Ability To Achieve Gain/Frequency Response and SSPL-90 Under Three Prescription Formulas with In-The-Ear Hearing Aids

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Abstract

Custom in-the-ear (ITE) hearing aids (standard linear amplifiers with single-pole-filter low-frequency tone control and a class A amplifier output stage) were fit to 90 ears using the revised National Acoustics Laboratories' formula (NAL-R), and to 20 ears each using Prescription of Gain/Output II (POGO II) and Memphis State University (MSU) formulas. Both real-ear insertion gain and 2-cc coupler gain were evaluated. Examination of differences between prescribed gain and that actually achieved in the fittings revealed that too much gain was often given in the low- and mid-frequency range and insufficient gain in the high frequencies. There was little difference among the formulas in the degree of deviation from target. For some fittings, the deviation resulted in poorer predicted speech recognition scores (modified Speech Transmission Index). For the POGO II and MSU methods, underfitting of prescribed SSPL-90 values was far more common than overfitting.

Key Words: Amplification, frequency response, hearing aids, maximum power output, prescription gain formulas, probe microphone measurement, real-ear insertion gain, saturation sound pressure level

Recently, there has been a proliferation of prescriptive hearing aid selection methods that provide gain/frequency response, and sometimes maximum power output characteristics, based on the audiometric test results of a given hearing-impaired listener. Some of the prescriptive formulas are based on audiometric threshold data alone (e.g., Berger et al, 1984; Byrne and Dillon, 1986; Libby, 1986; Schwartz et al, 1988), while others require suprathreshold loudness judgments (uncomfortable loudness or most comfortable loudness) on the assumption that these values cannot adequately be predicted from pure-tone thresholds (e.g., Shapiro, 1976; Skinner et al, 1982; Cox, 1985, 1988; Tyler, 1986). Each prescriptive procedure has a stated rationale; the most common goal being that of maximizing audibility of the speech spectrum or of amplifying the speech spectrum to the patient's most comfortable listening level (MCL).

With the current wide availability and use of probe microphone measurement systems, prescriptive fitting of real-ear insertion gain (REIG) is rapidly becoming the most accepted approach to hearing-aid fitting. Despite the popularity of prescriptive formulas, however, there is still limited information available to guide a clinician in determining which of the many formulas will provide the best amplification characteristics for a specific patient, other
than knowledge of the theoretical bases of the approaches. To examine differences between formulas, Humes (1986) calculated prescribed REIG values using 10 different prescriptive approaches with three different hypothetical audiometric configurations. He found that, although differences in prescribed gain/frequency response among the 10 formulas were relatively small, they sometimes caused the selection of different behind-the-ear (BTE) hearing aid models. Sullivan et al. (1988) evaluated modifications of four prescriptive approaches fit using a digital master hearing aid. Paired comparison judgments of relative speech intelligibility and speech quality were made for each of the prescriptions at three different presentation levels. Results indicated that no procedure was clearly superior to the others and that speech performance varied across the formulas as a function of stimulus level. Differences among the approaches were smallest when the level of presentation corresponded to the listener's most comfortable loudness level.

Neither Sullivan et al. (1988) nor Humes (1986) used commercially available hearing aids for testing. Most recently, Humes and Hackett (1990) evaluated differences in prescriptive methods under more clinically representative conditions. For each of 12 sensorineural hearing-impaired subjects, three BTE hearing aids were selected for best match to the gain/frequency response prescriptions under three formulas: the National Acoustic Laboratories revised formula (NAL-R; Byrne and Dillon, 1986), the Prescription of Gain/Output formula (POGO; McCandless and Lyregaard, 1983), and the Memphis State University formula (MSU; Cox, 1988). Evaluation of REIG for each aid, and aided CUNY Nonsense Syllable Test scores, indicated very little difference in performance under the three fitting methods.

Humes and Hackett used BTE hearing aids because they are more flexible electroacoustically than in-the-ear (ITE) fittings, and are therefore more able to achieve the prescribed gain/frequency response characteristics. However, ITEs make up the largest percentage of hearing aids sold today (Mahon, 1989; Cranmer, 1990), a statistic that is reflected in our dispensing practices. To examine the ability to achieve prescribed electroacoustic characteristics in the more popular ITE hearing aid, Bratt et al. (1987) evaluated 122 custom ITEs as they arrived from the manufacturer to determine how closely they matched the requested prescribed 2-cc coupler gain values using the NAL-R formula. Few of the aids provided a close match to prescribed coupler values, even though the manufacturer had been diligent in trying to provide the requested gain function.

This study extends the work of Bratt et al. (1987) and explores the degree of fitting error (deviation from target) that occurs in custom ITE hearing aids with REIG as well as 2-cc coupler measurements under three prescription gain formulas: the NAL-R approach, Prescription of Gain/Output II (POGO II; Schwartz et al., 1988), and the MSU approach. Specifically, this study addressed the following questions: (1) How closely is prescribed gain/frequency response achieved with ITE hearing aids fit using the NAL-R formula with 2-cc coupler and with REIG measurements across a large group of ears?; (2) To avoid rejecting too many hearing aids on first shipment, what degree of deviation from prescribed values would have to be accepted?; (3) Are there differences in the degree of fitting error among the three selected prescriptive formulas (NAL-R, POGO II, or MSU)?; (4) Is speech recognition performance as predicted by a modified Speech Transmission Index poorer due to deviation from target?; and (5) How closely are prescribed SSPL-90 values achieved using the POGO II and MSU formulas?

**METHOD**

**Subjects**

Fifty adults with sensorineural hearing impairment were fit with ITE hearing aids using the NAL-R prescriptive formula. All but 10 of the subjects were fit binaurally, resulting in a total of 90 aided ears tested. Subjects were patients receiving hearing aids at either the Department of Veterans Affairs Medical Center or the Bill Wilkerson Center, both in Nashville, Tennessee.

An additional 14 adults were fit with hearing aids using the POGO II formula, and 11 adults were fit using the MSU formula. Six of those subjects fit using the POGO II formula and nine of those fit using the MSU formula received binaural hearing aids, for a total of 20 additional aided ears tested under each of these two prescriptive approaches.

Means and standard deviations of audiometric thresholds for the ears fit under each prescription formula are shown in Figure 1. These data illustrate that, on average, subjects had mild/moderate to moderate/severe sloping...
Procedures

Each subject was fit with custom ITE hearing aids (standard linear amplifiers with single-pole-filter low-frequency tone control and a class A amplifier output stage) from one of several major manufacturers who had agreed to work closely with us to attempt to achieve the desired gain/frequency responses. The target gain/frequency responses were computer-calculated for each ear using IBM-compatible software called “Shaping Hearing Aids for Patients Effectively” (SHAPE; Venture 4th, 1987). The NAL-R formula is calculated only on the basis of audiometric thresholds. The MSU approach includes measurement of frequency-specific upper limits of comfortable loudness and the POGO II approach includes frequency-specific uncomfortable loudness level (UCL) measurements in order to determine prescriptions for output limitation. For purposes of output limiting with the NAL-R formula, a broadband speech UCL was determined under headphones using Hawkins’ closed-set response list (Hawkins, 1980) and a procedure similar to that used by Sammeth et al (1989).

With each ITE order, manufacturers were given only the earmold impression and the prescribed 2-cc coupler values for gain/frequency response; i.e., audiograms were not supplied. For POGO II and MSU fittings, the manufacturer was also supplied with the prescribed SSPL-90 curve values, and for NAL-R fittings, with the speech UCL value. For all SSPL-90 curve values, 5 dB was added for reserve, since output potentiometers are typically designed only to lower the output from maximum. To provide maximum flexibility in fitting the frequency response, each hearing aid was ordered with both a tone control and output potentiometer, and with Select-A-Vent variable venting inserts. All ITEs used in this study were hard peak-clippers; i.e., no compression or ASP circuitry was used.

When a hearing aid arrived from the manufacturer, electroacoustic measurements were accomplished using a Fonix 6500 system. First, a standard ANSI test (ANSI S3.22-1987) was run to ensure that each hearing aid was functioning properly, as indicated by manufacturer’s specifications. Then, with a swept pure-tone input of 50 dB SPL and the volume wheel turned to maximum, the tone control potentiometer was adjusted to achieve the closest match to prescribed gain/frequency response. The SSPL-90 curve was also adjusted with the output potentiometer so as to most closely match, but not exceed, if possible, the prescribed values (POGO II and MSU). Since tone and output potentiometers sometimes interact, both measurements were repeated until the best compromise was achieved. These “best-fit” 2-cc coupler values for the gain/frequency response were recorded for comparison with the prescribed 2-cc coupler full-on gain values to determine the degree of error that occurred.

Subsequently, the frequency/gain response of the hearing aid was fit to the patient’s ear using probe-microphone measurement of REIG with the Fonix 6500. With a broadband composite signal presented at 70 dB SPL from a loudspeaker positioned 1 meter from the subject at a 90-degree azimuth, trimpots, venting, and volume wheel were adjusted, as necessary, to achieve the closest possible match to target REIG values. These “best-fit” REIG values were recorded for comparison with prescribed REIG values to determine the degree of fitting error that occurred with the real-ear measurement procedure. Following the real-ear procedure, the SSPL-90 curve was again measured on the 2-cc coupler. For POGO II and MSU, these latter SSPL-90 values were compared to prescribed values to examine degree of SSPL-90 fitting error.
RESULTS

Gain/Frequency Response

The NAL-R Prescriptive Formula

Thirty-five of the 90 ears fit with the NAL-R formula were selected for depiction in scatterplot form in Figure 2. These data are illustrative of the trends found in the full data set. Data for 2-cc coupler measurements are shown in Figure 2A, and data for REIG measurements are shown in Figure 2B. Each datum point represents the difference between the gain that was actually obtained and that prescribed, with a positive value indicating that the gain obtained was greater than target gain, and a negative value indicating that the gain obtained was less than target gain. It can be seen that there was a trend toward providing too much gain in the low and mid frequencies, and too little gain in the high frequencies relative to the prescribed values. Note that, for REIG measurements, sufficient gain at 4000 Hz was achieved in only 3 of the 35 ears.

Tolerance values calculated for the data from all 90 ears fit with the NAL-R formula are depicted in Figure 3. Shown is the percentage of hearing aids that would be accepted for a given degree of fitting error in dB. Specifically, the ordinate shows the percentage of fittings in which deviations from target across the frequency band were within certain limits. Two functions are shown, representing a wider and narrower range of measurement frequencies. A, data for 2-cc coupler full-on gain measurement. B, data for real-ear insertion gain measurement.
Achieving Prescribed Gain/Sammeth et al

Figure 4 Means of the differences in prescribed real-ear insertion gain between the three prescription gain formulas for 15 ears representing a range of audiometric configurations and degrees of loss.

Frequency range were less than the dB value on the abscissa. Figure 3A illustrates data for 2-cc coupler measurements, and Figure 3B illustrates data for REIG measurements. Two functions are shown, each representing a different frequency range over which degree of error was considered. Note that, for 2-cc coupler measurements, an error of more than 15 dB would have to be tolerated at one or more frequencies in the frequency range of 250 to 4000 Hz to accept 90 percent of the hearing aids as received from the manufacturer. To accept 50 percent of the hearing aids, a fitting error of 10 dB would need to be tolerated at one or more frequencies in this range. Narrowing the frequency window by excluding 250 and 4000 Hz results in little change. The data for REIG measurements are similar to those for 2-cc coupler measurements.

Comparison of NAL-R, POGO II, and MSU

In comparing the POGO II and MSU procedures with NAL-R, we initially questioned how much actual difference in prescribed gain/frequency response there is among the formulas. To explore this issue, prescribed REIG for each frequency was calculated under each of the formulas for 15 ears that represented a range of audiometric configurations and degrees of loss. Then, for each ear, absolute differences in prescribed REIG between the formulas were calculated by frequency. The means of the differences are illustrated in Figure 4. Although some audiograms resulted in greater calculated differences than others, mean differences in prescribed gain among the formulas were small, except that POGO II prescribed an average of 13 dB greater gain at 4000 Hz than did the other two formulas.

The degree of fitting error that occurred under each of the formulas was then explored. In Figure 5, the means of the fitting error across the audiometric frequencies for the 20 POGO II and 20 MSU fittings are compared with those obtained for the 90 ears fit with the NAL-R formula. For this figure, the direction of the difference was ignored; that is, absolute values of the deviations from target were used to calculate the means. Figure 5A illustrates these data under the three formulas for 2-cc coupler measurements, and Figure 5B illustrates these data for REIG measurements (REIG data were unavailable for one ear in the POGO II group). Overall, there appears to be relatively little difference in mean absolute fitting error among the three groups. For both 2-cc coupler and REIG data, all three prescription formulas have a mean deviation from target of less than or equal to 10 dB in the frequency range from 250 to 4000 Hz. Examination of individual differences revealed that, as previously found with the NAL-R, MSU and POGO II data generally indicated overfitting in the mid frequencies and underfitting in the high frequencies.

Figure 5 The degree of fitting error under each of the three prescription gain formulas. Data shown are the means of the absolute differences between prescribed gain and that actually obtained, at each frequency. A, data for 2-cc coupler full-on gain measurement. B, data for real-ear insertion gain measurement.
Predicted Speech Intelligibility

A logical question to arise from these data is whether or not significant deficits in speech intelligibility can be expected to result from these fitting errors. To explore this issue, we calculated modified Speech Transmission Indices (mSTIs; Humes et al., 1986) based on REIG data for 20 ears randomly selected from the group fit under the NAL-R method, 19 of the ears fit under the POGO II method (REIG data was unavailable for one ear), and the 20 ears fit under the MSU method. The mSTI is an acoustical calculation scheme that is similar to the Articulation Index. For our purposes, it provided predictions of aided speech-recognition performance if the CUNY Nonsense Syllable Test (NST) had been given with speech fixed at a level of 70 dB SPL, and with a signal-to-babble ratio of +7 dB in average reverberant conditions. For each ear, the mSTI was calculated for each prescribed REIG and for each REIG actually obtained with the hearing aid.

Calculated mSTIs ranged from 34 percent to 82 percent, with similar ranges across the three formulas. For 2 of the 20 ears under the NAL-R method, 2 of the 19 ears under the POGO II method, and 3 of the 20 ears under the MSU method, the mSTI calculated for obtained REIG fell outside of the 95 percent confidence interval for the mSTI calculated for prescribed REIG. In each of these cases, the mSTI was poorer for obtained REIG than for prescribed REIG. The mean difference between the mSTI for prescribed REIG and that for obtained REIG in these seven fittings was 18.7 percent (SD = 3.6).

For most of the remainder of the ears (n = 29), the mSTI for obtained REIG was also poorer than that for prescribed REIG, although not exceeding the 95 percent confidence interval. In 10 ears, the two values were equal. In only three ears was the mSTI for obtained REIG slightly better than that for prescribed REIG.

Maximum Output Curves (SSPL-90)

Shown in Figure 6 are scatterplots of individual differences between prescribed SSPL-90 values and those actually obtained on the 2-cc coupler for the 20 ears under the MSU formula and 14 ears under the POGO II formula (SSPL-90 data were not available for 6 POGO II ears). Data from MSU fittings are shown in Figure 6A, and from POGO II fittings in Figure 6B. Frequencies shown are those provided by the respective prescriptive formulas. Positive values indicate that the SSPL-90 value obtained was greater than that prescribed, and negative values indicate that the value obtained was less than that prescribed.

Note that the vast majority of fittings provided lower SSPL-90 values than were prescribed. For most of these hearing aids, output potentiometers were turned to maximum; that is, they were providing the greatest output of
which they were capable. Only a few of the SSPL-90 values fit exceeded those prescribed. For these hearing aids, values exceeding prescribed output at one frequency were accompanied by values below prescribed output at other frequencies. Sometimes the clinician chose to have output at one frequency above the prescribed value in order to more closely match output for the remainder of the frequencies.

**DISCUSSION**

In this study, the degree of deviation from target demonstrated for 2-cc coupler measurements of gain/frequency response is similar to that found previously by Bratt et al (1987). The same trend was found with REIG measurements as with 2-cc coupler measurements. Most commonly, gain was overfit in the mid frequencies and underfit in the high frequencies. Differences in fitting error among the three formulas (see Fig. 5) were generally quite similar to differences in prescribed gain between the formulas (see Fig. 4). These data do not imply that one formula has more or less merit than another; rather, they simply suggest that there is no strong rationale for using any one of the three formulas over another until better fitting accuracy is achieved.

If a hearing aid is supplied with gain/frequency response and/or SSPL-90 values that appear to be too deviant from the target values ordered, the fitter must make a decision as to whether it is reasonable to return it with instructions that the manufacturer try to match the order more accurately. A major problem lies in determining what is a significant discrepancy, since it is neither time- nor cost-efficient to return too many hearing aids upon receipt, especially if the manufacturer is unlikely to do better on subsequent attempts. To make the issue more difficult, none of the published formulas, to our knowledge, specifically states how much fitting error can be tolerated before the principles driving the method are violated. As indicated by the data of Figure 3, acceptance criteria for the ITEs that we used would have to be lenient.

It is difficult to determine how much difference the deviations from target would make in terms of patient performance and satisfaction. Although the mSTI predictions do not account for all subject and amplification variables or all listening situations experienced, they suggest that the degree of fitting error found would detrimentally affect speech understanding in at least some of the fittings. In addition, our philosophy, like most of the developers of prescriptive approaches, is to consider the target gain/frequency response as only a starting point in the fitting process. The "best" gain/frequency response for an individual patient may deviate from the prescribed gain/frequency response for several reasons. First, most formula approaches are based on averaged data for a number of parameters, including real ear-unaided response (REUR) and real-ear-to-coupler correction factors. Some authors have recently recommended measurement of an individual's REUR for incorporation into the calculation of target 2-cc coupler gain (Mueller, 1989; Punch et al, 1990). Had this approach been used here, fitting error for REIG may have been reduced for some ears. Also, the MSU procedure recommends accomplishing audiometrics and loudness measurements with the use of 2-cc calibrated insert earphones, which directly compare to 2-cc calibrated hearing aids, rather than with the 6-cc calibrated supra-aural earphones that were used in this study.

Second, and perhaps more importantly, most of the prescriptive approaches are based only on audiometric threshold and loudness measurements, while it is well known that patients may differ in suprathreshold, psychoacoustic, and speech recognition abilities despite similarities in audiograms. For this reason, and as discussed by Bratt and Sammeth (1991), we believe that evaluation of an individual patient's aided performance using speech or speech-like stimuli, and adequate follow-up appointments, should be crucial components of the clinical protocol, following a reasonable approximation to target gain. Unfortunately, adjustments to improve speech intelligibility would most commonly be desired in the direction of greater high-frequency gain, which these data indicate would be difficult, if not impossible, to achieve without considerable alteration in earmolds and/or hearing aid circuitry.

The degree of deviation from target found in this study for SSPL-90 curves under the POGO II and MSU methods was also of concern. Although it is important to limit maximum power output so that there is neither danger of overamplification nor significant loudness discomfort, we found only a few instances where inadequate limiting occurred. Rather, the majority of hearing aids arrived from the manufacturers with less available output than was requested, even though a 5 dB reserve had been added. Significant underfitting of maximum
output may have detrimental effects on a patient's hearing aid satisfaction, just as overfitting does. High gain combined with low SSPL-90 in a hearing aid can lead to a condition known as "inadequate headroom" (Preves and Newton, 1989). When a hearing aid has inadequate headroom, clipping may occur too frequently, producing distortion products that may affect speech intelligibility and sound quality. Recently, Fortune and Preves (1992) reported that aided UCLs of hearing-impaired subjects decrease as SSPL-90 decreases, presumably because of increases in the distortion produced. As a consequence, measurement of UCLs under audiometric headphones for purposes of setting SSPL-90 in limited-headroom hearing aids, as proposed by the majority of formula approaches, may not be justifiable.

In summary, a relatively large mean degree of deviation from target for gain/frequency response and SSPL-90 were found with the custom linear ITE hearing aids that we evaluated. Although the prescribed gain/frequency response is considered to be only a starting point in the hearing aid fitting process, it would certainly be desirable to achieve closer approximations. Customizing the prescription using the individual's own REUR is one approach that may lead to a closer match to target. It is also important to note that there have been recent technological advances that allow greater flexibility in shaping the frequency response. The ITEs used in this study represent technology available from 1989 to 1991. Specifically, these ITEs had an amplifier with a class A output stage, tone controls with a limited range of variability, and receivers with a primary frequency response peak around 2000 Hz and a relatively narrow-band response. Many ITEs currently being produced use either class D or class B amplifier output stages, receivers with a wider band frequency response and a higher frequency primary resonance peak, and tone controls consisting of two- or even four-pole filters. With these newer-technology hearing aids and with wider availability of multichannel technology, better approximations to target values can be expected (e.g., see Sammeth et al, in press). Finally, the use of compression circuitry or of new class D amplifiers that provide higher output levels may help to reduce problems with excess distortion resulting from inadequate headroom.


References


