The Adequacy of Hearing Aid Fit for Severely/Profoundly Hearing-Impaired Children

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The purpose of this study was to examine the adequacy of hearing aid fit for 36 severely/profoundly hearing-impaired children using probe-tube in situ measurements and Popelka's PHASE IV program. The results showed that: (a) real-ear gain was not sufficient to make any portion of the speech spectrum audible through 42% of the hearing aids, (b) AI scores of 30% or less were obtained with 74% of the hearing aids, and (c) the real-ear peak output with a 90-dB SPL input exceeded 130 dB SPL in 67% of the hearing aids. Implications for hearing aid selection for severely/profoundly hearing impaired children are discussed.

While reliable detection thresholds for pure tones can be determined for severely/profoundly hearing-impaired children at a rather young age, it is much more difficult to measure their ability to perceive speech. Yet, early fitting of appropriate amplification and appropriate decisions about auditory-oral education depend on the extent to which the amplified speech spectrum is audible.

Several factors complicate the process of selecting hearing aids and verifying their appropriateness for children with severe and profound hearing impairments. First, conventional procedures of functional gain and speech perception measurement are difficult to do with a severely/profoundly hearing impaired child who may not have the language necessary to participate in the tasks. Subjective information about how speech sounds – whether it is too loud or not loud enough – may be unavailable. The high output required to obtain unaided soundfield measurements for functional gain for individuals with severe/profound hearing impairment often cannot be made without driving the loudspeakers beyond their capacity and/or causing acoustic feedback. Second, the time involved in conditioning a child for functional gain measurements may waste many precious months of appropriate amplification.

Recently, probe-tube microphone measurements have been recommended for

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use with children to eliminate some of these problems (Gabbard & Northern, 1987; Nelson Barlow, Auslander, Rines, & Stelmachowicz, 1988; Stelmachowicz & Lewis, 1988). This procedure allows rapid, precise measurements of hearing aid gain at the eardrum without behavioral responses from the child. In addition, probe-tube measurements provide data across many frequencies, rather than at only a few discrete intervals. Loudspeaker feedback is also not a problem.

Probe-tube measurements do *not*, however, indicate how much gain is appropriate for a particular child, nor do they determine how speech is perceived. Although there are many prescriptive formulas (Berger, Hagberg, & Rane, 1988; Byrne & Dillon, 1986; Libby, 1986; McCandless & Lyregaard, 1983) for selecting appropriate gain, the ideal gain would allow the entire speech spectrum to be audible without exceeding the child's uncomfortable loudness level (UCL) or driving the hearing aid into saturation.

Popelka's PHASE IV software program (Popelka, 1983) permits the audiologist to graph threshold, the aided speech spectrum, UCLs, and the hearing aid's maximum power output (MPO) on one CID field reference. This has been referred to as a "dynamic range configuration audiogram" (Gittelman & Popelka, 1987). The program also computes an articulation index (AI), which indicates the effective portion of the speech spectrum that is above threshold, yet below UCL and the MPO of the hearing aid. Gain and MPO may then be adjusted until the AI is at its maximum.

Because sounds must be audible to be perceived, maximizing the portion of the speech spectrum that is heard while minimizing speech spectrum distortion (that is, the portion of the speech spectrum which occurs above the MPO) should result in maximum speech perception. Unfortunately, many severely/profoundly hearing-impaired children have such reduced dynamic ranges that the gain and output resulting in the greatest AI may *not* be ideal. There may be unacceptable trade-offs in attempting to provide sufficient gain to maximize audibility of the speech spectrum, such as speech distortion, exceeding the child's UCL, or causing threshold shifts. The dynamic range audiogram allows the audiologist to examine these trade-off.

The purpose of this study was to examine the adequacy of hearing aid fit for 36 severely/profoundly hearing-impaired children using probe-tube microphone measurements of gain and dynamic range audiograms obtained via the PHASE IV program. These were analyzed to examine whether the aided speech spectrum was above threshold, below the MPO, or below levels which may cause discomfort or threshold shifts. The long-range objective was to gain insights for fitting younger severely/profoundly hearing-impaired children from whom measurements of UCL and speech recognition, or subjective comments, are unavailable.

METHOD

Subjects

Thirty-six severely/profoundly hearing-impaired children (4 yr, 1 mo to 10 yr, 11 mo) were included in the study. Fifteen subjects were aided monaurally and 21 were aided binaurally to give data for 57 hearing aids. The age the subjects were first aided ranged from 4 to 50 mo (M = 20.1 mo). Length of hearing aid use ranged from 27 to 114 mo (M = 68.2 mo). The pure tone average (PTA) for 500, 1000, and 2000 Hz for the 57 ears was 102.5 dB HL (ANSI, 1969). There were 44 ears with a profound hearing loss (PTA > 90 dB HL) and 13 ears with a severe hearing loss (PTA = 68-88 dB HL). Thirty-three ears had no measurable hearing sensitivity above 1000 Hz. All subjects attended a state school for the deaf and used manual signs as their primary means of communication. None of the subjects had had probe-tube measurements performed prior to the study.

Equipment and Calibration

Real-ear measurements of in situ gain (the sound pressure level in the ear canal with the hearing aid and earmold in place) were obtained using the Rastronics CCI 10-3 probe-tube microphone system. The system was calibrated at 50 cm from the loudspeaker with 70-dB SPL warble tones as suggested by Cox and Moore (1988) in order to approximate everyday listening conditions (Reid, Smiarowski, & McPherson, 1977). In situ responses were recorded so that the actual sound pressure levels at the tympanic membrane might be observed.

The probe tube was positioned 5 mm from the tympanic membrane of each subject using the Purdue University Probe tube (PUP tube) method of placement (D.P. Goldstein, personal communication, March 15, 1988). With this method, a tube with a 5-mm sponge tip is placed in the canal so that it just touches the tympanic membrane (usually an eyeblink is noted). This position is verified by otoscopic inspection. The tubing at the intertragal notch is then marked with a rubber ring. This tubing is removed and matched to the Rastronics probe tube (minus the 5-mm sponge tip) and the probe tube is marked accordingly. The probe tube is then inserted into the canal until the marker is at the intertragal notch, and then is locked in place using a plastic holder attached to the side of the head with adhesive. Otoscopic inspection is repeated to confirm proper placement.

Procedure

As the subject entered the testing room from his or her class, the hearing aid was turned off and removed without changing the volume control. An otoscopic inspection was done to insure that the ear canal was free of excessive cerumen. The probe-tube microphone was then placed as described above. An unoccluded (or open ear) frequency response was obtained using 70-dB SPL warble tones.

Next, the hearing aid was replaced without displacing the probe tube. The hearing aid was turned on and in situ measurements were obtained at use settings. If acoustic feedback occurred, petroleum jelly was applied around the earmold.

The input was then increased to 90 dB SPL, a common "loud" input level experienced by hearing aid users, and a second in situ hearing aid response was obtained. It was recognized that this input plus the hearing aid gain might drive the instrument into saturation; however, typical real-ear sound pressure levels that the child may have been experiencing several times a day were desired. Subjects were also asked if the 90-dB SPL input was too loud, too soft, or OK.

The hearing aids were once again removed and were evaluated electro-acoustically. Tympanometry was also done at this time to determine middle-ear function.

Pure tone thresholds under earphones, which had been obtained for all subjects as part of their annual evaluation, and computed real-ear insertion gain were entered into the PHASE IV program to obtain a dynamic range audiogram and AI score for each hearing aid. Insertion gain was calculated as the difference between the open ear and in situ frequency responses to a 70-dB input. Finally, a Parent/Teacher questionnaire (Appendix) regarding hearing aid use was completed by each subject's parents and teacher.

RESULTS AND DISCUSSION

Several factors were considered to contribute to determine adequacy of hearing aid fit and will be discussed separately:

Measured Real-Ear Gain vs. Prescribed Gain

Insertion gain was calculated at 250, 500, 1000, 2000, and 4000 Hz, averaged across the 57 hearing aids, and compared to prescriptive gains computed from earphone thresholds. The formulas used were those of NAL (Byrne & Dillon, 1986), POGO (McCandless & Lyregaard, 1983), Libby's 1/3 and 1/2 rule (Libby,

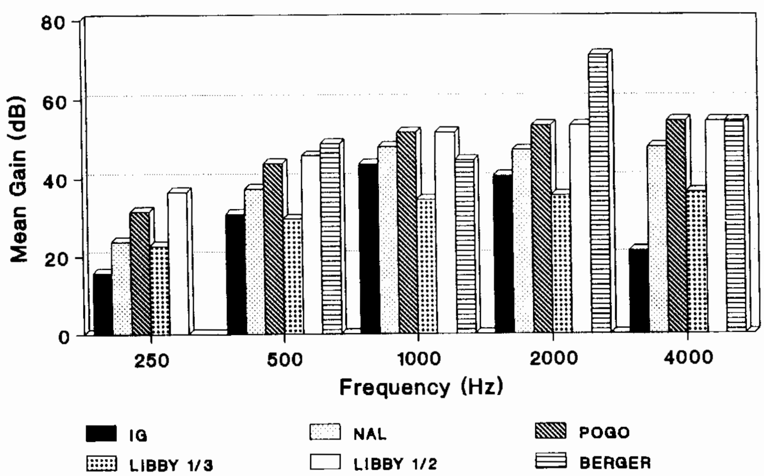

Figure 1. Mean real-ear insertion gain (IG) for 57 hearing aids and prescriptive gain calculated using the formulas of NAL, POGO, Libby (1/3 and 1/2 gain rules), and Berger, as a function of frequency.

1986), and Berger (Berger et al., 1988).

As can be seen in Figure 1, the measured real-ear insertion gain (IG) ranged from 15.7 dB at 250 Hz to a maximum of 43.5 dB at 1000 Hz and (with the exception of Libby's 1/3 formula) was less than the recommended insertion gain at all frequencies. Actual measurements missed the targets by as much as 30 dB, as observed at 4000 Hz.

One must question whether these hearing-impaired children really desired less gain than the formulas recommended or whether their hearing impairments were so severe that adequate gain could not be obtained without acoustic feedback or without exceeding the children's UCLs or safe output levels. One subject wore the hearing aid full on; 11 other hearing aids were worn just below the setting at which acoustic feedback would occur. It would be very difficult, if not impossible, to reach target insertion gains at those frequencies (particularly above 1000 Hz) for which the subjects had no measurable hearing sensitivity under ear-

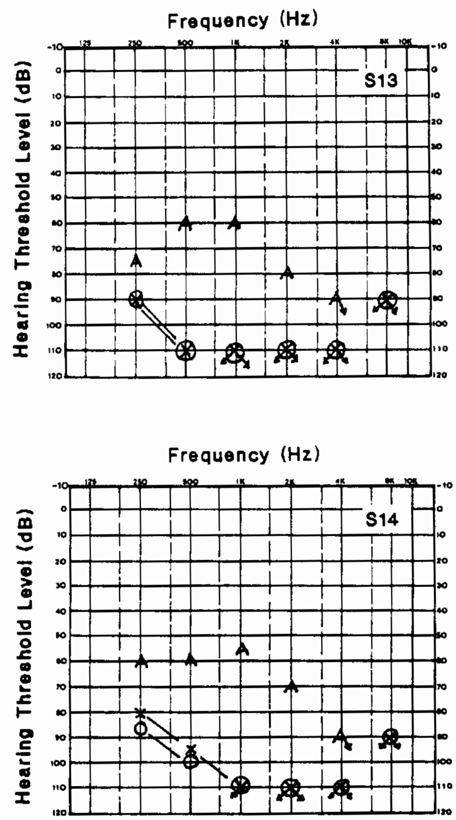

Figure 2. Pure tone and aided (A) soundfield thresholds for S13 and S14.

phones.

In addition, substantial individual differences were noted, even for those children with similar losses. For example, S13 and S14 had similar unaided and aided thresholds (Figures 2A and 2B). Both subjects wore hearing aids with similar SSPL-90 values (within 2 dB). Figure 3A illustrates that S13 had more coupler gain than S14, especially at 500 and 1000 Hz. S13 wore his aids at a volume setting of 2/4 while S14 wore hers at 3/4. The results of real-ear measurements at these use settings were quite different, however, than the coupler measurements at reference test gain position would have suggested. Figure 3B shows that S14 was receiving more real-ear gain than S13. This resulted in a greater AI score (15% and 13% for the right and left ears respectively for S14, compared to 0% for both ears of S13). It must also be noted that S14 had peak in situ levels as high as 138 dB SPL. S14 noted that the 90-dB SPL signal was

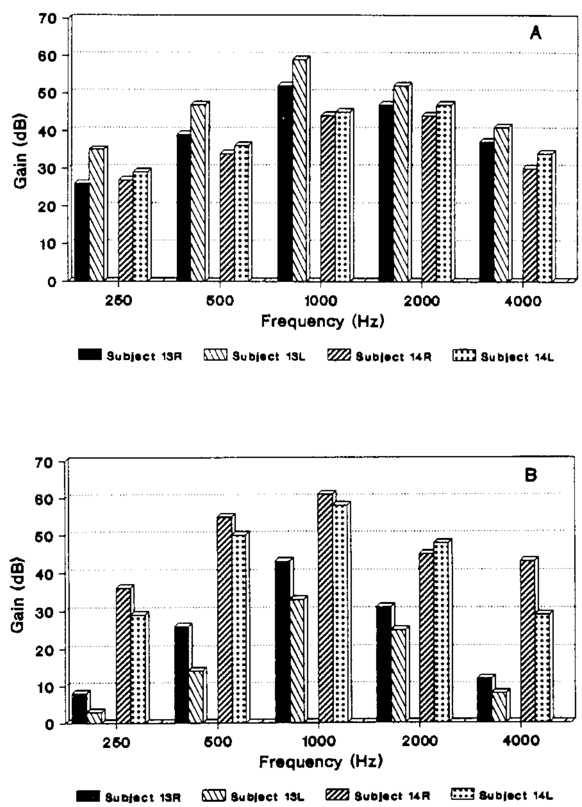

Figure 3. A comparison of hearing aid coupler gain (A) and real-ear gain (B) for S13 and S14, right (R) and left (L) ears.

loud but did not want the volume control or MPO reduced because she needed it that loud to hear. S13 also complained that the 90-dB input was loud, with in situ levels peaking at 133 dB SPL.

From these data it was concluded that the amount of real-ear insertion gain can be less than recommended insertion gain and is not predictable from coupler gain or thresholds in severely/profoundly hearing-impaired children. It may, however, be related to other factors, such as dynamic range, individual preferences, and acoustic feedback.

Speech Spectrum Levels in Relation to Real-Ear Gain

Although real-ear gain was less than recommended by several prescriptive formulas, was it sufficient to detect most of the speech spectrum? To answer this question, the computed real-ear insertion gain was entered into the CID PHASE IV program to obtain a dynamic range audiogram for each ear and hearing aid. Figure 4 is an example of a dynamic range audiogram for the left ear of S3. In it is shown the relationships among the aided speech spectrum (ASP), threshold (TH), the hearing aid MPO, and the AI value (shaded area). See Gittelman and Popelka (1987) for a description of dynamic range configuration audiograms.

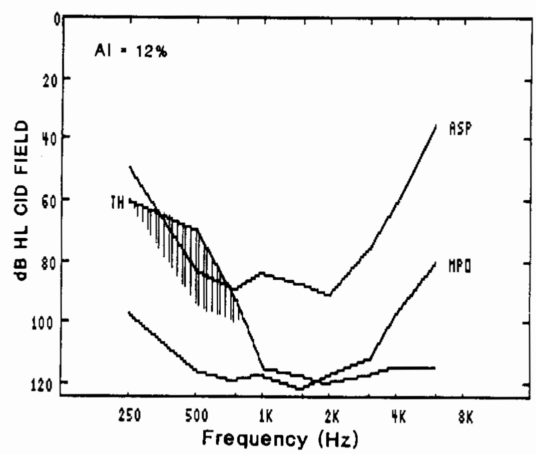

Figure 4. Dynamic range audiogram for S3, left ear. ASP = aided speech spectrum. TH = threshold. MPO = real-ear maximum power output. AI = articulation index score.

Of the 57 hearing aids, 24 (42%) did not provide sufficient gain for *any* portion of the speech spectrum to be heard (i.e., AI = 0%; see Figure 5). Forty-two (74%) demonstrated AI scores of 30% or less, and only 7% of the aids had AI scores over 50%. From these data it can be concluded that most of these subjects were not receiving sufficient gain to hear most of the aided speech spectrum.

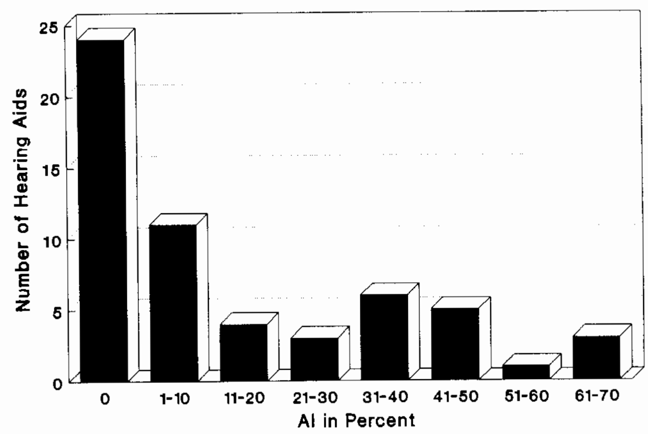

Figure 5. Distribution of articulation index scores for 57 hearing aids.

However, as mentioned above, any increases in real-ear gain would probably have caused the hearing aid to go into saturation (resulting in distortion), caused acoustic feedback, or caused the output to exceed a safe or comfortable level.

Maximum Output Levels

Cox (1986) suggested that the SSPL-90 for children should be adjusted to 100 dB plus one-fourth the hearing loss. Thus a child with 120-dB HL thresholds should not have output levels exceeding 130 dB SPL. Results of this study showed peak real-ear in situ outputs of 130 dB SPL and over with a 90-dB signal (ISG-90) for 67% of the hearing aids. These levels often occurred at frequencies that would not have been measured for functional gain and exceeded the peak

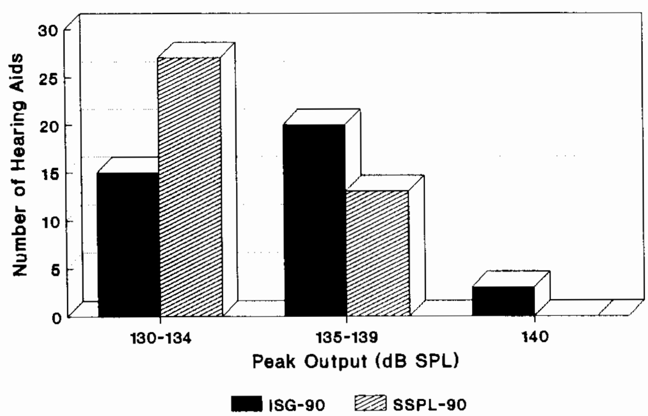

Figure 6. Distribution of peak output levels obtained in situ (ISG-90) and in a coupler (SSPL-90) using a 90-dB SPL input.

SSPL-90 measured in the coupler for 61% of the hearing aids, even though nearly all the hearing aids were not at full volume when real ear measurements were made. Figure 6 shows the peak output distribution for SSPL-90 and ISG-90.

Figure 7 compares the mean ISG-90 to the mean SSPL-90 coupler measurements. As can be seen, the sound pressure level at the tympanic membrane was higher on average than the coupler measurements for the frequencies of 1500, 2000, and 4000 Hz, even though the volume control was not full on for nearly all of the aids during in situ measurements. These data agree with those of Sachs and Burkhard (1972) who reported that 2-cc coupler measurements underestimate the SPL actually developed in the ear, especially above 1500 Hz.

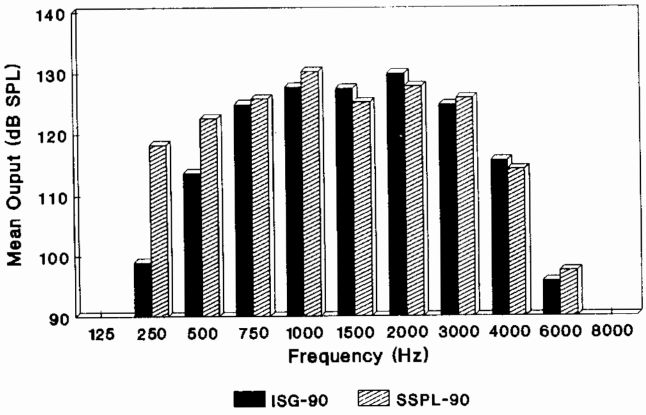

Figure 7. Mean real-ear in situ output (ISG-90) and coupler output (SSPL-90) as a function of frequency.

Subjects were asked if the 90-dB SPL signal was too loud, too soft, or OK. This procedure was not found to be reliable with the younger subjects or those with poor language skills, who tended to agree with all the statements. However, 27 of the 36 subjects responded consistently, and 15 of those 27 stated that this input was loud. The mean real-ear peak ISG-90 was 135.9 dB SPL for this group. For the 12 subjects with no complaints of uncomfortable loudness, the mean real-ear peak value was 131.0 dB SPL, although three subjects in the non-complaint group had real-ear peak values of 137, 139, and 140 dB SPL. This finding indicates a need for caution in interpreting subjective loudness measures in children.

In addition, seven subjects demonstrated a progressive threshold shift since their initial evaluation, and real-ear output levels over 130 dB SPL were obtained for all but one of these subjects. Thresholds for one of these subjects improved approximately 10 dB six months after the SSPL-90 was reduced (see Figures 8A, 8B and 8C). Clearly many of these children are receiving excessive amounts

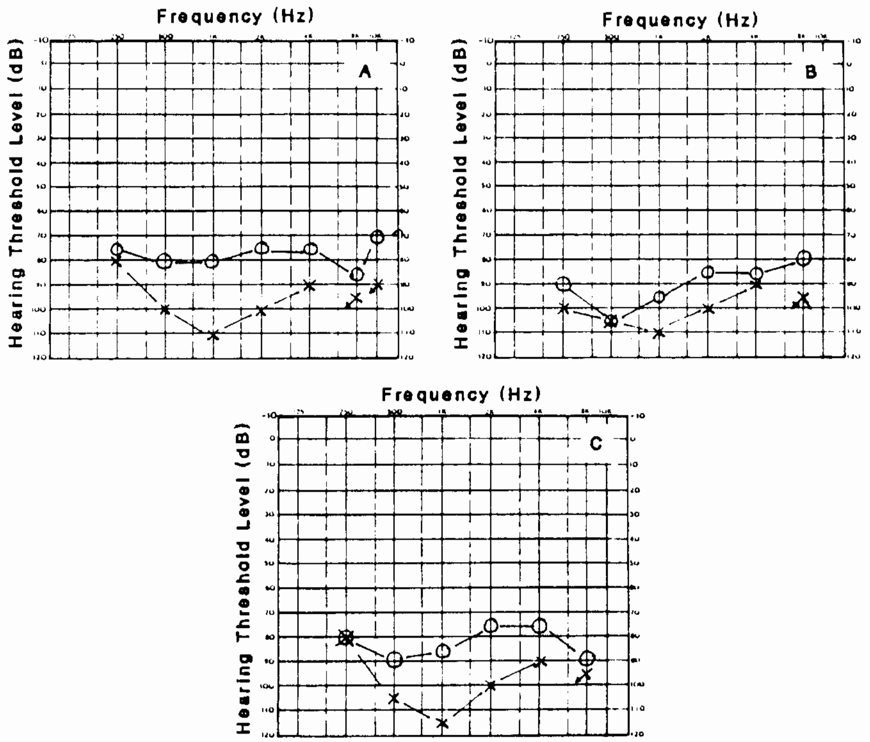

Figure 8. Pure tone audiograms for S10 obtained one year before the study (A), during the study (B), and 6 months following the study after the SSPL-90 was reduced in the right-ear hearing aid (C).

of output. This shows a need for real-ear monitoring of output levels. However, a reduction of the maximum output would have caused further restriction of the aided speech spectrum and a reduction in AI score.

Effects of Output Limiting

Speech spectrum distortion caused by the hearing aid must also be considered in determining adequacy of hearing aid fit. Figure 9 gives examples of three dynamic range audiograms with varying levels of speech spectrum distortion caused by hearing aid output limiting. Of the 33 hearing aids that allowed some portion of the aided speech spectrum to be heard, 24 (73%) had no speech spectrum distortion caused by the hearing aid's output limiting circuitry (see Figure 9A as an example), and nine (27%) demonstrated some limiting of the speech spectrum by the hearing aid (example, Figure 9B). Of the 24 hearing aids through which no portion of the speech spectrum could be heard, the output was limited in 12 hearing aids *before* the child's threshold could be reached

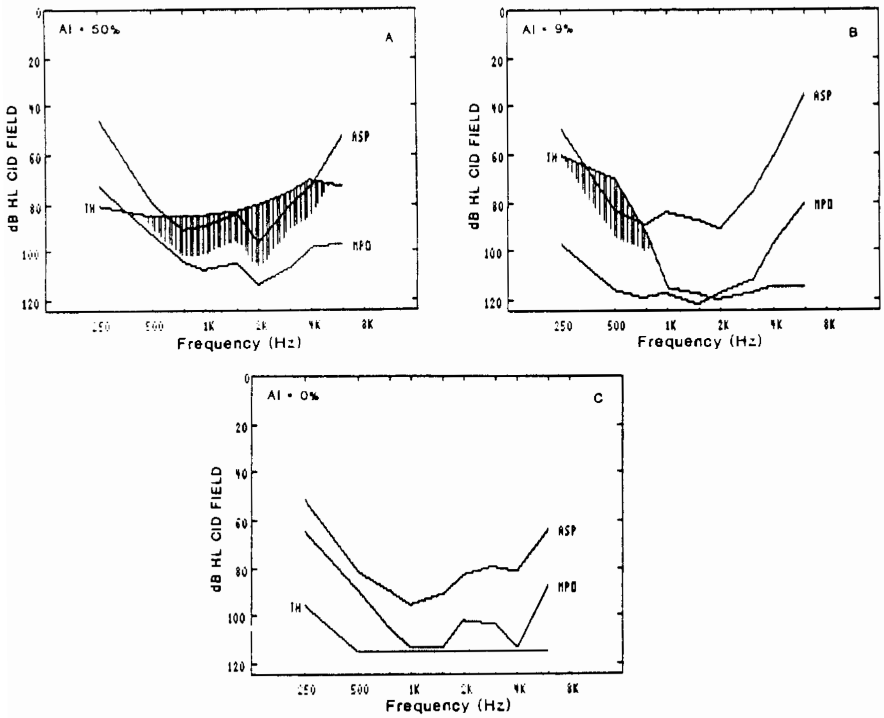

Figure 9. Dynamic range audiograms exemplifying effects of output limiting. A = No speech spectrum distortion (S8, right ear). B = Some limiting of the speech spectrum (S22, right ear). C = Limiting before threshold is reached (S26, right ear).

(example, Figure 9C). Should the SSPL-90 be increased so that environmental sounds or more of the speech spectrum can be heard, knowing that the output may exceed the child's comfort level or, worse yet, may provide SPLs that cause a progression of the hearing loss?

Characteristics of All-the-Time Hearing Aid Users

The parent and teacher questionnaire was used to determine (a) how often and in what situations the children wore their hearing aids, (b) whether they used audition for communication purposes, (c) what (if any) complaints they had about their hearing aids, (d) age of initial hearing aid fit, (e) history of middle-ear problems, and (f) whether the hearing loss was progressive. On the basis of this information, the subjects were divided into two groups: "successful" and "non-successful" hearing aid users. Subjects were considered successful users if they wore their hearing aids more than 8 hours a day, on weekends, and after school; had few (if any) complaints about the hearing aids; and were judged by teacher and parents to use audition for communication purposes. Using these criteria,

Table 1

Characteristics of Successful and Nonsuccessful Hearing Aid Users

Characteristics	Successful (n = 9)		Nonsuccessful (n= 27)	
	No.	%	No.	%
1. Has a severe hearing impairment in one or both ears.	7	78	1	5
2. Mean age at initial hearing aid fitting.	26.1 mos		19.6 mos	
3. Has AI scores greater than 30% for one or both hearing aid(s).	8	89	3	7
4. Wears hearing aid(s) at home and school, evenings and weekends.	9	100	11	41
5. Understands some words, phrases, sentences without vision.	9	100	1	5
6. Uses audition for everyday communication purposes.	7	78	0	0
7. Complains that hearing aid(s) are too loud or hurt.	2	22	13	48
8. Has other hearing aid complaints: earmold hurts or falls out, hot, feedback, noise, or not working.	2	22	8	30

only 9 of the 36 children were successful.

Table 1 compares traits of the successful and nonsuccessful hearing aid users. As can be seen, the successful hearing aid users as a group had less severe hearing impairments in one or both ears, and tended to have better AI scores (i.e., scored in the top 25% of the subject group with AI >30%).

There were exceptions however. The highest AI score (69%) was obtained for S9. Even though this subject had a bilateral severe hearing impairment, he was reported to hear little or nothing, and was not classified as a successful hearing aid user. He also, unfortunately, was not aided until after the age of 3 years.

A slightly greater delay of initial hearing aid fit was noted for many of the successful hearing aid users with severe hearing impairments. The average age that the hearing aids were initially fitted for successful hearing aid users was 26.1 months as compared to 19.6 months for those not classified as successful users. The two profoundly hearing-impaired subjects who were successful users were aided at the ages of 4 months and 20 months. These results suggest that the succesful users with severe impairments might have been even more successful had they been aided at an earlier age.

SUMMARY AND CONCLUSIONS

The adequacy of hearing aid fit for 36 severely/profoundly hearing-impaired children was examined by determining real-ear hearing aid gain and output using probe-tube microphones and by calculating AI using the PHASE IV program. It was found that:

1) Real-ear gain was lower than was recommended by selected prescriptive formulas, and was not sufficient to make any portion of the speech spectrum audible through 42% of the hearing aids.
2) AI scores ranged from 0-69%, with 74% of the hearing aids producing AI scores of 30% or less. Eight of the 11 subjects who had AI scores greater than 30% had severe rather than profound hearing impairments.
3) The real-ear peak output of the hearing aids with a 90-dB SPL warble tone input exceeded the peak coupler SSPL-90 output in 61% of the hearing aids, caused discomfort in at least 42% of the subjects, and exceeded 130 dB SPL in 67% of the hearing aids.
4) For 9 of the 57 hearing aids, saturation occurred before threshold could be reached (i.e., the MPO of the hearing aid was lower than threshold).
5) Only 9 of the 36 subjects could be classified as successful hearing users on the basis of parent/teacher report. Seven of these 9 had severe rather than profound hearing impairments.

From these results it was concluded that many of these subjects were not receiving sufficient real-ear gain to make the speech spectrum audible. At the same time, many were receiving environmental sounds at sound pressure levels which were uncomfortable and which could cause speech distortion or a threshold shift. For children with severe/profound hearing impairment and limited dynamic ranges, a good fitting (much less, an ideal one) is difficult if not impossible to achieve. Prescriptive formulas only give the audiologist a place to start (i.e., target values for gain and output). Using a dynamic range audiogram helps the audiologist visualize the consequences of a particular hearing aid adjustment. For some children, these consequences may include exceeding UCL or increasing hearing loss, versus foregoing early stimulation or not recommending a hearing aid at all. Some alternative strategies include compression amplification, tactile aids, and cochlear implants.

Caution must be used in interpreting these results, first because speech perception was not measured. Rather, parent/teacher reports were obtained to determine how audition was used for communication purposes. Although 9 of the 10 students who were reported to understand some words, phrases or sentences had the top AI scores, greater audibility does not necessarily imply better speech perception. Second, only manually-educated subjects were studied. Orally/aurally-educated children may have greater English language competencies which may result in better speech perception even with poor audibility (low AI score). Third, conventional UCL measurements were not available for all subjects for use with the PHASE IV program. With this information, we might have observed that even less of the amplified speech spectrum could be comfortably audible for some children.

For the subjects of this study, results demonstrated that probe-tube microphone measurements are needed to determine the sound pressure level delivered by a hearing aid at the tympanic membrane. These real-ear measurements are easy to perform and are time efficient with hearing-impaired children. When used with PHASE IV or a comparable computer analysis of AI function, they provide essential information for hearing aid selection and validation. Using a dynamic range audiogram helps the audiologist to see the results of choosing different trade-offs for maximizing speech audibility.

Further research is needed to determine which trade-offs yield best speech perception. For example, if the child's dynamic range is smaller than the range of the speech spectrum, should real-ear gain be selected so that all the softer speech sounds are audible and the louder speech sounds distorted by output limiting? Or, should the gain be reduced so that the softer speech sounds are not all audible but the louder sounds are not distorted? If these questions can be answered, we can more appropriately fit children with severe or profound hearing impairments.

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APPENDIX

PARENT/TEACHER QUESTIONNAIRE

Instructions: Please answer the following questions or indicate those that apply as completely as possible.

1. What is the student's date of birth?
2. At what age was the student first fitted with a hearing aid(s)?
3. Has the student had earaches, infections or ventilation tubes in one or both ears? If so, explain which ear(s) and how often.
4. Has the student's hearing loss become worse since the loss was first detected? Which ear(s)?
5. Approximately how many hours a day does the student normally wear his/her hearing aid(s)?
6. At home, does the student wear the hearing aid(s) while watching TV, playing, during sporting activities, during social activities, or all the time (except when sleeping)?
7. At school, does the student wear the hearing aid(s) during class time, lunch time, play time, sporting activities, social activities, free time in the dormitory, or all the time (except when sleeping)?
8. What do you feel the student understands with the hearing aid(s) on without looking at you?
9. Does the student use the hearing aid(s) for awareness (getting his/her attention)? For understanding speech?
10. Does the student primarily use signs, speechreading, or audition to understand what is being said to him? To express himself? How does the student communicate with hearing children or adults? Does he use speech, signs, gestures, audition, speechreading?
11. What complaints does the student have about the hearing aid(s)?