; and DSL [i/o], Cornelisse et al, 1995). These updated versions are discussed in the next section.

As mentioned earlier, linear prescriptive methods produce a single gain target (related to the coupler or real ear) because of the nature of linear amplification. Gain does not vary as a function of input level, so a single target tells the whole story. The gain is prescribed to optimize conversation level inputs, acknowledging that soft sounds will be inaudible and that the user will operate at the limits of the hearing aids in many situations (above conversation level inputs). If average conversational speech is at a comfortable loudness level, the linear fitting is typically successful. The user is provided with a volume control that would have to be manipulated very rapidly to keep the various input levels one expects in conversation and in the environment to be maintained in the audible range.

Considering that the user has access to a volume control in linear hearing aid fittings, differences in frequency-gain responses between prescriptive formulas would be minimized (Humes, 1986, 1988; Sullivan et al, 1988). Byrne and Cotton (1987) have argued, however, that even when allowing for patient volume control adjustments, speech

![Figure 1-2. 2-cc coupler gain for five linear fitting strategies. DSL, desired sensation level; NAL-R, National Acoustic Laboratories-Revised; POGO, prescription of gain output; SPL, sound pressure level.](image)
recognition is significantly better with some prescribed target criteria than with others. That is, some targets, even after being equated for loudness, are expected to yield higher speech recognition.

**Suprathreshold Fitting Strategies**

In the past, fitting strategies have been divided into threshold-based and suprathreshold-based. Watson and Knudsen (1940) used MCL measures in their fitting strategy and were the first group to use suprathreshold measures in a prescriptive formula. Currently, this is an arbitrary division because several strategies may be used either way (e.g., VIOLA, DSL [i/o]) (Cornelisse et al, 1995; Cox and Flamme, 1998). These approaches accept suprathreshold data (i.e., loudness contour, LDL), but also will predict these measures if only hearing thresholds are provided. Table 1–3 provides a description of several suprathreshold fitting strategies. The CID (Central Institute for the Deaf, Skinner et al, 1982b; Skinner, 1988) and Shapiro (Shapiro, 1976, 1980) methods employ MCL measures. The MSUv3 (Memphis State University; Cox, 1988) and Bragg (Bragg, 1977) methods bisect the dynamic range, therefore requiring threshold and LDL data. The Levitt method (Levitt et al, 1987) bases recommendations on LDL measurements. Some researchers have reported that some patients do not produce reliable MCLs (Stephens et al, 1977; Berger and Soltisz, 1981; Skinner and Miller, 1983), which puts methods based on MCL measurement in question. Palmer and Lindley (1998) found that full loudness contours (threshold to LDL) were reliable in a group of subjects. Based on a review of recent publications and presentations, none of these strategies appears to be in general use, but knowledge of the premise behind each (see Table 1–3) assists the student of prescriptive formulas in understanding the most recent (nonlinear) approaches.

### Examples of Fitting Strategies Designed for Nonlinear Signal Processing

In this section, four fitting strategies designed for hearing aids incorporating nonlinear processing are discussed: NAL-NL1, DSL [i/o], FIG6, and VIOLA. These state-
gies were chosen as they are device independent, are currently available in many hearing aid fitting software packages, and present different theoretical rationales and implementation approaches. For each, a description of the underlying theory and implementation is provided. Additional information regarding procedural aspects is provided in Table 1–1.

**NAL-NL1**

The National Acoustic Laboratories’ nonlinear fitting procedure, version 1 (NAL-NL1) is an extension of the NAL-R fitting strategy for linear amplification (Byrne et al, 2001). NAL-NL1 was designed for nonlinear signal processing and provides different prescriptive targets as a function of input level. With NAL-NL1, the goal is to maximize speech recognition for a given speech input level (dB SPL) within the constraint that the hearing aid wearer should perceive the overall level of speech no louder than an individual with normal hearing. Speech judged to be “soft,” “comfortable,” and “loud” by individuals with normal hearing should be perceived similarly by the patient wearing hearing aids. At a given input level, however, the relative loudness across frequency regions is prescribed with the goal of maximizing intelligibility. At least for conversational input levels (i.e., 60- to 70-dB SPL) this typically leads to prescriptions similar to NAL-R and significantly different from prescriptions with an LN rationale. As such, this fitting strategy would best be described as having an LE rationale.

In developing the formula employed by this strategy, a modified version of the Speech Intelligibility Index (SII) was used in conjunction with a loudness model to meet the goals of maximizing intelligibility while maintaining normal overall loudness perception (ANSI, 1997; Byrne et al, 2001). A unique aspect of NAL-NL1 is that the impact of high sensation levels and degree of hearing loss, with regard to speech recognition, is taken into account. Functionally, this results in less prescribed gain in regions of severe hearing loss than would be expected if audibility alone were considered. The NAL-NL1 also allows the user to enter the birth date of the patient to use age-appropriate correction factors (e.g., for RECD) or to enter these data directly. This fitting version is greatly enhanced compared with NAL-R and could be used with a pediatric population.

The audiologist enters the audiometric and hearing aid data (e.g., style, number of channels, etc.) into the fitting software. Additional individual-specific data such as RECD or real-ear unaided response (REUR) can be entered as well. Figure 1–3 provides an example of the printout provided by the NAL-NL1 software. The audiologist can choose to view the target data in a variety of forms including 2-cc coupler gain and REIG. Ideal crossover frequency(ies), CT(s), and CR(s) are provided in tabular format to facilitate adjustment of the hearing aids to meet the desired targets and to aid in choosing appropriate hearing aids. These values can be overridden if desired, and the targets are automatically recalculated accordingly.

**DSL [i/o]**

The goal of the DSL [i/o] hearing aid fitting procedure is to prescribe amplification characteristics such that the entire range of acoustic signals available to a patient with normal hearing is placed within the dynamic range of the patient with hearing loss (Cornelisse et al, 1995). The underlying rationale, with regard to relative loudness across frequency bands, varies according to the parameters chosen. For example, when the variable compression (nonlinear) ratio mode (CR changes as a function of input level) is chosen, the targets generated are based on an LN rationale. When linear compression ratio mode is chosen (CR remains constant above the CT), the targets generated are based on an LE rationale (Seewald et al, 1997). As outlined earlier, with the LE rationale, the goal is to provide amplification such that relative loudness across frequency bands is equalized. The long-term average speech spectrum (LTASS) should fall along the individual’s MCL level across frequency. Thresholds and the upper limit of comfort (either measured or pre-
dicted) across frequency are used to define the dynamic range.

The extent to which the DSL [i/o] goal can be met depends on the compression threshold. Input levels that fall below the compression threshold will not be audible for the patient with hearing loss. Given that the lowest commercially available compression threshold is approximately 30-dB SPL, it is apparent that the goal of providing all acoustic
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The use of nonlinear technology, however, in conjunction with an appropriate fitting strategy such as DSL [i/o], allows one to functionally approach this goal.

The DSL [i/o] allows for as much or as little individual data (e.g., LDL, RECD) to be entered as desired by the audiologist and provides age-appropriate corrections for RECD and LDL. These elements and the choice of multiple transducers (Table 1) make this fitting strategy very popular for use with infants and young children, but also appropriate for an adult population. Target data can be viewed in a variety of formats.

In Figure 1–4, for example, coupler verification data for a variety of input levels are provided. The software also lists recommended CR(s) and SSPL90 as a function of frequency. Verification data for real-ear measures also can be provided. Alternatively, the audiologist (and patient) can view the target data in the form of an SPL-O-Gram (Fig. 1–5). The patient's threshold and LDL data, as well as aided output targets, actual aided output values, and/or unaided output values, can be viewed on one graph. This can be a useful counseling tool, as the patient can see which sounds are inaudible when unaided, and the improvement in audibility afforded by the hearing aids. Several additional output formats are available.

FIG6

The FIG6 fitting strategy employs a loudness normalization rationale (Gittles and Niquette, 1995). Only threshold data are employed in generating fitting targets. FIG6 provides targets for low (40-dB SPL), middle (65-dB SPL), and high (90-dB SPL) input levels. For low input levels, gain is prescribed with the goal of providing aided thresholds of 20 dB HL when the hearing loss is mild-to-moderate in severity. For greater degrees of hearing loss, aided thresholds increase as a function of increasing severity. At middle to high input levels, the gain required for normal loudness perception assuming 65- and 95-dB SPL input levels is prescribed.

The amount of gain required is based on average data obtained from individuals with hearing loss.

FIG6 is a good example of a fitting protocol that assumes the audiologist is working with an adult who can provide feedback and with flexible technology that can be adjusted to account for individual differences that were not accounted for in any premeasurements (e.g., RECD, LDL). As seen in Figure 1–6, REIG and coupler targets are provided as well as CRs in a low- and high-frequency channel.

VIOLA

VIOLA is part of the Independent Hearing Aid Fitting Forum (IHAFF) protocol for the selection, fitting, and verification of hearing aids (Valente and Van Vliet, 1997; Cox and Flamme, 1998). VIOLA employs a loudness normalization rationale, and the IHAFF protocol is best described as patient-driven. Loudness rating data for warble tones obtained using the Contour Test of Loudness Perception are used in deriving the ultimate fitting targets (Cox et al, 1997). The current version of the fitting protocol will estimate the loudness contours if only threshold data are available.

The patient rates the loudness of warble tones using a seven-point scale ranging from “very soft” to “uncomfortably loud.” An ascending approach is employed, and several trial runs are obtained at each frequency (typically 500 and 3000 Hz at a minimum). VIOLA uses this information to generate targets that should re-create the loudness relationships between speech and warble tones found in individuals with normal hearing. As such, aided perceptions of warble tone and speech stimuli demonstrated by the hearing aid wearer should be similar to those demonstrated by a group of individuals with normal hearing.

Figure 1–7 provides an example of the target data provided by VIOLA. Input/output curves are provided at frequencies designated by the audiologist. A hearing aid parameter table is provided to assist the audiologist in choosing appropriate hearing aids.
The audiologist also may enter these parameters from a given hearing aid, and the resulting output can be plotted on the input/output graphs to see how closely the target is matched and where compromises may be necessary.

Comparison among Various Nonlinear Fitting Strategies

Fitting strategies employing an LE versus an LN approach would be expected to generate differing prescriptions. Byrne et al (2001)
found that the degree of difference among several fitting strategies (DSL [i/o], FIG6, VIOLA, and NAL-NL1) varied with different degrees and configurations of hearing loss. For example, one would expect to find relatively greater amounts of low-frequency amplification using the LN rationale. Figure 1–8 demonstrates this finding when comparing the REIG targets generated by FIG6 and NAL-NL1 for a flat, 50-dB sensorineural hearing loss. The NAL-NL1 prescription demonstrates relatively less low-frequency gain and greater amounts of amplification in the midfrequencies.

What is somewhat surprising is the degree of difference found among fitting prescrip-
tions that incorporate a similar underlying rationale. In these instances, the differences are likely related to how a given rationale is implemented. For example, NAL-NL1 and DSL [i/o] can prescribe a dramatically different degree of high-frequency amplification even when DSL [i/o] is configured to generate targets meant to result in loudness equalization. Figure 1–9, for example, provides REAG targets generated by DSL [i/o] and NAL-NL1 for a steeply sloping, high-frequency sensorineural hearing loss. DSL [i/o] prescribes a much greater amount of high-frequency gain for soft and average

Figure 1–6. Example of prescriptive output provided by FIG6.
Strategies that incorporate an LN rationale also can differ substantially. Figure 1–10 provides coupler targets generated by VIOLA and FIG6 for a mild-to-moderate, gently sloping sensorineural hearing loss. Ricketts (1996) found substantial differences between prescriptions generated by various LN strategies. These differences were attributed to differing algorithms, frequency response rules, and as-
Figure 1–8. Insertion gain targets prescribed by FIG6 and NAL-NL1 for flat, 50-dB sensorineural hearing loss (HL).

Figure 1–9. Real-ear-aided gain targets provided by DSL [i/o] and NAL-NL1 for a mild-to-severe, steeply sloping, high-frequency sensorineural hearing loss.

Figure 1–10. Coupler gain targets from VIOLA and FIG6 for a gently sloping, mild-to-moderate sensorineural hearing loss.
sumptions regarding the signal processing employed by the hearing aid (i.e., number of independent compression channels).

**Which Method Is Best?**

Considering the varying underlying theories and implementations employed with the fitting strategies outlined above, one might ask whether use of any particular strategy will yield more successful hearing aid fittings. Intuitively, one might assume that restoration of normal loudness perception through use of patient-specific measures of dynamic range has the greatest face validity and represents a good starting point (Valente and Van Vliet, 1997). Unfortunately, there is scant empirical research that has addressed the relative real-world performance provided by fitting strategies incorporating an LN rationale versus strategies incorporating a different rationale (e.g., LE).

Several researchers have suggested that the loudness relations among various frequency regions are not important so long as speech sounds are made audible, but not uncomfortably loud (Humes, 1996). This suggestion is based on the results from research conducted with linear fitting strategies that have shown that a fairly wide range of frequency responses can lead to similar speech recognition ability and acceptable sound quality when audibility of the signal has been controlled (Sullivan et al, 1988). The goal is to fit as much of the speech signal as possible within the patient’s dynamic range. Other researchers have suggested that the loudness relations among various frequency regions are important when prescribing fitting targets, and that restoring normal loudness relations may not be an appropriate goal (Byrne, 1996).

With an LN response, the lower frequencies are likely determining the overall use gain, and it is possible that the higher frequencies may be presented at a less than ideal level, especially if significant background noise is present and/or soft speech is encountered. Although this is normal (i.e., an individual with normal hearing would perceive the higher frequency speech sounds at a low sensation level), such a response may not be ideal for the patient with hearing loss who has a compromised auditory system. In this case, an LE approach may be better as it ensures that the critical high-frequency regions contribute more to the overall loudness of the signal (Byrne, 1996).

There also is empirical support for the assumption that restoration of normal loudness perception may not lead to the highest speech recognition ability when predicted speech recognition ability is compared via calculations of the Articulation Index (AI) or the SII (Rankovic, 1995; Ricketts, 1996; Stelmachowicz et al, 1998). The higher AI results from a greater amount of gain, most notably in the higher frequencies, prescribed by strategies that attempt to maximize intelligibility using threshold data.

Whether these same findings would remain if actual speech recognition ability was obtained is unknown. In addition, comparison in this manner does not address differences in perceived loudness and sound quality that must be considered when comparing prescriptions (Studebaker, 1992). In the Ricketts (1996) study, for example, differences were minimized once loudness was equalized. The question of whether the majority of patients with hearing loss would tolerate or eventually adapt to the greater amount of high-frequency amplification prescribed by some strategies has not been answered (Lindley et al, 2001).

**Summary**

Prescriptive fitting strategies calculate the desired electroacoustic characteristics of a hearing aid based on the results of various psychoacoustic data such as pure-tone thresholds, MCL, LDL, and dynamic range. Currently, the audiologist has access to a variety of independent prescriptive formulas that achieve selective amplification for a given patient. Several of the prescriptive formulas now are flexible enough to provide the audiologist with the ability to use as much or as little psychoacoustic data as de-
sired (e.g., NAL-NL1, DSL [i/o]) and allow the audiologist to deal with both linear and nonlinear technology within the same prescriptive formula (e.g., DSL [i/o], VIOLA). The audiologist using advanced technology is faced with a variety of proprietary fitting formulas that have not been well defined in the clinical or research literature. A historical perspective on prescriptive formulas and an understanding of the current independent fitting strategies should assist the audiologist in evaluating proprietary fitting algorithms in the future.

References
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