Prescribed Clinician-Fit Versus As-Worn Coupler Gain in a Group of Elderly Hearing-Aid Wearers

This study reports the prescribed, clinician-fit, coupler gain and the user-adjusted, as-worn coupler gain measured in 55 adults ranging in age from 60 to 83 years (M = 72.2 years). All participants were fit with linear, output-limiting compression, Class D circuits in full-concha, in-the-ear (ITE) shells. The NAL-R prescription rationale was used to generate target real-ear insertion gain (REIG) and coupler gain values. The clinician-fit gain was measured when the hearing aid was dispensed initially and was found to be a close match to the prescribed coupler gain. Both clinician-fit and as-worn gain were measured subsequently at approximately 2 weeks, 1 month, 6 months, and 1 year after the initial fitting. As-worn gain was measured as soon as the participant returned to the clinic for one of the follow-up visits by simply removing the hearing aids and placing them in the test chamber without any adjustments in volume control. At each follow-up session, the clinician then inspected the hearing aids, evaluated the instruments electroacoustically, readjusted the volume control to the setting used to match the prescribed gain in the initial fit, and measured the clinician-fit coupler gain once again. Results revealed that, despite the capability of the hearing aid to achieve coupler gain that is a close match to the prescribed gain, these users consistently selected as-worn gain that was generally 6–9 dB below that prescribed by the NAL-R formula. Of this 6–9 dB disparity, however, as much as 3–6 dB could be due to binaural summation effects not taken into consideration in the NAL-R prescriptive formula. In addition, 5.4% of the time, the hearing aids were found to be in less than ideal operating condition when removed for the as-worn gain measurements (e.g., weak or dead battery, cerumen occluding the sound bore, telecoil switch in the incorrect position).

KEY WORDS: hearing aids, elderly, gain, coupler gain, electroacoustic measures

Prescriptive approaches to hearing-aid selection and fitting have become the dominant approach used by audiologists since the early 1980s, although they have enjoyed an even longer history among hearing-aid dispensers and manufacturers, as in, for example, the “1/2-gain rule” (Byrne, 1983; Humes, 1996). Throughout the 1980s, a myriad of prescriptive rationales emerged, and several studies and detailed analyses were conducted subsequently to examine the differences among them (Byrne, 1986, 1987; Humes, 1986, 1991; Humes & Hackett, 1990; Humes & Halling, 1994; McCandless, 1994). In general, more similarities were observed among the approaches than differences, especially when the limitations of the available circuit choices and practical fitting constraints, such as electroacoustic feedback, were taken into consideration. Based on recent surveys of clinical practices in the U.S.
has not been observed (e.g., Berger & Hagberg, 1982; underamplification among elderly hearing-aid wearers conflicting reports, however, in which this tendency toward confusion or background noise. There have been some contention that the prescribed gain is not the same as that as-worn gain selected by the user has been found to be well below that measured by the clinician at the time the aid was delivered. There is evidence in the literature that the prescribed gain is not the same as that recommended by the audiologist in the high frequencies (3000–6000 Hz; Humes & Hackett, 1990). This discrepancy between the gain prescribed by NAL-R and that prescribed by DSL is noteworthy in that the DSL approach is based on a rationale of amplifying speech at each frequency to the minimum sensation level that will just maximize speech understanding. Thus, one could argue that the NAL-R approach, from the perspective of maximizing the understanding of speech, underamplifies moderate level inputs. This argument, moreover, is made on the basis of the prescribed gain targets, not those actually realized in the wearer’s ear. It is often the case, due to limitations of electroacoustic feedback or to gain limitations of smaller cosmetically appealing instruments, that the best match to the prescribed target gain is considerably below target in the high frequencies (3000–6000 Hz; Humes & Hackett, 1990). Finally, the underamplification error can be compounded even further in that the discrepancies between prescribed and observed gain noted above involve the clinician’s best match to the target at the time the aid was delivered. There is evidence in the literature that the prescribed gain is not the same as that either used or preferred by the wearer on a daily basis (Cox & Alexander, 1991; Kuk & Lau, 1996; Leijon, Eriksson-Mangold, & Beck-Karlsen, 1984; Leijon, Lindkvist, Ringdahl, & Israelsson, 1990). Specifically, “as-worn” gain selected by the user has been found to be well below that measured by the clinician at the time of hearing-aid delivery (“clinician-fit” gain), especially in typical listening environments involving reverberation or background noise. There have been some conflicting reports, however, in which this tendency toward underamplification among elderly hearing-aid wearers has not been observed (e.g., Berger & Hagberg, 1982; Byrne & Cotton, 1988; Ryals & Auther, 1990).

The purpose of the present study was to measure as-worn gain in a large group of elderly hearing-aid wearers and to do so over a period of 1 year following initial delivery. These measurements were made as part of a large-scale longitudinal investigation of hearing-aid outcome measurements. The results permit assessment of any tendency toward underamplification on the part of elderly hearing-aid users and, through a series of repeated measurements during the 1st year of use, will allow for the assessment of any changes in this tendency over time.

**Method**

**Participants**

The participants in this study were recruited for a longitudinal study on hearing-aid outcome measures via newspaper ads, flyers posted in the community, printed announcements in church/synagogue bulletins, and word of mouth. All participants enrolled in the study met the following selection criteria: (1) age between 60 and 89 years; (2) hearing loss that was flat or gently sloping (from 250–4000 Hz, no interoctave change in hearing thresholds of more than 20 dB); (3) hearing loss that was of sensorineural origin (normal tympanometry and air-bone gaps no greater than 10 dB at three or more frequencies); (4) hearing loss that was bilaterally symmetrical (interaural difference within 30 dB at all octave and half-octave intervals from 250–4000 Hz); (5) pure-tone thresholds within the following ranges at frequencies of 250, 500, 1000, 1500, 2000, 3000, 4000 and 6000 Hz, respectively: 5–85, 5–85, 10–90, 20–95, 25–95, 30–120, 30–120, and 30–120 dB HL (ANSI, 1989); (6) no known medical or surgically treatable ear-related condition; (7) no known fluctuating or rapidly progressing hearing loss; (8) no cognitive, medical, or language-based conditions that may have limited the participant’s ability to complete the procedures used in the longitudinal study of outcome measures; (9) no use of medications that could affect hearing or cognition; and (10) completion of a signed medical clearance form, or waiver of such by the participant, and a signed informed consent form.

Over the first 2 years of this study, 336 individuals have been recruited as potential participants, and approximately 169 have met the selection criteria and are at various stages of completion in the large-scale, longitudinal study. The present study reports on a group of 55 of these individuals who represent the first participants to have completed a variety of measures at various times throughout the 1st year of enrollment in the longitudinal study. The 55 participants, of when 38 were men and 17 were women, had a mean age of 72.2 years.
The median educational level for this group of 55 participants included some college after high school, and all participants reported that they lived independently at home alone (21%), with a spouse (77%), or with another family member (2%). Sixty percent of the participants reported that they participated in social activities with family or friends on an almost daily basis, 33% on a weekly basis, and 7% on a monthly basis. Regarding attendance at activities, such as religious services, movies, theater, sports events, or lectures, 73% did so on a weekly basis, 25% on a monthly basis, and 2% at least twice per year. In general, the participants had many opportunities to wear and benefit from their hearing aids in their daily living activities.

The mean air-conduction hearing thresholds (circles) and loudness discomfort levels (inverted triangles) for each ear of the 55 participants are plotted in Figure 1. Standard errors for the mean pure-tone thresholds were all less than 2.3 dB, and the standard deviations ranged from 12.3 to 16.8 dB across frequency. Loudness discomfort levels were measured using the scaling categories and instructions described by Hawkins, Walden, Montgomery, & Prosek (1987) and an ascending approach with 5-dB step size. Corresponding mean speech-recognition thresholds (SRTs) were 35.3 and 37.5 dB HL for the left and right ears, respectively. Word-recognition scores in quiet, obtained with the Auditec recordings of the NU-6 materials (Tillman & Carhart, 1966) at 40 dB SL (re: SRT) were 82.2% and 84.4% for the left and right ears, respectively. All audiologic measurements were obtained using ER-3A insert earphones.

Regarding prior hearing-aid use, 54.5% of the participants had not previously worn hearing aids. Approximately two-thirds of the experienced hearing-aid users had worn hearing aids for 4 or more years, 55% were binaural users of amplification previously, and about 90% reported using their hearing aids at least 4 hours per day.

**Procedures**

Following audiologic testing that was conducted to assure that the participants met all of the selection criteria for this study, participants returned for an extensive battery of cognitive, psychological, and auditory tests administered prior to hearing-aid delivery and over a series of five 90- to 120-minute sessions. Once this pre-fit testing was completed, the participants returned for the initial fit and delivery of their hearing aids. Based on the previously obtained audiologic information and using the Hearing Aid Selection Program (HASP, Version 2.07) fitting software, produced and distributed by the National Acoustics Laboratories (NAL), NAL-R targets, including corrections to targets for severe or profound hearing loss (Byrne et al., 1990), were generated for each ear, and the corresponding circuit was selected and ordered. The HASP software returns a variety of targets, including real-ear insertion gain and full-on coupler gain. The latter was adjusted downward by the 10-dB reserve gain incorporated into the HASP software to create recommended coupler-gain values. It is important to note that, consistent with the NAL-R fitting philosophy (Dillon, 1999, personal communication), there are no adjustments to the NAL-R target for binaural hearing-aid fittings in the HASP software.

All hearing aids made use of linear circuits with output-limiting compression and Class D amplifiers. All instruments were full-shell, in-the-ear (ITE) devices and included a telecoil switch on one instrument (determined by the wearer's preference). Active tone (low-cut only) and output-limiting controls, adjustable select-a-vent...
venting, and wax guards were included on all devices. The volume-control wheels were marked by the manufacturer with a small white dot at the perimeter to provide a visual reference for its position and adjustments.

Using real-ear insertion gain targets for the NAL-R prescription formula incorporated in the HASP fitting software, the clinician adjusted the settings of the controls and vent to achieve the closest match possible to target for a 60 dB SPL swept pure-tone signal using either Frye 6500 or Audioscan real-ear measurement equipment. Matching criteria were ±10 dB from 250 to 2000 Hz and ±15 dB at 3000 and 4000 Hz. If a match could not be obtained using these fairly broad matching criteria, the participant would not have been permitted to continue in the study. In fact, no participants were eliminated from the study for this reason, and the quality of the matches to target gain were considerably better than the broad exclusion criteria cited above, as will be seen below.

After having accomplished the best possible match to the NAL-R targets, a 90-dB pure-tone sweep commenced, and the wearer was instructed to raise his or her hand if the sound became uncomfortably loud. If the wearer signaled discomfort, the output-limiting threshold was decreased, and the pure-tone sweep was repeated. This process continued until discomfort was no longer indicated. The final control and vent settings, including the volume control, were recorded. It should be noted that adjustment of the output-limiting control had no effect on the coupler gain measured at moderate input levels. Moreover, the output limiting made use of an output-dependent compression limiter and therefore was independent of the volume-control setting.

The hearing aids were then removed, inserted into a hearing-aid test chamber, and the gain achieved in an HA-1, 2-cm³ coupler for the final control and vent settings was measured for a 60-dB-SPL swept pure-tone input signal. This is referred to as the clinician-fit coupler gain.

Participants returned for the longitudinal study of hearing-aid outcome measures at approximately 2 weeks, 1 month, 6 months, and 12 months following the initial fit and delivery of the hearing aids. The typical activities associated with each visit and preceding the gain measurements included checking in with the clinic’s receptionist, taking a seat in a general clinic waiting area prior to being greeted by the audiologist, being escorted down a 30-meter corridor, and having a brief conversation with the audiologist both along the route to the hearing clinic and after being seated in the sound booth. At the beginning of each session, the position of the volume controls was noted, and the hearing aids were removed from the wearer and placed in the hearing-aid test chamber for the measurement of coupler gain in an HA-1, 2-cm³ coupler. This is referred to here as the as-worn coupler gain. After these measurements were completed for each instrument, the hearing aids were inspected for wax occlusion; the position of the telecoil switch was examined; and the batteries were tested. Any problems in the physical appearance or electroacoustic function observed at this time were recorded on a data-entry form by the clinician. After any observed problems with the hearing aid were remedied, the instrument was evaluated electroacoustically according to ANSI (1996) standards; the volume control was returned to the position noted during the initial set of clinician-fit gain measurements; and frequency response was measured again in an HA-1, 2-cm³ coupler. To facilitate the return of the volume control to the correct location, the coupler gain at 1000-Hz achieved during the initial set of clinician-fit measurements was re-established in each subsequent session prior to obtaining the entire frequency-gain function for each instrument.

**Results**

As noted previously, when the hearing aids were removed from the wearer’s ears prior to performing the as-worn gain measurements, the instruments were inspected by the clinician. Based on these inspections across all participants, hearing aids, and post-fit intervals, 5.4% of the time the instruments were found to have a problem that likely restricted their performance in the coupler. Figure 2 illustrates the frequency of occurrence of various hearing-aid problems, expressed as the percentage of participants exhibiting each problem for their left or right hearing aids. The top panel illustrates the prevalence of cerumen-occlusion problems over the course of the study. Occlusion of the sound bore with cerumen was observed in about 7–9% of the instruments at the 2-week post-fit interval, then declined sharply 2 weeks later to about 3–4%, followed by a gradual rise to approximately 13–18% after 1 year of use. It should be noted that, if the clinician observed any of the hearing-aid problems noted in Figure 2, the participant was instructed again in the use and care of the hearing aid. This may explain the sharp decline in cerumen-occlusion problems from 2 weeks to 1 month post-fit. The percentage of hearing aids with weak or dead batteries is plotted in the middle panel and is seen to gradually increase for both ears over the course of the study. The growth apparent in each of these functions in the middle panel is primarily due to increasing occurrence of weak batteries. The percentage of dead batteries remained at about 2–4% throughout the study and in each ear. The data in the bottom panel of Figure 2, in contrast to the other two panels, suggests that the participants had fewer problems with the position of the telecoil switch by the study’s completion. Data are shown
only for the left ear because none of the participants opted for the telecoil in the right ear.

Individual differences in the frequency of occurrence of hearing-aid problems were also examined. Approximately 31% of the participants, for example, did not experience any of these problems in either ear, and 60% of the participants experienced fewer than 5% occurrence of any of these hearing-aid problems in either ear throughout the entire 12-month study.

If the battery was dead or the telecoil switch was in the incorrect position, the coupler-gain values were coded as “could not test” and treated as missing data in the analyses. Otherwise, large negative numbers would have been recorded and entered as the as-worn gain values in each of these cases. Note that if the battery was weak rather than dead or positive gain values were still observed even though cerumen occluded the sound bore, the values were included in the analysis. These data were included because, in the case of either a weak battery or cerumen occlusion, the aid was still functional, and it was possible for the wearer to compensate for the reduced gain by using an increased volume control setting. (Recall that all prescriptions included 10 dB of reserve gain available when matched to target gain.) In the case of a dead battery or an incorrect telecoil-switch position, the user either would not be able to or would not want to compensate by adjustments to the volume control, and these data were treated as missing values. Given the low percentage of missing data and their appearance at arbitrary locations in the database, missing data were replaced with the group mean for that particular measurement in all analyses of group data reported here.

Figure 3 depicts the mean clinician-fit, coupler-gain values obtained at each of the five test sessions during the 1st year of hearing-aid use. Error bars above and below each symbol represent plus and minus one standard error. Data for the left ear appear in the top panel, and those for the right ear in the bottom panel. Also appearing in each panel are the HASP-generated NAL-R coupler-gain targets (unfilled squares) for that particular ear (reduced by 10 dB, as noted previously, to eliminate the reserve gain used to generate full-on gain targets by HASP).

Two observations can be made readily from the data in each panel. First, the clinician-fit coupler gain was very stable throughout the year-long study. This was confirmed statistically by performing a repeated-measures analysis of variance with frequency and trial as the two independent variables. For the left ear, the effect of trial was not significant \( F(4, 212) = 2.45, p > .01 \), but the interaction between trial and frequency was significant \( F(20, 1060) = 2.05, p < .01 \). For the right ear, the effect of trial was not significant \( F(4, 212) = 0.99, p > .01 \), nor was the interaction between trial and frequency \( F(20, 1060) = 1.78, \)

![Figure 2. Relative frequency of occurrence (percentage of 55 hearing aids) of various hearing-aid problems observed at each of the four post-fit intervals in this study. Top panel provides data for cerumen occlusion of the sound bore, the middle panel for a weak or dead battery, and the bottom panel for the telecoil switch in the incorrect position. Percentage occurrence of each problem for the left hearing aid is shown by the filled circles and for the right hearing aid by the unfilled circles.](image-url)
The significant interaction for the data from the left ear appears to be due to the fact that clinician-fit gain is slightly higher in the high frequencies and lower in the low frequencies later in the study (e.g., at 1 year post-fit—filled squares) compared to that measured earlier in the study (e.g., at 2 weeks post-fit—unfilled circles).

Second, the clinician-fit coupler gain is a close match to the NAL-R target coupler gain. In general, deviations between the measured clinician-fit and target coupler gain values are less than 3 dB across frequency.

Figure 4 provides a session-by-session comparison of clinician-fit coupler gain (filled circles) and as-worn
Figure 4. Mean clinician-fit (filled circles) and as-worn (unfilled circles) coupler gain as a function of frequency. Left panels provide data for the left ear and the right panels depict results for the right ear. Post-fit interval progresses from two weeks in the top panel to 1 month, 6 months, and then 1 year in the bottom panel. Vertical bars above and below each symbol represent one standard error. For reference, the mean NAL-R target coupler gain for each ear is shown as filled inverted triangles in the top two panels.
coupler gain (unfilled circles). Left panels show the coupler-gain values for the left ear, whereas the right panels show corresponding values for the right ear. As left and right panel pairs progress from top to bottom in this figure, the post-fit interval increases from 2 weeks (top) to 1 month to 6 months to 1 year (bottom). For comparison purposes, the HASP-generated NAL-R target coupler gain is displayed in the top left and right panels (filled inverted triangles). Some general conclusions drawn from visual inspection of the data in this figure are as follows. First, as-worn gain is about 6–9 dB lower than clinician-fit gain at and above 1000 Hz.

**Figure 5.** Comparison of mean as-worn coupler at each of for post-fit intervals to the initial clinician-fit (filled circles) and prescribed (filled inverted triangles) coupler gain. Results for the left ear are in the top panel, and those for the right ear are in the bottom panel. The dashed line in each panel represents the prescribed NAL-R coupler gain minus 3 dB (representing a possible binaural target).
Second, the difference between these two sets of values decreases at lower frequencies (250 and 500 Hz). Finally, the difference between as-worn and clinician-fit coupler gain is fairly stable over time.

The latter point is illustrated more clearly in Figure 5. In this figure, the as-worn coupler gain values from each panel of Figure 4 are replotted here with the values for the left ear appearing in the top panel and those for the right ear in the bottom panel. For comparison purposes, the initial clinician-fit coupler gain (filled circles) and the HASP-generated NAL-R target coupler gain values (filled inverted triangles) are also shown. As noted previously, all participants were fit binaurally, and 85% continued to use binaural amplification throughout the 1st year of the study. As noted previously, NAL’s HASP software does not include any provision for gain decrease associated with binaural hearing-aid use. Frequently, a decrease in prescribed target gain of from 3 dB (e.g., Berger, Hagberg, & Rane, 1977; Libby, 1985) to 6 dB (Hawkins, Prosek, Walden, & Montgomery, 1987) is recommended for binaural hearing-aid users. According to Dillon (1999, personal communication), the most appropriate correction for binaural fittings would be a 3-dB decrease from the prescribed target. The rationale for this adjustment is that 5–6 dB of binaural loudness summation is the best estimate for moderate input levels in impaired ears, but the validation of the NAL-R prescriptive formula was derived from the preferred settings of a diverse set of hearing-aid users, including many who were fit binaurally. Thus, according to Dillon (1999, personal communication), it would be most consistent with the NAL-R fitting formula to decrease the calculated target by half that amount (3 dB) for binaural fits and increase it by a like amount for monaural fits. The dashed line in each panel illustrates the target NAL-R coupler gain once it has been adjusted 3 dB for binaural fittings. Clearly, this improves the match between target coupler gain and as-worn coupler gain. Of course, the fit would be improved even more if a larger binaural correction (5–6 dB) was applied to the target.

The as-worn gain data in Figure 5 were analyzed using a repeated-measures ANOVA with four levels of trial, representing each of the post-fit intervals, and six levels of frequency. No significant effects of trial [F(3, 156) = 3.83, p > .01 for left ear and F(3, 156) = 0.05, p > .01 for right ear] or significant interactions of frequency with trial [F(15, 780) = 1.08, p > .01 for left ear and F(15, 780) = 0.63, p > .01 for right ear] were observed for either ear. The effect of trial for the left ear, however, was very close to statistical significance (p = .011) and reflects the slight, but consistent, changes in as-worn gain over time in the left ear (Figure 5, top panel).

So far, the focus of the data analysis has been the stability of group results over time, rather than on the individual data. Insight into the reliability of the clinician-fit gain measurements and the individual differences in as-worn gain measurements can be attained by examining the test-retest correlations for the shortest measurement interval in the study. Recall that clinician-fit measurements were made at the initial fit, then 2 weeks and 1 month later, whereas as-worn gain measurements were obtained at the 2-week and 1-month post-fit visits. These 2-week intervals in data collection are the shortest ones available and offer an opportunity to examine the reliability of these measurements without the likely interference of longer term accommodation or acclimatization effects that could affect retest measurements for the other retest intervals in this study. Table 1 provides the Pearson-r test-retest correlations for clinician-fit coupler gain, both initial fit versus 2 weeks post-fit and 2 weeks post-fit versus 1 month post-fit, and for as-worn coupler gain (only 2 weeks post-fit versus 1 month post-fit). Correlations are shown for each ear and all six measurement frequencies.

Several comments can be made regarding these correlations. First, all but one of the correlations appearing in the table are statistically significant at the p < .01 level (as-worn gain in the right ear at 250 Hz was significant at the p < .05 level). Second, with the possible exception of the data at 250 Hz, for which only moderately

Table 1. Test-retest correlations for two-week test-retest intervals for clinician-fit and as-worn coupler gain. Except for the correlation coefficient marked with an asterisk, which is significant at the p < .05 level, all others are significant at the p < .01 level.

<table>
<thead>
<tr>
<th>Measurement type</th>
<th>Measurement interval</th>
<th>Ear</th>
<th>Frequency (Hz)</th>
<th>250</th>
<th>500</th>
<th>1000</th>
<th>2000</th>
<th>3000</th>
<th>4000</th>
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</thead>
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<tr>
<td>Clinician-fit</td>
<td>0 vs. 2 wk</td>
<td>L</td>
<td>0.72</td>
<td>0.95</td>
<td>0.97</td>
<td>0.93</td>
<td>0.83</td>
<td>0.92</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>R</td>
<td>0.72</td>
<td>0.97</td>
<td>0.96</td>
<td>0.89</td>
<td>0.85</td>
<td>0.80</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2 wk vs. 1 mo</td>
<td>L</td>
<td>0.68</td>
<td>0.96</td>
<td>0.96</td>
<td>0.90</td>
<td>0.85</td>
<td>0.87</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>R</td>
<td>0.67</td>
<td>0.95</td>
<td>0.91</td>
<td>0.88</td>
<td>0.80</td>
<td>0.89</td>
<td></td>
</tr>
<tr>
<td>As-worn</td>
<td>2 wk vs. 1 mo</td>
<td>L</td>
<td>0.60</td>
<td>0.60</td>
<td>0.65</td>
<td>0.53</td>
<td>0.55</td>
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</tr>
<tr>
<td></td>
<td></td>
<td>R</td>
<td>0.37*</td>
<td>0.74</td>
<td>0.64</td>
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<td>0.66</td>
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strong correlations were observed, the clinician-fit data demonstrate excellent test-retest correlations. Given the acoustically based method of adjusting the volume control for these measurements (matching the gain at 1000 Hz to that achieved at the initial fit), this is not surprising. The somewhat lower test-retest correlations for these measurements at 250 Hz most likely reflect some variability in the measurement of the acoustical effects of the vent in an enclosed acoustical test chamber and the presence of greater amounts of ambient noise at this frequency. Third, although all the correlations for as-worn gain are statistically significant and of moderate degree, they are clearly lower than those for clinician-fit gain. Nonetheless, the observed magnitude and direction of these correlations for as-worn gain indicate that there are fairly systematic individual differences in as-worn gain. The square of these test-retest correlations can provide an estimate of the systematic variance in the as-worn gain settings. From the values appearing in the lower portion of Table 1, it appears that approximately 30–40% of the variance in as-worn gain measurements is systematic and reflects true individual differences.

As a means of evaluating individual differences in the observed mismatch between clinician-fit and as-worn coupler gain, various summary measures of average gain mismatch were explored. Average differences between as-worn and clinician-fit coupler gain were calculated from the data obtained at the 1 month post-fit interval, separately for each ear, and for each of three different frequency groupings: (1) 250, 500, and 1000 Hz; (2) 2000, 3000, and 4000 Hz; and (3) 1000, 2000, and 4000 Hz. Correlations among these six potential measures of average gain mismatch are provided in Table 2. Within an ear, all three averages for that ear are strongly correlated with one another, but not with any of the averages from the other ear. The strong positive correlations among the various averages for a given ear simply reflect the fact that the user had access only to a volume control that adjusted the gain at all frequencies in a similar fashion. Based on the correlations in Table 2, it was decided to use an ear-specific average value for 1000, 2000 and 4000 Hz (a two-octave range within the primary amplification region for these wearers) as an acceptable measure of average gain mismatch. Figure 6 depicts the cumulative distributions of the average mismatch between as-worn and clinician-fit gain for each ear. These data indicate that approximately 80% of the individual gain mismatch values were less than 0 dB and that the median gain mismatch was about −7 dB. The actual distribution of average gain mismatch values was found to be well described by a normal distribution without significant skewness or kurtosis. Thus, the average discrepancies in clinician-fit and as-worn gain that appear in the group data depicted previously in Figures 4 and 5 are not due to a small number of participants with extreme mismatches.

### Discussion

The results of this study indicate that the typical elderly hearing-aid user in this study demonstrated as-worn gain values that were consistently 6–9 dB below the NAL-R target (or 3–6 dB below a binaurally adjusted NAL-R target). This was true, moreover, even though it was possible for the hearing aids in this study...
to maintain coupler gain values that were generally consistent with those prescribed according to the NAL-R formula at the initial fit, as verified through the stability of clinician-fit gain throughout this study. Based on the average disparity between the clinician-fit and as-worn gain values from 2 weeks to 1 year following initial fit, the lack of statistically significant effects of trial, and the significant, moderate, positive test-retest correlations for as-worn gain, it appears that there are stable individual differences in as-worn gain from roughly the initial fit through the 1st year of use. That is, there doesn't appear to be a systematic migration of the average as-worn gain values toward either higher or lower values as the user gains experience with amplification. The as-worn gain measured 2 weeks or 1 month after fit is representative of what one can expect to measure 1 year after fit.

The physical inspections of the hearing aids carried out prior to the as-worn gain measurements found that approximately 5–6% of the hearing aids were not functioning or were not set properly. Compared to similar measurements performed in large samples of school-age children fit with hearing aids (Bess, 1977; Gaeth & Lounsbury, 1966; Hoversten, 1981), this rate of user-controlled malfunction is much lower in the elderly. It should be noted, however, that all of the elderly included in this study were living independently and not confined to nursing homes.

It was also apparent that some hearing-aid problems were encountered increasingly as the participants wore their hearing aids longer. In particular, cerumen occlusion of the sound bore and weak batteries in the hearing aid were two problems that were 2–3 times more common at the study's completion than observed at the outset of the study. Both of these hearing-aid problems are likely to reduce the output of the hearing aid in the coupler. Yet, as-worn gain remained fairly stable for the duration of this study. Thus, it is possible that the user compensated for the attenuation resulting from the cerumen occlusion or weak battery by adjusting the volume control to a higher setting than used prior to experiencing these problems and, by doing so, maintained fairly stable as-worn coupler gain throughout the study.

The results of this study confirm and extend those of some earlier studies conducted with elderly adults (Lejon et al., 1984; Lejon et al., 1990). The study by Lejon et al. (1990) is most like the current study in that a reasonable sample (N = 26) of elderly hearing-aid wearers with average hearing loss nearly identical to that illustrated in Figure 1 were fit with linear devices according to the NAL-R formula. Lejon et al. (1990) examined the hearing-aid wearer's "preferred" gain setting, defined as the typical setting used in a range of everyday listening conditions based on detailed diaries maintained by the hearing aid wearers during 9 months of hearing-aid use following the initial fit. The underamplification observed by Lejon et al. relative to the NAL-R target for their preferred setting is very similar to the disparity observed in this study between clinician-fit and as-worn coupler gain. The agreement between studies is illustrated in Figure 7. Although the present study made use of as-worn coupler gain and Lejon et al. (1990) measured preferred real-ear insertion gain, the similarity of the disparities between the measured and targeted NAL-R gain values in each study are striking. It should be noted, however, that the participants in the Lejon et al. (1990) study were all fit with monaural amplification. Lejon et al. (1984) conducted a somewhat similar study, but with binaural amplification, and found the underamplification relative to NAL targets to be about 2–4 dB greater than that depicted in Figure 7.

Of course, the amount of underamplification is to a large extent dependent upon the reference used for target or recommended gain, both the formula and the specific binaural adjustment. Here, the NAL-R formula, without adjustment for binaural fitting, provided the reference or target gain. The clinician-fit gain measurements made throughout this longitudinal study, moreover, document that the hearing aid was capable of generating gain compatible with this target. As noted previously, this formula has been developed to approximate "preferred" gain, not necessarily the gain that will optimize some aspect of aided performance, such as the understanding of speech. Had the reference or target gain been derived with another common formula, such as POGO-II (Schwartz et al., 1988) or Desired Sensation Level (DSL; Seewald, 1992), and the as-worn gain...
remained the same as measured in this study, then the observed “underamplification” would have been greater. Since only one prescriptive formula was evaluated here, however, it is not possible to determine whether the as-worn gain is relatively constant for a given hearing loss and hearing-aid technology or whether it varies as a function of the initial fitting formula. That is, it is possible that higher target gain could lead to higher as-worn gain, with 6–9 dB of underamplification still observed. This might be the case, for example, if the primary factor responsible for the underamplification was binaural summation of loudness, although it would not likely account for all of the 6–9 dB of underamplification.

As noted previously, these data represent part of the results of an ongoing longitudinal study of hearing-aid outcome measures in a larger group of hearing-aid wearers. All participants in the broader study have met the same selection criteria outlined above and have gone through identical hearing-aid fitting procedures. Having documented the stability of as-worn and clinician-fit gain measurements in this study of 55 hearing-aid wearers through the 1st year of hearing-aid use, it was possible to make use of a larger set of data for 106 hearing-aid wearers who had completed all the same measurements, but only through the 1st month of hearing-aid use. Data from an additional 51 hearing-aid wearers completing the same protocol and sharing the same demographic profiles as the 55 participants in this study would enable the investigators to apply regression models to the analysis of underamplification. To do so, a global measure of underamplification was generated which was the binaural average gain difference between as-worn and clinician-fit gain at 1000, 2000, 3000, and 4000 Hz. The average binaural underamplification observed for these 106 hearing-aid wearers was –5.82 dB, which is consistent with that reported here for 55 of these hearing-aid wearers. Multiple regression analysis was then conducted, making use of a wide range of pre-fit and post-fit measurements obtained from the participants in the course of the broader study of hearing-aid outcome measures. Four variables were found to be predictive of the amount of underamplification with all four accounting for a total of 18.2% of the variance in the data. Although this is not a tremendous amount of the total variance that can be accounted for by these variables, it should be recalled that the test-retest correlations for as-worn gain measurements suggest that only 30–40% of the variance is systematic variance that can be attributed to individual differences, with the balance attributed to random error (including different acoustic experiences by the wearer prior to removal of the hearing aids and measurement of as-worn gain, variability in manual positioning of the volume control from day to day, etc.). Thus, approximately half of the systematic variance could be accounted for by the four predictor variables that emerged from the regression analyses applied to the 106 hearing-aid wearers.

The specific regression equation that emerged from these analyses was as follows:

\[
\text{UNDERAMP} = -1.522 - 0.092(\text{pegtest}) + 1.463(\text{dlyuse}) + 0.096(\text{rnst}) - 4.21(\text{satcomdisp}),
\]

where UNDERAMP is the average binaural underamplification from 1000 through 4000 Hz as described above, pegtest is a manual dexterity measure obtained without visual feedback, dlyuse represents the hours per day of prior hearing-aid use reported by the participant, rnst is the aided binaural speech-recognition score obtained by the participant for a 65 dB SPL speech level in quiet with the aids adjusted to clinician-fit gain values, and satcomdisp is the wearer’s reported satisfaction with communication by the dispensing audiologist. The order of each variable in the regression equation reflects their order in terms of proportion of variance accounted for with pegtest accounting for 5.8%, dlyuse 5.5%, rnst 3.6%, and satcomdisp 3.3%. The positive and negative valences for the Beta coefficients associated with each predictor variable in the regression equation permit the following interpretation. First, the amount of underamplification increases (becomes more negative) as manual dexterity without visual assistance gets worse or satisfaction with communication by the dispenser decreases. Thus, if the a wearer has difficulty adjusting the volume control while the hearing aid is worn (manual dexterity without visual assistance) or is dissatisfied with the communication provided by the dispenser about the hearing aid, the wearer is more likely to use a volume setting well below that yielding target gain. The dexterity factor seems logical in that, if a wearer has difficulty finding and adjusting the volume control, they would most likely keep it set at a lower setting so as not to experience occasional uncomfortably loud sounds, rather than setting it high so as not to miss some soft sounds. Second, if the wearer had worn hearing aids previously for several hours per day or had demonstrated higher speech-recognition scores when using target (clinician-fit) amounts of gain, the amount of underamplification was less. Thus, experienced users who had used their hearing aids several hours per day prior to this study, or who essentially showed the best speech recognition for higher gain settings, tended to prefer higher gain settings closer to the target (clinician-fit) gain values (i.e., less underamplification was likely).

In general, the regression model described here appears to be logical and has identified some variables that may be capable of predicting hearing-aid wearers’ tendencies toward underamplification, or their as-worn gain. It remains to be seen whether similar amounts of underamplification are observed for other technologies,
especially nonlinear wide-dynamic-range compression (WDRC), and whether comparable predictor variables will emerge. For example, one might hypothesize that individual differences in manual dexterity, the predictor variable that accounted for more variance than any of the others in the regression model above, would play a lesser role for instruments capable of automatic volume adjustments.

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