Target-Matched Insertion Gain Derived from Three Different Hearing Aid Selection Procedures

Jerry L. Punch
Amy H. Shovels
William W. Dickinson
Jaynee H. Calder
Colleen Snead

Abstract

Three hearing aid selection procedures were compared to determine if any one was superior in producing prescribed real-ear insertion gain. For each of three subject groups, 12 in-the-ear style hearing aids with Class D circuitry and similar dispenser controls were ordered from one of three manufacturers. Subject groups were classified based on the type of information included on the hearing aid order form: (1) the subject’s audiogram, (2) a three-part matrix specifying the desired maximum output, full-on gain, and frequency response slope of the hearing aid, or (3) the desired 2-cc coupler full-on gain of the hearing aid, based on real-ear coupler difference (RECD) measurements. Following electroacoustic adjustments aimed at approximating a commonly used target insertion gain formula, results revealed no significant differences among any of the three selection procedures with respect to obtaining acceptable insertion gain values.

Key Words: Hearing aids, hearing aid fitting, hearing aid selection, real-ear coupler difference (RECD)

A variety of procedures are available to audiologists for use in selecting the appropriate electroacoustic characteristics of hearing aids. Only a few of these procedures, however, are used today on a widespread basis in the selection of conventional, nonprogrammable hearing aids (Leadbetter and Bonta, 1993). Two of the most frequently used procedures, particularly with respect to the selection of custom in-the-ear (ITE), in-the-canal (ITC), and completely in-the-canal (CIC) hearing aids are (1) an audiogram procedure, in which the audiologist requests the manufacturer to choose the frequency-gain and output characteristics of the desired hearing aid on the basis of the patient’s audiometric thresholds, most comfortable listening level (MCL), and the uncomfortable loudness level (UCL); and (2) a matrix procedure, consisting of identifying specific electroacoustic characteristics of the desired hearing aid by specifying them as parametric values associated with a particular manufacturer’s matrix specifications (Leadbetter and Bonta, 1993). The major difference between these two procedures is that the matrix is generated internally by the manufacturer in the former case and externally by the audiologist in the latter case (McCandless, 1994). Hearing aid fittings achieved with either procedure can be verified against a target formula considered by the audiologist as theoretically appropriate, particularly if the hearing aids are linear in a substantial portion of their input-output (I/O) functions. Such verification is frequently performed using probe-microphone measurements, which allow specification of frequency-dependent gain in ear canals of individual hearing-impaired listeners.

In addition, a third approach offers considerable potential in achieving desirable electroacoustic characteristics in hearing aid fittings.
This approach is the real-ear coupler difference (RECD) procedure (Punch et al, 1990; Studebaker et al, 1991; Mueller, 1992; Revit, 1994). This procedure is not only compatible with probe-microphone measurements in verifying the real-ear response, but, more importantly, it allows the audiologist to provide a manufacturer, on a prescriptive basis, with desired 2-cc coupler values that account for the unique characteristics of the hearing aid user’s ear. By definition, the RECD procedure accounts for individual ear canal resonance characteristics, ear canal volume, middle ear impedance, differences in microphone location for different style hearing aids, and acoustic coupling in the selection of hearing aid gain characteristics. Tecca (1993) originally found little difference in achieving target-gain values when hearing aid measurements entailed individual versus average real-ear unaided responses, or REURs (Mueller, 1989). He has reported more recently (Tecca, personal communication, 1994), however, that in a relatively large subject sample, the individualized approach showed an advantage over the average REUR method in achieving the desired real-ear outcomes.

The individualized RECD procedure derives a conversion factor (the RECD) from comparison of the frequency response and/or output characteristics of a hearing aid’s response in a standard 2-cc coupler with the same aid’s response in an individual’s ear canal. The aid used for this measurement does not necessarily need to bear any physical resemblance to that fitted on the patient and, for convenience, may be a behind-the-ear (BTE) device. While differences in venting and physical fit may affect measured sound pressure level (SPL) at the eardrum, these differences can be minimized by ensuring that the physical characteristics of the earmold coupling used in the test procedure—including venting and slit leaks—are as close as possible to those of the aid to be fitted. For the conversion to be applicable to the patient’s hearing aid and to the utilization of a given target-gain fitting formula, it is important that the frequency response measurement be made in the aid’s linear I/O range. To the extent that the desired 2-cc coupler values can be achieved by the manufacturer, and the hearing aid’s response can be finetuned by the audiologist, the procedure has the potential to derive target-gain values specifically prescribed for an individual ear.

Although any of these three procedures can be used to derive both the frequency-gain response and output characteristics of a hearing aid, our interest in this study was confined to a comparison of the procedures with respect to their relative ability to provide prescribed frequency-gain characteristics in hearing aids acquired for a clinical population of hearing-impaired individuals. The research questions posed for this study were (1) To what extent are manufacturers able to provide requested 2-cc coupler gain values when hearing aids are ordered via an RECD approach? (2) Does the match between real-ear insertion gain (REIG) and target real-ear gain values differ significantly for hearing aids ordered by the audiogram, matrix, and RECD procedures? and (3) Is there evidence that any existing differences between REIG and target real-ear gain values vary among the manufacturers studied?

METHOD

Subjects

Subjects consisted of 31 male patients, ranging in age from 27 to 89 years (mean = 69.3 years), who were in the process of obtaining hearing aids from the Audiology Clinic at the Ann Arbor Department of Veterans Affairs (VA) Medical Center. Each subject had completed routine audiometric testing within 6 months and had received medical clearance for hearing aids within 1 year, prior to participation in the study. All subjects had sloping mild to moderately severe or severe sensorineural hearing loss in the test ear. The mean pure-tone average of 500, 1000, and 2000 Hz across subjects was 40.6 dB HL, with a standard deviation of 9.7 dB. All subjects were considered candidates for full-shell ITE-style hearing aids with linear circuitry.

Hearing Aid Selection Procedures

A total of 36 hearing aids from three different manufacturers were fitted using one of three hearing aid selection procedures described below. Twelve hearing aids, four per manufacturer, were ordered based on each of the three procedures. Assignment of subjects to selection procedure was random except as necessary to complete each of the three selection and three manufacturer blocks. Only one ear of a given subject was used as the test ear, unless an asymmetric hearing loss existed (i.e., where pure-tone thresholds differed by 15 dB or more at any octave frequency or 3000 Hz) and the hearing loss in both ears met predetermined audiometric criteria. When only one ear was used as a test ear but the
patient was being seen in the clinic for binaural fitting, the same selection procedure was applied to both ears to maintain intrasubject consistency in selection rationales. Twenty-six subjects were fitted monaurally as part of the experiment, while five were fitted binaurally.

All hearing aids ordered were linear full-shell instruments with Class D circuitry. The only criteria used to select the three manufacturers for the study were that they (1) were on current VA hearing aid contract, (2) offered similar gain and output characteristics and optional controls that were appropriate for the subject population, and (3) offered a comparable range of adjustment in their active low-cut controls. Importantly, at no time prior to or during the study did any of the manufacturers have knowledge that they were part of an experimental research protocol.

For all procedures, hearing aids were ordered with gain, low-cut, and high-cut or resonant peak controls (depending on which was offered by the manufacturer) and select-a-vent (SAV) venting. Five hearing aids were ordered without gain control potentiometers (due either to lack of space on the faceplate or, in one case, inadvertent omission of a request on the order form). Gain controls were ordered primarily to allow for a reasonable volume range for the users. The extensive use of dispenser controls was consistent with the general practice of the audiology staff at the Ann Arbor VA Medical Center. The ordering of such controls, therefore, was believed necessary to achieve the best possible outcomes for the clinical patients who served as subjects in the study.

All hearing aids, when delivered, were analyzed electroacoustically in an HA-1 2-cc coupler, in conjunction with the Fonix 6500 analyzer and the current ANSI hearing aid standard (ANSI, 1987). As specified in the standard, high-frequency average (HFA) full-on gain was obtained with controls fully open and vents occluded.

**Audiogram.** For hearing aids ordered by the audiogram procedure, the subject’s MCL and UCL for speech, obtained by monitored live voice, and audiometric pure-tone thresholds at 250, 500, 1000, 2000, 3000, and 4000 Hz were included on the manufacturer’s order form.

**Matrix.** For the matrix subject group, audiometric thresholds, MCL, and UCL were omitted on the order form. Omission of these items assured the experimenters that manufacturers used only the specified matrix information, and not the audiometric data, in the selection of hearing aid circuitry. Information provided in ordering the hearing aids for this group included the desired make and model and a manufacturer-specific matrix indicating the maximum output, full-on gain, and slope of the desired frequency response. It should be noted that one of the manufacturers specified its matrix gain value as HFA full-on gain, while the other two specified peak full-on gain. Only slight differences between average and peak values were observed, however, due to the relatively smooth frequency responses offered by the Class D circuitry. While the range of available gain differed among the three manufacturers, selections were limited to average full-on gain values between 38 and 48 dB and peak full-on gain values between 40 and 50 dB. These values provided appropriate gain for the range of hearing losses included in the study.

**RECD.** Included on the order form for hearing aids requested by the RECD procedure were the desired target coupler full-on gain at 250, 500, 1000, 2000, 3000, and 4000 Hz and the subject’s MCL and UCL for speech in dB HL. Target coupler gain was determined by use of a modification of the formula recommended by Punch et al (1990):

\[
target \text{ coupler gain} = target \text{ REIG} - (Rear - \text{coupler gain}) + \text{REUR}
\]

where, at a given frequency, REIG is real-ear insertion gain, REAR is real-ear aided response, and REUR is real-ear unaided response (see Mueller, 1992, for definitions).

Table 1 displays the worksheet used to determine the desired coupled gain. A linear BTE hearing aid (Unitron UM-60) was used in computing the target coupler gain. Measurements of the aid’s 2-cc coupler gain were made using a 60 dB SPL composite signal, at the
beginning of the study and periodically throughout, with the aid's volume control taped at a fixed setting in the linear operating range (approximately ¾ on). Small instabilities of 1 to 1.5 dB were noted at selected frequencies during the course of the study, and adjustments were made on the worksheet twice during the experiment to correct for these minor changes. For each subject, a conventional measurement of REUR was made, followed by a measurement of REAR, using the Unitron hearing aid at the same fixed volume control setting. An unvented foam earmold with 15-mm #13 tubing was used for these real-ear measurements. The foam mold was seated deeply in the ear canal to provide an adequate acoustic seal; none of the subjects complained of physical discomfort from the molds. A composite signal of 70 dB SPL, the equipment default level, was utilized. Although this level was 10 dB higher than that used in the coupler measurements, the fact that the experimental BTE hearing aid was perfectly linear (+ 0.3 dB) for input levels through 75 dB SPL ensured that the discrepancy in input levels did not contaminate the measurements.

Two modifications to the above formula were incorporated into the computation of target coupler gain. Small corrections were used (see Table 1) to account for microphone placement differences between the BTE experimental aid and the ITE aids that were being ordered for the subjects (Madaffari, 1974). In addition, a reserve gain factor of 10 dB was arbitrarily added at 1000 to 4000 Hz to ensure a usable volume range for the subjects in this mid-to-high frequency region. Target REIGs were computed by the real-ear analyzer as the NAL-R response (Byrne and Dillon, 1986), based on the subject's audiometric thresholds. The above formula (Punch et al., 1990), with microphone correction and reserve gain values added, was used to establish the target coupler gain provided to manufacturers.

Real-Ear Measurement Procedures

A Fonix 6500 Hearing Aid Test System with Quick-Probe II option was utilized for all coupler and real-ear measurements. For the audiogram and matrix ordering procedures, probe-microphone measurements were performed to verify a delivered aid's response, whereas for the RECD procedure, these measurements were used both to prescribe the hearing aid's frequency-gain characteristics and to verify the delivered aid's response.

The test stimulus was always a composite sound source produced by the system loudspeaker, located at 0° azimuth and 18 inches from the subject's test ear. On a few occasions, the loudspeaker had to be moved as close as 12 inches from the subject to level the sound field. The signal was routinely delivered at 70 dB SPL unless the system automatically lowered the source level during aided testing to avoid exceeding the output limit of the system (120 dB SPL). This level was measured at the over-the-ear reference-microphone position (Mueller, 1992), located just above the pinna of the test ear. Leveling of the reference and probe microphones was completed prior to each test session and between ear-specific measurements when both ears served as test ears. A clinical method of probe-tube placement was utilized in which a marker was placed 3/4 to 1 inch from the end of the tube. This procedure effectively marked the tragus position when the hearing aid was placed in the ear canal, while allowing the probe tube to extend at least 3 to 5 mm beyond the earmold tip.

Table 1 Components of Worksheet Used to Compute Target 2-cc Coupler Gain

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>250</th>
<th>500</th>
<th>1000</th>
<th>2000</th>
<th>3000</th>
<th>4000</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC threshold</td>
<td>(Ear : HL)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Target REIG</td>
<td>(+)</td>
<td>23</td>
<td>30</td>
<td>44</td>
<td>42</td>
<td>38</td>
</tr>
<tr>
<td>NAL-R</td>
<td>(-)</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>3</td>
</tr>
<tr>
<td>RELR</td>
<td>(+)</td>
<td>0</td>
<td>0</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>REAR</td>
<td>(-)</td>
<td>0</td>
<td>0</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Coupler gain</td>
<td>(+)</td>
<td>0</td>
<td>0</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Microphone</td>
<td>correction</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reserve gain</td>
<td>(+)</td>
<td>0</td>
<td>0</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Target coupler gain</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Based on coupler and probe-microphone measurements made using a linear experimental hearing aid.
In every case, the hearing aids ordered by matrix selection were delivered with the requested matrix.

Table 2 shows the mean differences between requested and delivered coupler gain for hearing aids ordered by the RECD procedure. A positive value indicates that the gain delivered by the manufacturers exceeded the requested gain, while a negative value indicates that the delivered gain value was less than that requested. The gain of each of the three manufacturers' aids exceeded the requested gain by an average of 22.8 dB and 28.1 dB at 250 Hz and 500 Hz, respectively. At the remaining frequencies, the average discrepancy varied only from -4.6 dB to 3.5 dB. No pattern was observable from these data to suggest that discrepancies between requested and delivered gain values differed across manufacturers.

While representing the mean discrepancies actually obtained, the data in Table 2 also reflect cancellations of positive and negative values. Such cancellations have the net effect of portraying the magnitudes of existing discrepancies as less than they actually are. Because the amount of any discrepancies was of more interest than their direction, the absolute values of the differences between requested and delivered coupler gain were computed. These absolute values, along with standard deviations, are shown in Figure 2.

It can be seen that, when the direction of the discrepancies was not part of the calculation (see Fig. 2), the overall discrepancies between requested and delivered gain were somewhat greater at 1000 Hz and 2000 Hz than when direction was considered in the calculations (see Table 2), but the discrepancies were similar at the other

### Table 2  Mean Frequency-specific Differences between Requested and Delivered Coupler Gain for Hearing Aids Ordered by the RECD Procedure

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>250</th>
<th>500</th>
<th>1000</th>
<th>2000</th>
<th>3000</th>
<th>4000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manufacturer 1</td>
<td>19.6</td>
<td>25.1</td>
<td>3.2</td>
<td>2.3</td>
<td>-7.6</td>
<td>-5.8</td>
</tr>
<tr>
<td>Manufacturer 2</td>
<td>24.0</td>
<td>32.1</td>
<td>9.6</td>
<td>-2.2</td>
<td>0.5</td>
<td>0.2</td>
</tr>
<tr>
<td>Manufacturer 3</td>
<td>24.7</td>
<td>27.0</td>
<td>0.2</td>
<td>3.8</td>
<td>-6.8</td>
<td>-7.6</td>
</tr>
<tr>
<td>Grand mean</td>
<td>22.8</td>
<td>28.1</td>
<td>3.5</td>
<td>0.2</td>
<td>-4.6</td>
<td>-4.6</td>
</tr>
</tbody>
</table>

### RESULTS AND DISCUSSION

#### Subjects' Hearing Sensitivity

- Mean audiograms of subjects comprising the three experimental groups are shown in Figure 1. A mixed-design multiple analysis of variance (MANOVA) revealed no significant group differences in audiometric thresholds (p > .05). None of the outcomes from the study, therefore, can be attributed to differences in hearing sensitivity among subject groups.

#### Delivered Hearing Aids

Although unsolicited, all hearing aids ordered by audiogram were accompanied by manufacturers' specification sheets containing the manufacturers' choice of matrix. This situation provided a basis for an internal validation check of our matrix-ordering procedures by a comparison of the manufacturers' chosen gain values with those that would have been selected by the authors, using the above-described protocol. Such an analysis, conducted on the gain values, revealed that there would have been similar outcomes in most cases. Three gain values would have been equal, six would have been different by ± one matrix selection (± 5 dB), and three would have been two matrix selections apart (± 10 dB).

In every case, the hearing aids ordered by matrix selection were delivered with the requested matrix.
frequencies. The particularly close agreement between values in Table 2 and Figure 2 at 250 and 500 Hz resulted from the fact that the mean gain of the delivered aids was greater than the requested gain on a highly consistent basis at these frequencies. At the same time, the variability of the data across subjects, or hearing aids, was also greater in the lower frequencies.

These results show that each of the hearing aid manufacturers consistently provided significantly more low-frequency full-on coupler gain than was requested, in the context of the RECD fitting procedure. It is interesting to recall that no additional reserve gain had been requested by the examiners at either 250 or 500 Hz. The extreme differences between requested and delivered coupler gain at 250 and 500 Hz likely were due to the ordering of active low-cut tone controls. Manufacturers specify such controls as having the ability to cut low-frequency gain to values equal to their mid-slope values. While one of the three manufacturers offers only a flat slope, five of the eight RECD-ordered aids from the remaining two manufacturers were delivered with flat slopes, even though mid-slope values were available. The manufacturers, then, may have provided their widest frequency responses so as not to limit the effect of their active low-cut controls. They may have intended for the required slope to be obtained through the clinician’s use of these controls, rather than to provide circuitry with mid- or high-sloping values that might limit the potential of the dispenser to make broader slope adjustments that could prove more effective for the wearer. The ability of the manufacturers to provide adequate gain in the middle and higher frequencies was commendable, given that achieving sufficient gain in the higher frequencies can be an especially difficult aspect of hearing aid fitting.

A mixed-design MANOVA, using values in Figure 2, revealed no significant differences (p > .05) in the ability of the three manufacturers to provide full-on gain values requested by the experimenters. Such a finding supports the lack of any observable differences across manufacturers.

**Measured Versus Target REIG**

For each of the three fitting procedures, mean differences between measured and target REIG values are shown in Table 3. These data were obtained by subtracting the target REIG values from probe-microphone REIG values, with the measured REIG values reflecting those achieved after optimal electroacoustic adjustments by the examiner. Positive values, therefore, indicate that the measured REIG values were greater than the target values, whereas negative values indicate that the aids produced less real-ear gain than desired.

Mean REIG values were in remarkably good agreement with target REIG values at all frequencies. For all three procedures, agreement ranged from -2.4 dB to +2.8 dB. Based on the experience of the authors, this degree of agreement is considered exceptionally high. As in the preceding analysis, however, the data in Table 3 take into account the direction of the differences, thereby reducing the apparent magnitude of the differences by cancellation of positive and negative values.

Absolute values of the differences between mean measured and mean target REIG values, as well as standard deviations, are given in Figure 3. It is evident that the magnitude of the absolute discrepancies become somewhat more notable when direction of the differences is not considered. Still, however, the discrepancies were not great, falling well within 5 dB at all frequencies for each of the three procedures. Variation among subjects was substantial for all procedures and at all frequencies. Although the values obtained with the matrix procedure were slightly lower than those obtained with the RECD procedure at all frequencies, a mixed-design MANOVA revealed no significant differences (p > .05) for the three procedures or for the three manufacturers. The audiogram, matrix, and
each of the three selection strategies investigated, the agreement instead demonstrates a high degree of success in achieving prescribed results through adjustments of the aids' dispenser controls. This is particularly evidenced by the successful attainment of target REIG values in the low frequencies where, at least for the RECD group, manufacturers provided significantly more gain than was requested. Given the high degree of flexibility afforded by the electroacoustic controls, it is reasonable to assume that differences among various formulas may be relatively noncritical with respect to the issues under investigation.

**CONCLUSION**

Our data revealed that none of the three fitting procedures, under the conditions of this study, emerged as unequivocally superior or inferior to the others, nor were there any notable differences in the fitting results obtained from the three participating manufacturers. It should be evident that results may be generalized only to those clinical situations in which the audiologist makes effective use of optional dispenser controls. To optimize measured REIG with respect to target REIG in nonprogrammable hearing aids, the authors consider it both wise and necessary to use such controls extensively in clinical practice. Had dispenser options not been used as extensively as they were in this study, or had these options not been as effective as they were demonstrated to be, the different procedures may well have produced different outcomes.

It may be tempting to speculate, despite the findings of our investigation, that the RECD procedure might still offer greater potential than either the audiogram or matrix procedures for achieving target gain in cases where fewer dispenser controls are utilized. In one particular respect, the data from this study do not support such a premise. Namely, none of the three manufacturers was able to provide hearing aids that yielded coupler gain values that agreed well with requested values across the entire frequency range from 250 to 4000 Hz. To achieve measured REIG values that more reasonably approximated target REIG, it was necessary to use the available dispenser controls to fine-tune electroacoustic responses. With the flexibility afforded by these controls, we were easily able to optimize the frequency-gain characteristic of the aids. Had we not employed such controls, optimization would certainly have been less adequate for all of the three selection procedures.

---

**Table 3** Mean Differences between Measured and Target REIG Values for Hearing Aids Ordered by the Three Experimental Procedures

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>250</th>
<th>500</th>
<th>1000</th>
<th>2000</th>
<th>3000</th>
<th>4000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Audiogram</td>
<td>2.8</td>
<td>-0.8</td>
<td>1.7</td>
<td>-0.2</td>
<td>-0.6</td>
<td>0.0</td>
</tr>
<tr>
<td>Matrix</td>
<td>2.4</td>
<td>0.6</td>
<td>-0.6</td>
<td>-1.0</td>
<td>-2.4</td>
<td>0.0</td>
</tr>
<tr>
<td>RECD</td>
<td>2.7</td>
<td>1.3</td>
<td>-1.6</td>
<td>0.5</td>
<td>-1.4</td>
<td>-0.4</td>
</tr>
</tbody>
</table>
differences between insertion and target are observable in individual listeners.

In the interest of keeping patient costs as low as possible, some audiologists may be unwilling to order the number of dispenser controls ordered for many of the subjects in this study. Our results suggest, however, that if audiologists order and effectively use the relatively active dispenser controls that are currently available in nonprogrammable hearing aids, optimization of REIG is equally likely through use of an audiogram, matrix, or individualized RECD approach.

Acknowledgment. Unitron Industries, Inc. is gratefully acknowledged for providing the Unitron UM-60 hearing aid used in the study. Assistance with data collection was provided by Anne Wanzeck.

Portions of this paper were presented at the Annual Convention of the American Speech-Language-Hearing Association, San Antonio, Texas, November 1992.

REFERENCES


