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Gain, frequency response, and maximum output requirements for hearing aids

John H. Macrae, PhD and Harvey Dillon, PhD
National Acoustic Laboratories, Chatswood, NSW 2067 Australia

Abstract—This article applies the gain and frequency response and maximum output selection procedures currently recommended by the National Acoustic Laboratories (NAL) of Australia to the audiograms of a representative group of adult and child clients of Australian Hearing Services (AHS) to specify the performance that is required of various types of hearing aids in order to ensure that they can provide adequate gain, frequency response, and maximum output levels for at least 90% of the AHS client population. Cumulative frequency distributions of required 2-cc coupler gain slopes were calculated for each type of aid and used to design required frequency response variations. Coupler slope requirements in different octaves were found to be independent of one another. The required range of gain-maximum output combinations was determined for each type of aid.

Key words: *frequency response, gain, hearing aids, maximum output.*

INTRODUCTION

Hearing aid designers and institutional purchasers of hearing aids have a common need to specify what performance is required of hearing aids if those hearing aids are to provide adequate gain, frequency response, and maximum output levels to a desired proportion of individuals in a target population. If hearing aids are fitted according to a prescriptive procedure, it is possible to derive such performance requirements on the basis of the audiological characteristics of the target population. This article applies the selection procedures currently recommended by the National Acoustic Laboratories (NAL) of Australia to the audiograms of a representative group of adult and child clients of Australian Hearing Services (AHS).

Gain, frequency response, and maximum output are the basic specifications for a hearing aid model or family of hearing aids. Gain refers to a measure of the overall degree of amplification and is usually quantified either by the maximum gain irrespective of frequency, by the average gain at specified frequencies, such as 0.5, 1, and 2 kHz, or by the gain at a single reference frequency. Frequency response refers to the shape of the gain requirements across frequency, an important aspect of which is the required slope in each octave, given by the differences between required gains at adjacent octave test frequencies. Maximum output refers to the highest SPL that the hearing aid can generate and again can be quantified by the maximum irrespective of frequency, by an average across specified frequencies, or by the value at a single reference frequency. For convenience, maximum output is usually measured with a 90 dB SPL input level and will be referred to as Saturated Sound Pressure Level (SSPL).

In a previous article (1) and associated report (2), hearing aid specifications were presented, which were based in part on the Byrne and Tonisson (3) gain and frequency response selection procedure then used by NAL. However, after this procedure was evaluated (4), it was revised (5). Consequently, the hearing aid requirements were also revised, and the details were presented in an article (6) and an associated report (7).

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Address all correspondence and requests for reprints to John H. Macrae, PhD, National Acoustic Laboratories, 126 Greville Street, Chatswood, NSW 2067 Australia

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As a result of an extension of the NAL procedure to clients with severe and profound loss (8), the development of a procedure for selecting the maximum output level of hearing aids (9), and the development of new types of hearing aids, it has become necessary to carry out further updating of the requirements. For the purposes of this article, the extension of the procedure to severe and profound hearing losses will be referred to as the NAL-RP procedure. Real ear insertion gain (REIG) requirements remain the same whether they are provided by behind-the-ear (BTE), in-the-ear (ITE), in-the-canal (ITC), completely-in-the-canal (CIC), or body-level (BL) hearing aids. However, the required coupler responses differ for each of these types of hearing aid, so this article presents coupler gain and frequency response requirements separately for each type of hearing aid.

METHOD

Hearing Thresholds

New data were collected. These data were 700 pure-tone audiograms obtained from the case records of adult (pensioner and war veteran) clients and 400 pure-tone audiograms obtained from the case records of child clients who had been provided with hearing aids by AHS. The records were selected at random from the files of two AHS Hearing Centers. Where both ears of the client had been fitted with hearing aids, both right and left ear audiograms were included in the sample. Sensorineural, conductive, and mixed hearing losses were included in the samples. Losses were treated as sensorineural if the 3-frequency (500, 1000, and 2000 Hz) average air-bone gap was less than 15 dB. The number of audiograms with a conductive component was 105/700 (15 percent) for the adults and 64/400 (16 percent) for the children. These values are significantly less than those reported by Macrae and Dillon (6), who found 122/468 (26 percent) for adults and 80/229 (35 percent) for children. The relative frequency of each category of case in the AHS client population has also changed. Children now comprise only 6 percent of the population, whereas in 1986 they comprised 17 percent of the population. Although children are now only a very small percentage of the AHS client population, exactly the same calculations and analyses were carried out on the data for children as on the data for adults, to determine whether, in meeting the requirements of adults, the requirements of children could also be met.

For both samples, air-conduction thresholds were available at octave frequencies from 0.25 to 8 kHz and bone-conduction thresholds were available at octave frequencies from 0.25 to 4 kHz. In cases where the air-conduction threshold exceeded the limit of the audiometer, the threshold was assumed to be 5 dB greater than the audiometer limit. Bone-conduction thresholds that exceeded audiometric limits were assumed to be the same as the air-conduction thresholds in cases where the hearing loss was sensorineural. Bone-conduction thresholds for 8 kHz were estimated on the basis of the air-bone gaps at the frequencies up to 4 kHz. A k-means clustering algorithm devised by Hartigan (10) was used to cluster the air-conduction audiograms into 20 clusters, for both adults and children, separately.

Insertion Gains

Both air-conduction and bone-conduction thresholds were used in the calculation of required REIGs (RREIG). For each audiogram, the RREIG at each octave frequency from 0.25 to 8 kHz was calculated by means of the NAL-RP gain and frequency response selection procedure (**Appendix A**). In the case of conductive and mixed hearing losses, the bone-conduction thresholds were corrected for the Carhart notch and then one-quarter of the air-bone gap was added to the REIG that would have been required had the loss been purely sensorineural, as recommended by Lybarger (11). The Hartigan k-means clustering algorithm was used to cluster the REIGs into 20 clusters, for both adults and children, separately.

Coupler Gains

The RREIGs were then converted into required coupler transmission gains for each type of hearing aid (BTE, ITE, ITC, CIC, and BL hearing aids). The coupler gains are for HA1 configuration couplers (12) in the case of ITE, ITC, and CIC aids and HA2 configuration couplers (12) in the case of BTE and BL aids. For BTE hearing aids, the HA2 coupler requirements assume that the hearing aids will be fitted with a #13 constant inner diameter (1.93 mm) tube running from the tip of the earhook to the medial tip of the earmold. For ITE, ITC, and CIC hearing aids, audiograms with three-frequency average (3FA) thresholds (at 0.5, 1 and 2 kHz) greater than 70 dB were deleted from the sample. The sample size for these aids was, therefore, 587 for adults and 302 for children. For BTE and BL hearing aids, response requirements were computed separately for those with 3FA hearing losses less than (or equal to), and greater than, 70 dB HL.

The conversion of REIGs to coupler transmission gains allowed for the effects of hearing aid venting in the manner described by Dillon (13). This conversion includes the coupler response for flat insertion gain (CORFIG) values applicable to each hearing aid type, and also includes an allowance for the sound transmitted into and out from a vent and leakage around the mold. CORFIG values for BTE and ITE aids were those reported by Dillon (13). Based on the data of Fikret-Pasa and Revit (14), the ITC CORFIGs were derived by subtracting 3 dB at 4 kHz and 2 dB at 8 kHz from the ITE CORFIGs. CORFIGs used for CIC aids were those reported by Gudmundsen (15). The CORFIG values used are shown in **Table 1.** Reserve gains of 15 dB (BTE and BL aids) and 10 dB (ITE, ITC, and CIC aids) were added to these CORFIG figures.

To make the conversion, the optimum vent size had to be determined for each client record. The optimum vent size was calculated after estimating the maximum and minimum acceptable vent sizes. The maximum vent size was calculated from two constraints. Firstly, the maximum vent size that would avoid feedback, for each type of hearing aid, was calculated. This was derived by linearly interpolating the required insertion gain at 3 kHz and comparing it with the maximum real ear gain at 3 kHz that could be achieved for each vent size. A frequency of 3 kHz was chosen because the maximum insertion gain before feedback is less at that frequency than at other frequencies. (Because the real ear unaided response has its greatest value, on average, around 3 kHz, a greater real ear aided response is needed at 3 kHz than at other frequencies.) In the selection of the maximum vent size, a safety margin of 10 dB was allowed, to cover people who choose more gain than would be expected for clients with this degree of loss, and to allow for individual variation in the amount of leakage through vents and around earmolds.

A second maximum vent size was determined from the required insertion gain at 250 Hz. If that gain is significant, a large vent should not be used, otherwise an excessive coupler gain will be needed because of the low-frequency gain reduction effects of vents. This maximum vent size was calculated according to **Table 2.** Finally, the maximum vent size was selected to be the lesser of the two maxima described above.

The minimum vent size was determined to minimize difficulties associated with the occlusion effect. The minimum vent size was calculated from the air conduction threshold at 250 Hz according to **Table 3.**

Where two vents were equally ranked midway between the minimum and maximum vent sizes (the optimum vent size), the larger of the two vents was chosen. Optimum vent sizes were calculated for BTE, ITE, and ITC hearing aids. For CIC and body aids, an occluded (but with an average degree of leak, based on BTE earmolds) hearing aid was selected for all hearing losses.

The results of the calculations for each audiogram were the maximum and the minimum values of the range of coupler gains that would provide the RREIG at each frequency. As described in Dillon (13), a tolerance of ±2 dB in achieving the RREIG (averaged across

Table 1.
CORFIG values used for each type of hearing aid.

	Frequency (Hz)					
Aid	**250**	**500**	**1k**	**2k**	**4k**	**8k**
BTE	4	2	0	1	5	−1
ITE	1	2	−1	0	−2	−11
ITC	1	2	−1	0	−5	−13
CIC	−7	−7	−9	−7	−18	−23
BL	−2	−5	−3	12	4	−11

CORFIG = coupler response for flat insertion gain, BTE = behind the ear, ITE = in the ear, ITC = in the canal, CIC = completely in the canal, BL = body level.

Table 2.
Maximum vent size constrained by low frequency insertion gain required.

Required Insertion Gain at 250 Hz (dB)	Maximum Vent Size
0 dB	Tube (open)
0.1 to 9.9 dB	1 mm
≥10 dB	Occluded

Table 3.
Minimum vent size constrained by prevention of the occlusion effect.

AC HTL at 250 Hz	Minimum Vent Size
<20 dB HL	2 mm
20 to 25 dB HL	1 mm
≥30 dB HL	Tight

AC HTL = air conduction hearing threshold level, dB = decibel, HL = hearing level.

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clients with the same audiogram), was allowed. For frequencies of 1000 Hz and above, the range of acceptable coupler gains was, consequently, about 4 dB. For audiograms requiring REIG of less than 3 dB at 250 and 500 Hz, coupler gains from negative infinity to about 20 dB (depending on the vent size) were acceptable, because the REIG provided by the aid would be determined by transmission of sound in through the vent. No single coupler gain value could be considered necessary at these frequencies for these audiograms. However, representative coupler gain values could be obtained for audiograms requiring more than 3 dB of REIG at the low frequencies. These representative values were obtained by averaging the maximum and minimum values of acceptable coupler gain.

The Hartigan k-means clustering algorithm was used to cluster the required maximum and minimum coupler gains (simultaneously) into 20 clusters for each type of hearing aid, for both adults and children, separately. Cumulative probability distributions of required representative coupler gains were also calculated for each type of hearing aid, for both adults and children.

Coupler Frequency Response

Next, the required octave slopes (differences between the representative coupler gains at adjacent octave frequencies) and cumulative frequency distributions of the required slopes were determined for each type of hearing aid, for both adults and children. Correlations between the required slopes at adjacent octaves were also calculated to ascertain the degree to which the required slope in one octave was independent of the required slope in adjacent octaves.

Maximum Output Level

The required SSPL was calculated for each audiogram according to the selection procedure whose basis is described in Dillon et al. (9). This procedure estimates the required 3FA SSPL (0.5, 1, and 2 kHz) from the 3FA threshold values, and aims to avoid loudness discomfort and hearing aid saturation. The formula used, including an allowance for conductive hearing loss (not included in the original reference), is given in **Appendix B.** For CIC aids, an additional 11 dB (16) was subtracted from the formulae given in **Appendix B.** As discussed later in this paper, this reflects the larger real ear to coupler differences (RECD) applicable to CIC aids.

RESULTS

As mentioned earlier, exactly the same calculations and analyses were carried out on the data for children as on the data for adults, to determine whether, in meeting the requirements of adults, the requirements of children could also be met. This proved largely to be the case. For this reason, the findings presented in this article are confined to adults, with the exception of the median hearing losses of the two groups.

Hearing Thresholds

The means of the 20 clusters of adult audiograms are given in **Figure 1,** along with the percentage of audiograms in each cluster. **Figure 2** shows the median hearing loss for each group at each frequency.

Insertion Gains

The means of the 20 clusters of RREIGs for adults are given in **Figure 3,** along with the percentage of insertion gains in each cluster.

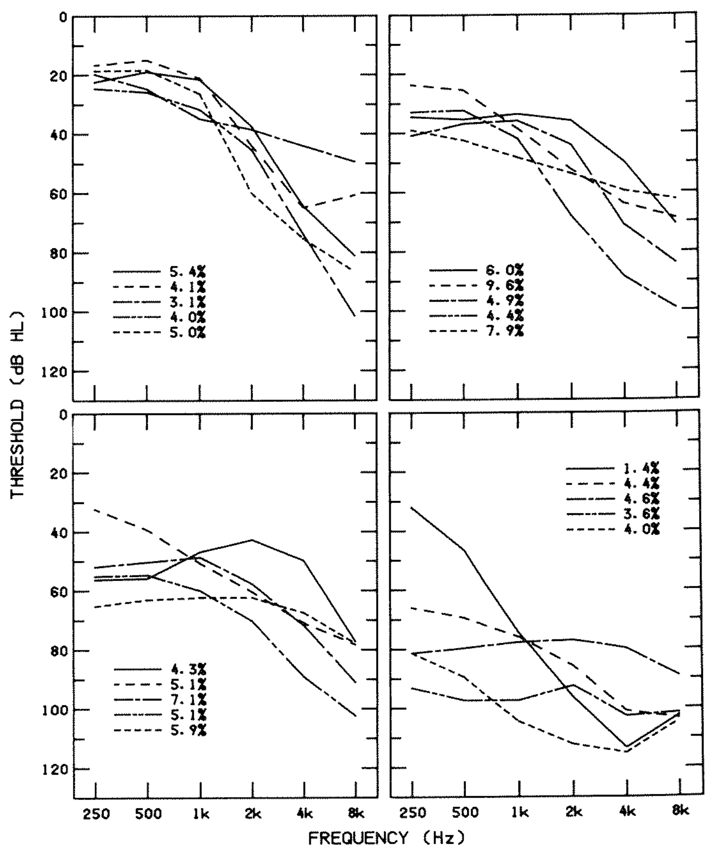

Figure 1.
The means of the 20 clusters of thresholds and the percentage of thresholds grouped into each cluster.

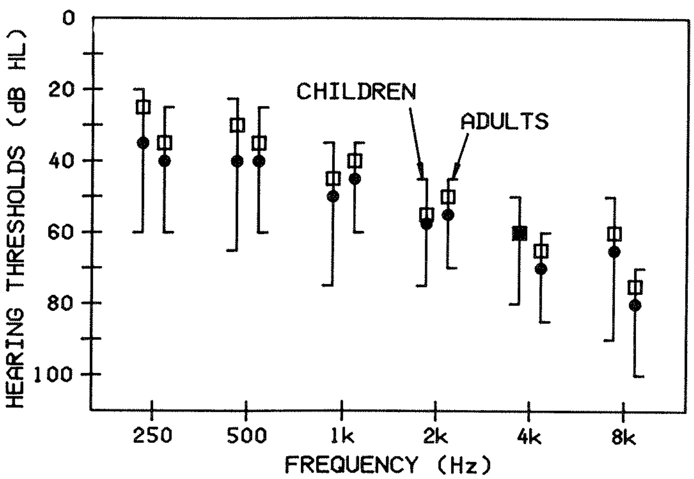

Figure 2.
Median air conduction thresholds (filled circles) and bone conduction thresholds (open squares) for the child data (left facing bars) and the adult data (right facing bars). The bars indicate the inter-quartile range of the air conduction hearing thresholds.

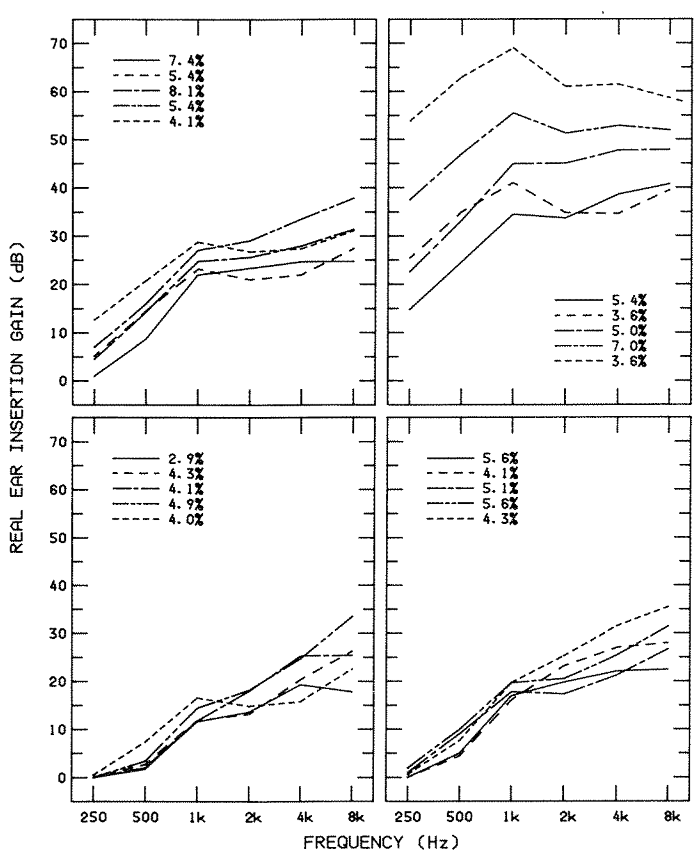

Figure 3.
The means of the 20 clusters of the required insertion gain curves and the percentage of curves grouped into each cluster.

Coupler Gains

Cumulative frequency distributions of representative 2-cc coupler gains are given in **Table 4.** At each frequency, the required coupler gain was excluded from the distribution if the RREIG was less than 3 dB. These low RREIG values can be satisfactorily approximated by sound traveling in through the vent/leakage paths, so the required coupler gain is unimportant, provided it is not excessive. Consequently, the number of cases is considerably less at 250 Hz and slightly less at 500 Hz, than at the higher frequencies, for all aid types except the high gain BTE and BL hearing aids, as shown in the second column of **Table 4.**

Figures 4 and **5** show the 20 clusters for BTE and ITC coupler gains. (Similar data for BL, ITE, and CIC aids, and data for all aid types for children, are available from the authors). The unimportance of coupler gain at 250 Hz (for approximately 50 percent of clients), and at 500 Hz (for approximately 10 percent of clients), can be seen in these figures as the widened region between the maximum and minimum acceptable coupler gains.

Coupler Frequency Response

Cumulative frequency distributions of required 2-cc coupler gain slopes are given in **Table 5.** Again, data are only included when the RREIG is greater than, or equal to, 3 dB.

The coupler frequency response variations required for each type of hearing aid are shown in **Figure 6.** These figures were constructed from **Table 5** by including the range of slopes from the 5th to the 95th percentiles. The range of responses should thus meet the expected requirements for 90 percent of clients. (This statement assumes that the CORFIG values are correct for individual clients, as well as being appropriate when averaged across clients).

Table 6 shows the product-moment correlations between the coupler gain slopes required in adjacent octaves for each type of hearing aid and the probability that each correlation is significantly different from zero. Some of the correlations are significant at the $p<0.01$ level but all are too small to be of any practical importance. The same conclusion is, therefore, reached as has been reached on previous occasions. For all practical purposes, the slope requirements in different octaves are independent of one another.

Maximum Output Level

For each of the 700 audiograms from the adult clients, the required 3FA gain is plotted in **Figure 7**

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Table 4.
Distributions of required 2-cc coupler gain for adults (HA2 configuration for BTE and BL aids; HA1 configuration for ITE, ITC, and CIC aids), based on N valid data points for each frequency. 3FAT is average threshold at 500, 1000, and 2000 Hz.

			Percentile									
Freq. (Hz)	**N**	**MIN**	**1**	**5**	**10**	**25**	**50**	**75**	**90**	**95**	**99**	**MAX**
BTE HIGH GAIN 3FAT>70 dB												
250	113	29	29	32	34	42	49	59	69	75	79	82
500	113	39	40	42	47	52	60	69	78	83	88	89
1000	113	51	51	54	56	61	69	78	85	89	93	98
2000	113	52	52	53	56	60	66	72	79	82	85	85
4000	113	51	53	56	61	65	71	77	84	86	88	91
8000	113	49	49	53	56	60	64	70	76	78	80	80
BTE MED. GAIN 3FAT<=70 dB												
250	208	19	20	21	22	23	26	31	35	41	47	52
500	501	17	17	20	21	24	28	33	39	44	54	60
1000	587	20	24	26	28	31	35	41	46	52	60	64
2000	587	22	24	28	30	33	37	42	47	51	60	71
4000	587	28	32	36	38	42	45	49	55	58	71	76
8000	587	24	28	33	35	38	42	48	53	55	64	70
ITE 3FAT<=70 dB												
250	208	10	10	11	11	13	17	21	27	30	39	44
500	501	12	14	15	16	18	22	27	34	38	49	55
1000	587	13	16	20	22	25	29	35	40	46	54	58
2000	587	17	19	23	25	28	32	36	41	45	54	65
4000	587	16	20	25	27	30	33	37	43	46	59	64
8000	587	9	12	18	21	24	28	33	38	40	49	55
ITC 3FAT<=70 dB												
250	208	10	10	11	11	13	16	21	27	30	39	44
500	501	13	14	15	15	18	21	26	33	38	49	55
1000	587	13	16	20	22	25	29	35	40	46	54	58
2000	587	17	19	23	25	28	32	36	41	45	54	65
4000	587	13	17	22	24	27	30	34	40	43	56	61
8000	587	7	11	16	19	22	26	31	36	38	47	53
CIC 3FAT<=70 dB												
250	208	4	5	5	6	8	11	16	22	26	34	40
500	501	5	6	6	7	10	14	19	26	31	42	48
1000	587	5	8	12	14	17	21	27	32	38	46	50
2000	587	11	13	16	18	21	25	29	34	38	47	58
4000	587	0	5	8	11	14	17	21	27	30	43	48
8000	587	−1	2	7	9	12	16	21	26	28	37	43
BL HIGH GAIN 3FAT>70 dB												
250	113	25	27	29	32	40	47	57	67	73	77	80
500	113	32	35	37	42	47	55	64	73	78	83	84
1000	113	48	48	51	53	58	66	75	82	86	90	95
2000	113	63	63	64	67	71	77	83	90	92	96	96
4000	113	50	52	55	60	64	70	76	83	85	87	90
8000	113	39	39	43	46	50	54	60	66	68	70	70
BL MED. GAIN 3FAT<=70 dB												
250	208	15	15	15	16	18	21	27	33	36	45	50
500	501	12	13	13	14	17	21	26	33	38	49	55
1000	587	16	19	23	25	28	32	38	43	49	57	61
2000	587	35	36	40	42	45	49	53	58	62	71	82
4000	587	28	32	36	38	41	44	48	54	57	70	75
8000	587	15	19	24	26	29	33	38	43	45	54	60

BTE = behind the ear, BL = body level, ITE = in the ear, ITC = in the canal, CIC = completely in the canal, 3FAT = three-frequency average threshold, dB = decibel.

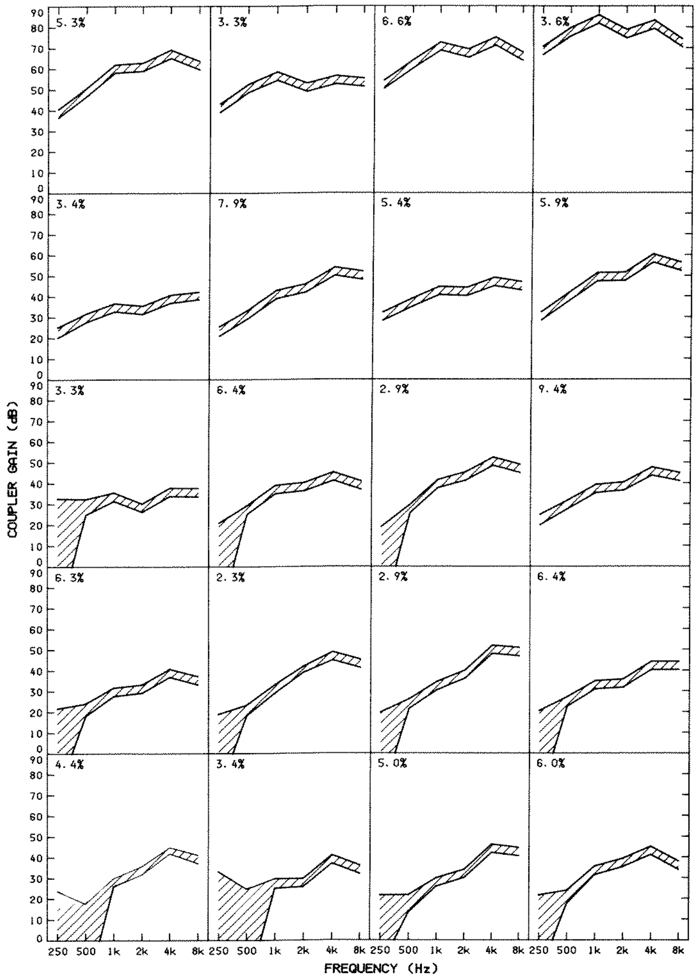

Figure 4.
Coupler gains, derived from 700 audiograms, for BTE hearing aids grouped into 20 clusters of variable size (as indicated). The two lines in each panel show the mean of the minimum and maximum acceptable coupler gains that are included in each cluster.

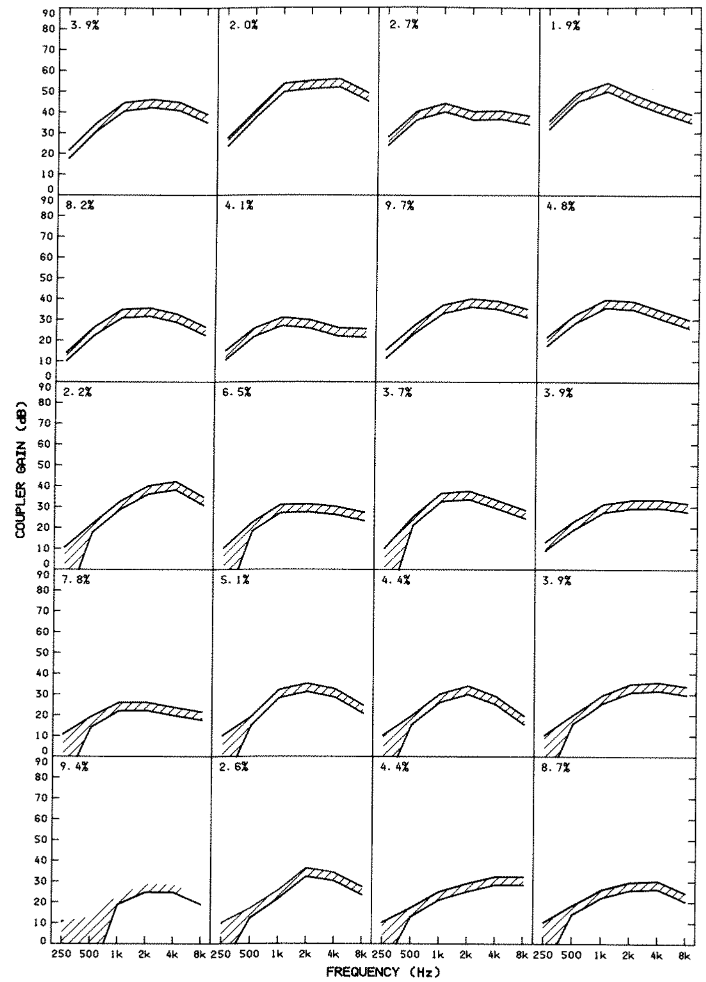

Figure 5.
Coupler gains, derived from 700 audiograms, for ITC hearing aids grouped into 20 clusters of variable size. The two lines in each panel show the mean of the minimum and maximum acceptable coupler gains that are included in each cluster.

against the required 3FA SSPL for BTE hearing aids. (A random value between −1 and +1 dB was added to the gain and SSPL for each point prior to plotting to minimize exactly overlapping points.) The points that appear to fall along a monotonic curve are those arising from clients with sensorineural losses. The other points that lie above this curve arise from clients with conductive or mixed losses. Based on the gain-SSPL combinations that appear to be necessary, the solid line was drawn around the data. Similar data for the other four aid types are shown in **Figure 8.**

DISCUSSION

Hearing Thresholds

As shown in **Figure 2,** thresholds of the children with hearing aids were similar to those of the adults. The largest differences occurred at 4 and 8 kHz, where the children's losses were substantially less than those of the adults. This presumably reflects the absence of presbycusis and noise damage in the children's losses. Hearing aids with a high-frequency response that rises sufficiently steeply to meet the needs of adults will thus also rise steeply enough to meet the needs of children, but some children may require responses that fall more steeply from 4 kHz to 8 kHz than is the case for hearing aids optimally designed for adults.

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Table 5.
Distributions of required 2-cc coupler gain slopes for adults (HA2 configuration for BTE and BL aids; HA1 configuration for ITE, ITC, and CIC aids), based on N valid data points for each octave. 3FAT is average threshold at 500, 1000, and 2000 Hz.

			Percentile									
Freq. (Hz)	**N**	**MIN**	**1**	**5**	**10**	**25**	**50**	**75**	**90**	**95**	**99**	**MAX**
BTE HIGH GAIN 3FAT>70 dB												
250/500	113	−1	3	5	6	7	10	12	13	14	16	17
500/1k	113	−4	0	2	4	6	8	12	15	16	18	19
1k/2k	113	−14	−14	−11	−9	−6	−3	1	4	5	10	12
2k/4k	113	−8	−7	−4	0	3	6	8	11	13	15	19
4k/8k	113	−13	−12	−11	−11	−10	−7	−4	−2	0	3	7
BTE MED. GAIN 3FAT<=70 dB												
250/500	208	1	1	4	4	6	7	9	12	14	16	17
500/1k	501	−4	−1	2	4	6	9	11	13	15	19	23
1k/2k	587	−18	−9	−6	−4	−1	2	4	7	10	12	19
2k/4k	587	−4	−1	1	3	5	7	10	13	15	20	28
4k/8k	587	−15	−12	−10	−8	−6	−3	0	3	5	8	16
ITE 3FAT<=70 dB												
250/500	208	6	6	8	9	10	12	13	16	17	19	20
500/1k	501	−4	−2	3	4	6	8	11	13	14	18	21
1k/2k	587	−18	−9	−5	−3	−1	2	5	8	10	13	19
2k/4k	587	−10	−7	−5	−3	−1	1	4	7	9	14	22
4k/8k	587	−18	−16	−12	−11	−9	−6	−3	0	2	5	13
ITC 3FAT<=70 dB												
250/500	208	6	6	8	9	10	12	13	16	17	19	20
500/1k	501	−4	0	3	4	7	8	11	13	14	18	21
1k/2k	587	−18	−9	−5	−2	−1	2	5	8	10	13	19
2k/4k	587	−12	−9	−7	−5	−3	−1	1	4	7	11	19
4k/8k	587	−16	−14	−10	−9	−6	−4	−1	1	3	6	14
CIC 3FAT<=70 dB												
250/500	208	3	4	5	6	8	9	11	14	15	17	18
500/1k	501	−5	−1	2	4	6	8	10	12	15	18	20
1k/2k	587	−17	−8	−4	−2	0	3	6	9	11	14	20
2k/4k	587	−19	−16	−14	−12	−11	−8	−6	−2	0	5	12
4k/8k	587	−14	−11	−8	−7	−4	−1	2	5	6	10	17
BL HIGH GAIN 3FAT>70 dB												
250/500	113	−4	0	2	3	4	7	9	10	11	13	14
500/1k	113	−2	2	4	6	8	10	14	17	18	21	21
1k/2k	113	0	0	3	5	8	11	15	18	19	24	26
2k/4k	113	−20	−19	−16	−12	−9	−6	−4	−1	1	3	7
4k/8k	113	−23	−21	−20	−20	−19	−16	−13	−11	−9	−6	−2
BL MED. GAIN 3FAT<70 dB												
250/500	208	0	0	2	3	4	6	8	10	12	14	14
500/1k	501	−1	3	6	8	10	12	14	16	19	22	24
1k/2k	587	−4	5	9	11	13	16	19	22	24	27	33
2k/4k	587	−16	−12	−11	−9	−7	−5	−2	1	4	8	16
4k/8k	700	−24	−21	−18	−17	−14	−12	−9	−6	−4	−1	7

BTE = behind the ear. BL = body level. ITE = in the ear. ITC = in the canal. CIC = completely in the canal. 3FAT = three-frequency average threshold. dB = decibel.

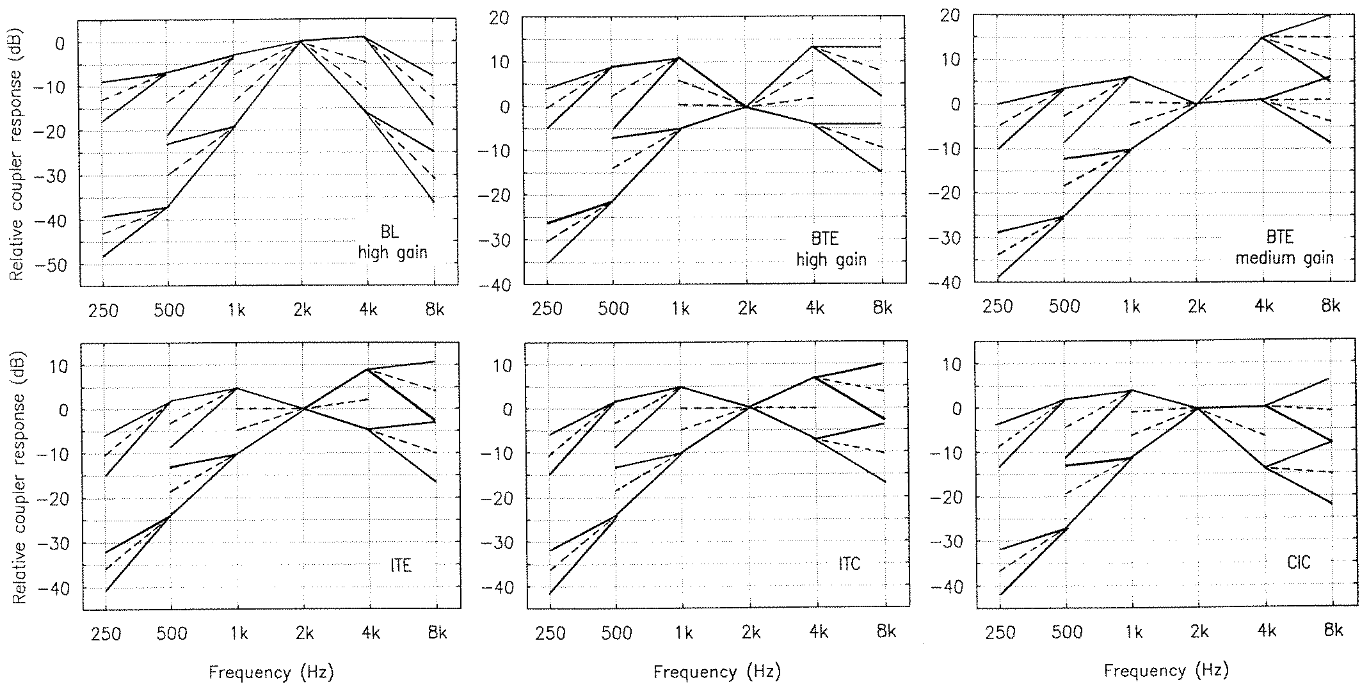

Figure 6.
Coupler frequency response ranges, relative to gain at 2 kHz, to meet the slopes required for 90 percent of clients within each octave.

Table 6.
Product-moment correlations (r) between the coupler gain slopes required in adjacent octaves and the probability (p) that each correlation is significantly different from zero, for each type of hearing aid.

Hearing Aid Type		Correlation 250/500 with 500/1k	500/1k with 1k/2k	1k/2k with 2k/4k	2k/4k with 4k/8k
BTE	r	0.197	0.082	−0.012	−0.121
	p	0.000	0.043	0.757	0.001
ITE	r	0.016	0.059	−0.068	−0.191
	p	0.819	0.186	0.102	0.000
ITC	r	−0.020	0.045	−0.062	−0.184
	p	0.777	0.319	0.132	0.000
CIC	r	−0.014	0.080	−0.049	−0.192
	p	0.840	0.072	0.234	0.000
BL	r	0.117	0.098	0.034	−0.111
	p	0.036	0.015	0.371	0.003

BTE = behind the ear, ITE = in the ear, ITC = in the canal, CIC = completely in the canal, BL = body level.

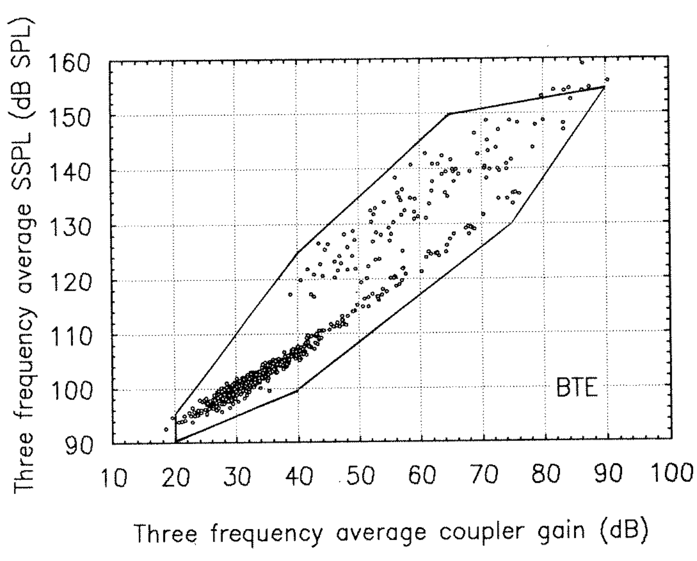

Figure 7.
Three-frequency average SSPL plotted relative to 3FA coupler gain for BTE hearing aids. The solid line encloses the region considered necessary to optimally fit clients with BTE aids.

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Insertion Gains

The means of the insertion gain clusters for adults, shown in **Figure 3,** tend to increase at a rate of about 12 dB/octave from 250 Hz to 1 kHz and then tend to increase at a slower rate of about 3 dB/octave at frequencies above 1 kHz. The means of the insertion gain clusters for children increase at a rate similar to that for adults at the low frequencies, but tend not to increase at frequencies above 1 kHz, as could be expected from the hearing threshold results.

Coupler Gains

The highest coupler gains indicated in **Table 4** and in **Figure 4** are unachievable with currently available technology because of feedback from the receiver to the microphone, both within the hearing aid and external to the aid. It can be inferred from **Figure 7** that these highest gains are needed for people with substantial conductive components to their loss. It is also apparent from **Figure 7** that these gains are to be used in hearing aids that have extremely high SSPLs. If the high SSPLs cannot be achieved, there is no point in achieving the extremely high gains, because it would just result in the hearing aid being saturated for most sounds in most environments.

Coupler Frequency Response

The independence of response slope requirements between adjacent octaves implies that no matter what shape a hearing aid response is with all tone controls at maximum gain, a hearing aid will need more than one or two tone controls to meet a target response. Ideally, a separate tone control is required for at least each octave over which the hearing aid response is to be fitted. With recent developments in hearing aids, it is now becoming feasible to achieve this ideal.

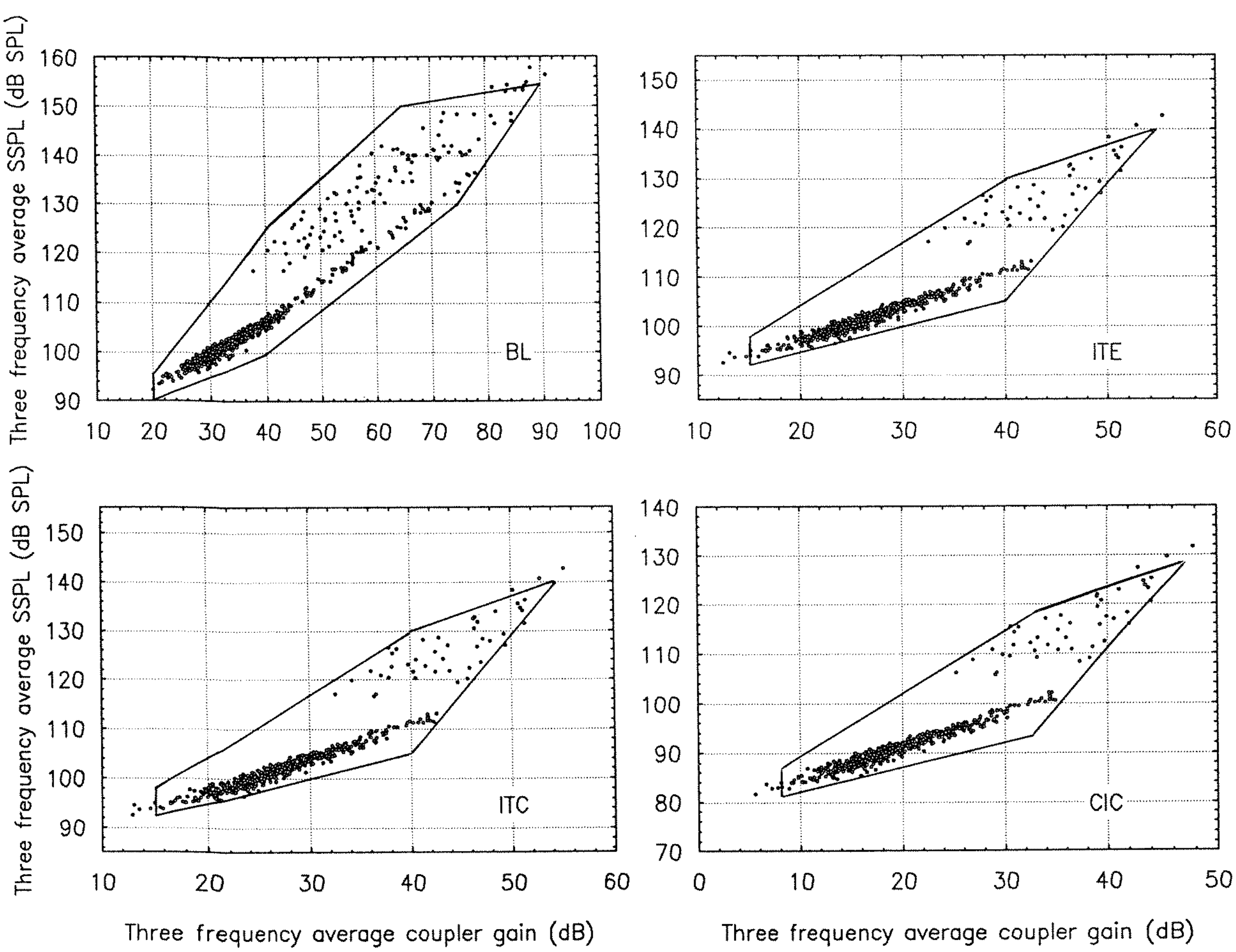

Figure 8.
Three-frequency average SSPL plotted relative to 3FA coupler gain for BL, ITE, ITC, and CIC hearing aids. For each graph, the solid line encloses the region considered necessary to optimally fit clients with that type of aid.

At first sight, designing frequency response variations that will meet the needs of only 90 percent of clients seems to be less than adequate. We believe it to be a reasonable target, however, because of the extremely large range of response variations that this results in when the 90 percent criterion is independently applied to each octave. For example, for ITE hearing aids, **Figure 6** shows that the 4 kHz gain can be as much as 33 dB greater than the 500 Hz gain. Examination of the data for the 700 gain-frequency responses, however, reveals that the maximum gain increase from 500 Hz to 4 kHz is only 28 dB. In terms of overall slope from 500 Hz to 4 kHz, the variations shown in **Figure 6** thus exceed the requirement for 100 percent of the audiograms sampled, even though they are based on meeting only 90 percent of requirements within each octave. This incongruity has occurred because the response slope required in each octave is practically uncorrelated with the response slope needed in any other octave. It is thus very unlikely that any client will need slopes corresponding to the 90th percentile or higher in every octave. This means that although we would like the response slope in each octave to be as steep as that shown in **Figure 6,** there is no need for the hearing aid to operate satisfactorily when all octaves are set to their steepest slopes. This is fortunate as it is difficult to maintain an adequate signal-to-noise ratio over a wide range of gains and/or response slope variations.

The data shown for each of the clusters in **Figures 4** and **5** do not appear to require the same flexibility of response shape as implied by **Figure 6.** Undoubtedly, this occurs because the data shown for each cluster represent only the average frequency response of that cluster. A range of response slopes exists within each cluster, so the range of slopes shown in **Figure 6** or **Table 5** should be considered if either **Figure 4** or **Figure 5** is used as the basis of hearing aid design. The clusters of **Figures 4** and **5** nevertheless provide a good overview of the range of absolute gains and response slopes that are needed to fit a wide (but not complete) range of audiograms.

Because our data have been calculated and presented at octave frequencies, we have not addressed the question of whether the real ear aided response (REAR), and hence the coupler gain, should contain a peak around 3 kHz to compensate for the peak inthe aid wearer's real ear unaided response (REUR). The concept appears reasonable, provided the peak can be tuned to the same frequency as the individual's peak, or provided a fixed peak is sufficiently broad that it encompasses the frequency range over which REUR peaks most commonly occur.

Maximum Output Level

The clear separation of data points representing the requirements of people with sensorineural losses from those that have mixed or conductive losses is totally a consequence of our definition of mixed hearing loss. Had air-bone gaps of less than 15 dB been classified as mixed losses, there would presumably have been a more continuous distribution of requirements.

Two opposing factors need to be taken into account when determining the range of gain-SSPL combinations that are necessary. Firstly, the SSPL requirement was calculated according to a procedure that, at best, is correct on average. Individuals may require a little more or less than the predicted values. Based on recently collected unpublished data, such variations rarely exceed 10 dB. Secondly, it may not be economical to design a family of hearing aids that provides the requirements for the most extreme hearing losses. The region enclosed by the solid line in **Figures 7** and **8** is our estimate of an appropriate compromise considering these two factors. For any given coupler gain, the range of SSPL values required is less than 30 dB, and ranges of this size are possible now with several of the programmable aids on the market.

It should be remembered that the values shown are 3FA SSPL (because this is the value calculated by the SSPL selection procedure used). These 3FA values will typically be 3 to 8 dB less than the peak SSPL values by which hearing aids are often described.

We have not allowed for what is feasible with currently available transducers, and it is clear that the higher SSPL values are impossible to obtain with currently available hearing aids. Were it possible to design hearing aids to have SSPLs of 155 dB SPL, it would also be necessary to examine the safety of such aids. Hearing aids with an SSPL this high are only needed for people with substantial conductive losses. It appears to be established that a conductive loss acts as simple attenuation (17). Consequently, a hearing aid with an SSPL of 150 dB SPL fitted to an ear with a 50 dB conductive loss should represent no more danger to the cochlea than a hearing

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aid with an SSPL of 100 dB SPL fitted to an ear with no conductive component to the loss. What is not known is the input level at which sound can cause physical damage to the middle ear. Damage to the cochlea would also be possible if such aids were fitted to ears that subsequently proved to have fluctuating conductive losses.

The CIC SSPL data is noticeably different from that of the other ear level aids, but all the data relating to CIC aids should be regarded as more approximate than for the other aids because less is known about the relationship between coupler and real ear responses for these aid types. For a given hearing loss the SSPL required (referred to a 2-cc coupler) and the coupler gain required both decrease as the real-ear-to-coupler difference (RECD) increases. To avoid discomfort, the SSPL should decrease by 1 dB for every 1 dB increase in RECD. The effect of RECD on the SSPL needed to avoid saturation is less direct. Every 1 dB increase in RECD means that 1 dB less coupler gain is required, and in turn this means coupler SSPL can be reduced by 1 dB without increasing the likelihood of saturation. The increased input to a CIC aid, relative to that received by, for example, an ITE aid, means that less coupler gain is needed for the same hearing loss. This decrease in coupler gain does not, however, imply that the SSPL of the aid can be reduced without the hearing aid saturating, because saturation is also affected by the input signal reaching the aid. In summary, SSPL requirements for CIC aids should be lower than those for ITE aids by the extent of the RECD differences between the two aids, whereas coupler gain requirements differ by the extent of the CORFIG differences.

CONCLUSION

The NAL-RP selection procedure used to derive the response requirements reported in this article is directly applicable to linear instruments. Such instruments use compression (if at all) only to control the SSPL of the hearing aid. A matching set of specifications for nonlinear hearing aids must await the emergence of an accepted and validated set of rules for prescribing such aids. The present data do, however, have several implications for such aids. The NAL-RP frequency response aims to provide comfort and intelligibility when speech at an average level (70 dB SPL) is input to the hearing aid. Therefore, it seems reasonable that nonlinear hearing aids will need to provide similar amounts of gain and similar frequency responses when speech at an average input level is input to those hearing aids, even if they have vastly different amplification characteristics for speech at other levels, or for signals with other long-term average spectra. This issue is considered in more detail by Byrne (18).

We are not sure whether other client populations will have hearing losses, and hence amplification requirements, different from those presented here. The median age of AHS clients is approximately 77 years, and nearly all clients are over 60-years-of-age, so it is possible that populations with a younger median age will have different characteristics. The similarity of the adult and child data, and the relatively small proportion of hearing aids provided to children and younger adults suggest, however, that the characteristics of other populations wearing hearing aids are not likely to be very different.

APPENDIX A

NAL-RP Procedure for Selecting the Gain and Frequency Response of Hearing Aids

In the NAL-RP procedure for selecting the gain and frequency response of hearing aids, the recommended real ear insertion gain (RREIG) at the particular frequency is given, for sensorineural hearing loss, by the formula

$$RREIG(f) = X + 0.31\ HTL(f) + K(f) + P(f)$$

where

RREIG(f) is recommended real ear insertion response, in dB
HTL(f) is hearing threshold level, in dB HL
K(f) is a constant with the values given in **Table A1**
P(f) is a correction for profound hearing loss, the values of which depend on HTL at 2000 Hz and are given in **Table A2**
$X = 0.05\ (SUM)$ for $SUM <= 180$
$X = 0.05\ (SUM) + 0.2\ [(SUM - 180)/3]$ for $SUM > 180$
$SUM = HTL500 + HTL1000 + HTL2000$

Table A1.
Values of the additive constant K(f).

	FREQUENCY (Hz)									
	250	500	750	1000	1500	2000	3000	4000	6000	8000
K(f)	−17	−8	−3	+1	+1	−1	−2	−2	−2	−2

Table A2.
Values of the correction P(f) for profound hearing loss, as a function of HTL at 2000 Hz.

	FREQUENCY (Hz)									
HTL2k	250	500	750	1000	1500	2000	3000	4000	6000	8000
<95	0	0	0	0	0	0	0	0	0	0
95	4	3	1	0	−1	−2	−2	−2	−2	−2
100	6	4	2	0	−2	−3	−3	−3	−3	−3
105	8	5	2	0	−3	−5	−5	−5	−5	−5
110	11	7	3	0	−3	−6	−6	−6	−6	−6
115	13	8	4	0	−4	−8	−8	−8	−8	−8
120	15	9	4	0	−5	−9	−9	−9	−9	−9

HTL = hearing threshold level.

APPENDIX B

NAL SSPL Prescription Formulae

The three-frequency average (3FA) estimated optimum SSPL (referred to dB SPL in a 2-cc coupler) is selected on the basis of the 3FA hearing thresholds using the following formulae. In each case the 3FA is calculated for the frequencies 500 Hz, 1 kHz, and 2 kHz.

$$\text{For 3FA loss} < 60 \text{ dB SPL: 3FA SSPL} = 0.3{*}\text{HTL} + 89 \text{ dB SPL}$$
$$\text{For 3FA loss} \geq 60 \text{ dB SPL: 3FA SSPL} = 0.533{*}\text{HTL} + 75 \text{ dB SPL}$$

These formulae apply to sensorineural losses. For mixed losses, the above procedure should be applied to the sensorineural component of the loss, and 0.875 times the conductive portion of the loss (the 3FA air-bone gap) should then be added to the result.

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