Updated performance requirements for hearing aids

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Abstract—This article updates the design specifications for a family of hearing aids required by the National Acoustic Laboratories (NAL) in order to meet the needs of its clients. The required range of coupler gains and frequency responses of behind-the-ear (BTE), in-the-ear (ITE) and body-level (BL) hearing aids has been recalculated on the assumption that the aids will be fitted using the new Byrne-Dillon procedure for selecting gain and frequency response. In the light of recently acquired data, the specification of maximum allowable internal noise has been changed slightly and no relaxation of the equivalent input noise criterion for high gain aids is allowed. Since the Byrne-Dillon procedure demands a somewhat smaller (though still quite substantial) range of hearing aid response shapes, the subdivision of the total response requirements has also been repeated. The number of hearing aid models specified is still 18, but the number of fitter-adjusted controls has been reduced from 6 to 4. The fitter-adjusted controls comprise a maximum power output (MPO) level control, an MPO shape control, a low-tone cut control and a high-tone cut control, with MPO control being achieved by means of low-distortion compression limiting.

INTRODUCTION

The National Acoustic Laboratories (NAL) of Australia fits hearing aids to three main client groups: children, old-age pensioners, and war veterans. Some of these aids are designed at NAL and manufactured for NAL by subcontractors and others are purchased from hearing aid manufacturers. Either way, it is necessary for NAL to specify the performance characteristics that the various models of hearing aids should have, in order to ensure that the needs of its clients are met. As the cross section of hearing losses seen by NAL audiologists is quite wide, hearing aids which provide the most appropriate amplification characteristics for the NAL client population will, presumably, also be appropriate for any hearing-impaired population fitted with the procedure used at NAL.

A previous article (6) and associated report (5) presented the performance range needed in a family of hearing aids if a reasonable proportion of NAL’s clients were to be adequately fitted. The requirements specified in those publications were based partly on the Byrne-Tonisson (4) gain and frequency response selection procedure then used at NAL, partly on the results of specially conducted experiments, and partly on consideration of basic theoretical principles. However, in the light of recently acquired data, some of these requirements have had to be updated: First, on the basis of data gathered in an extensive evaluation of the Byrne-Tonisson procedure (1,3), Byrne-Dillon (2) have devised a new gain and frequency response selection procedure then used at NAL, partly on the results of specially conducted experiments, and partly on consideration of basic theoretical principles. However, in the light of recently acquired data, some of these requirements have had to be updated: First, on the basis of data gathered in an extensive evaluation of the Byrne-Tonisson procedure (1,3), Byrne-Dillon (2) have devised a new gain and frequency response selection procedure which will be adopted for use in hearing-aid fittings at NAL. Second, additional measurements have been carried out on the long-term average spectrum of speech, leading to a revision of the permissible equivalent input noise of hearing aids. Third, data concerning the gains provided to severely and profoundly deaf children have led to a reversal of the decision to allow relaxation of the equivalent input noise criterion for high-gain hearing aids. Finally, since the new gain and frequency response selection procedure demands a somewhat smaller (though still quite substan-
tional range of hearing aid response shapes, the subdivision of the total response requirements has been repeated. Many of the original specifications remain unchanged, but those which have had to be altered are presented in this article and in an associated report (11). The real ear gain requirements on which the specifications are based remain the same whether they are met with body-level (BL), behind-the-ear (BTE), in-the-ear (ITE), or in-the-canal (ITC) hearing aids. The required coupler responses differ for each of these types of aid, however, and this article presents coupler requirements separately for ITE, BTE, and BL hearing aids.

GAIN AND FREQUENCY RESPONSE

Gain and frequency response requirements are probably the most important specifications for a hearing aid model or family of aids. Gain refers to the overall degree of amplification and is usually quantified by the maximum gain irrespective of frequency, by the average gain at specified frequencies, or by the gain at 1 kHz or 2 kHz. Frequency response refers to the shape of the gain requirements across frequency. The required slopes in each octave, given by the differences between required gains at adjacent octave tests frequencies, are an important aspect of frequency response.

Data and Calculations

The data used in calculating the gain, slope, and frequency response requirements were the same as used previously. These data consisted of pure-tone audiograms obtained from the case records of 229 children, 249 war veterans, and 219 old-age pensioners who were fitted with hearing aids and selected at random from the files of a few NAL Hearing Centers. Sensorineural, conductive, and mixed hearing losses were included in the samples. The number of cases with a significant conductive component was 44/219 (20.1 percent) for the pensioners, 80/229 (34.9 percent) for the children, and 78/249 (31.3 percent) for the veterans; i.e., 202/697 (28.9 percent) for the total sample. However, the estimated incidence of conductive components in the NAL client population as a whole, obtained by combining the percentages for the three samples according to the relative frequency of each category of case, is 24.4 percent. For all three samples, air-conduction hearing threshold levels (HTL's) were available at octave frequencies from 250 Hz to 8 kHz and bone-conduction thresholds were available at octave frequencies from 250 Hz to 4 kHz. Bone-conduction thresholds for 8 kHz were estimated on the basis of the relationship between the air- and bone-conduction thresholds at the frequencies up to 4 kHz. Both air-conduction and bone-conduction thresholds were used in the calculations, but only the HTL's of the left ears were used.

The calculations were initially carried out separately for the three different categories of case and the results were subsequently combined into overall population estimates by adding the results for the three categories together in the proportions with which they occur in the population as a whole (children 16.8 percent, veterans 16.7 percent, and pensioners 66.4 percent). For each audiogram, the required real ear insertion gain at each octave frequency from 250 Hz to 8 kHz was calculated by means of the Byrne-Dillon gain and frequency response selection procedure. In this procedure, the required real ear gain at a particular frequency is given for sensorineural hearing losses by an equation of the form:

\[ G(f) = X + 0.31 \text{HTL}(f) + K(f) \]

where \( G(f) \) = required real ear insertion gain, \( \text{HTL}(f) \) = air-conduction hearing threshold level, and \( K(f) \) = additive constant.

\[ X = 0.05 (\text{HTL}(500) + \text{HTL}(1K) + \text{HTL}(2K)) \]

In the case of conductive- and mixed-hearing losses, one-quarter of the air-bone gap was added to the real ear gain that would have been required had the loss been purely sensorineural, as recommended by Lybarger (9). Although we have reservations about this rule, no better method of dealing with conductive components is presently available; a survey of fittings of mixed-loss cases by NAL clinical audiologists indicated that, on the average, this rule is being used. In cases where the threshold exceeded the limit of the audiometer, the HTL was assumed to be 5 dB greater than the audiometer limit.

Having calculated the required real ear insertion gains, we determined the required open-access (HA1 configuration, ANSI S3.7 - 1973) 2-cc coupler gains (at full-on volume control setting). Open-access coupler gain (as well as the standard HA2 coupler gain) was calculated so that the effects of acoustic modifications of the earmold could be allowed for in the assessment of required electronic frequency response modifications and because open-access coupler response requirements correspond directly to ITE hearing aid response requirements. HA2 coupler requirements were obtained from the calculated HA1 requirements by adding the 6BO to HA2 earmold differ-
ences [derived from the data presented in section 3.5.1 of NAL Report No. 102 (5) and given in Table 1 of this article] to the HA1 requirements. The HA2 coupler requirements given in this article thus assume that, unless acoustic modification is considered to be necessary, hearing aids will be fitted with a Killion 6BO earmold system (i.e., a conventional No. 13 constant inner diameter tube running from the tip of the earhook to the medial tip of the earmold). As discussed later, the use of other earmold styles enables corresponding reduction of the range of electronic modifications needed to obtain the required range of high-frequency coupler response shapes.

Table 1
HA1 to HA2 2-cc coupler gain and slope corrections derived from response differences between 6BO and HA2 earmolds.

<table>
<thead>
<tr>
<th>Frequency, Hz</th>
<th>250</th>
<th>500</th>
<th>1K</th>
<th>2K</th>
<th>4K</th>
</tr>
</thead>
<tbody>
<tr>
<td>HA1 to HA2</td>
<td>-5</td>
<td>-7</td>
<td>0</td>
<td>+10</td>
<td>-1</td>
</tr>
</tbody>
</table>

Slope Corrections

<table>
<thead>
<tr>
<th>Octave, Hz</th>
<th>250/500</th>
<th>500/1K</th>
<th>1K/2K</th>
<th>2K/4K</th>
</tr>
</thead>
<tbody>
<tr>
<td>HA1 to HA2</td>
<td>-2</td>
<td>+7</td>
<td>+10</td>
<td>-11</td>
</tr>
</tbody>
</table>

The required open-access coupler gains were obtained by adding the correction factors given in Table 2 to the required real ear insertion gains. These correction factors were obtained by the following rationale: The required real ear insertion gain is converted into required real ear transmission gain by addition of the average transmission gain of the open ear reported by Shaw (12), which is given for the various frequencies in Table 2. The average ear can be represented by an ear simulator, so the required transmission gain in a 2-cc coupler (with as-used volume control setting) can be obtained by subtracting the ear simulator to 2-cc coupler corrections reported by Sachs and Burkhard (13) (see Table 2) from the required real ear transmission gains. Reserve gain of 15 dB is then added to the required 2-cc coupler transmission gain at as-used volume control setting, to allow for the fact that hearing aid performance in a 2-cc coupler is customarily measured at full-on volume control setting. The corrections for open ear transmission gain, simulator to 2-cc coupler, and reserve gain are then added together to obtain the total correction factors.

When the required open-access 2-cc coupler gains at the various frequencies had been calculated, the peak required gain (the highest gain required, regardless of frequency) was determined for each audiogram and the cumulative frequency distributions (in percent) of the various gain requirements were calculated. Next, the required slopes (differences between required gains at adjacent frequencies) and cumulative frequency distributions of the required slopes were determined. Correlations between the slopes at adjacent octaves were also calculated to ascertain whether the required slope in one octave was predictable from the slope in adjacent octaves.

A k-means clustering algorithm devised by Hartigan (7) was used to cluster the required gains into a smaller number of frequency responses. It was found that 54 clusters (frequency responses) would enable 77 percent of clients to be provided with their required gains to within ±3 dB at all frequencies and 95 percent to within ±5 dB at all frequencies. The differences between individual required gains and the gains provided by means of the 54 frequency responses were distributed approximately normally, with a mean of 0 dB and a SD of about 2.5 dB, at all frequencies. Additionally, the required gains were clustered into 10 clusters for each category of case after they had been normalized to 500 Hz by subtracting the required gain at 500 Hz from the required gains at the other frequencies.

Table 2
Derivation of correction factors for obtaining required open-access (HA1) 2-cc coupler gain from required real ear gain.

<table>
<thead>
<tr>
<th>Frequency, Hz</th>
<th>250</th>
<th>500</th>
<th>1K</th>
<th>2K</th>
<th>4K</th>
<th>8K</th>
</tr>
</thead>
<tbody>
<tr>
<td>Open ear transmission gain</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>12</td>
<td>14</td>
<td>2</td>
</tr>
<tr>
<td>Simulator to 2-cc coupler</td>
<td>-3</td>
<td>-3</td>
<td>-5</td>
<td>-8</td>
<td>-12</td>
<td>-19</td>
</tr>
<tr>
<td>Reserve gain</td>
<td>15</td>
<td>15</td>
<td>15</td>
<td>15</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>Total correction</td>
<td>13</td>
<td>14</td>
<td>13</td>
<td>19</td>
<td>17</td>
<td>-2</td>
</tr>
</tbody>
</table>

RESULTS AND DISCUSSION

Cumulative frequency distributions of required open-access coupler gain at the various frequencies for the entire sample are given in Figure 1. The required gains vary from a minimum of -1 dB at 250 Hz to a maximum of 87 dB at 2 kHz. The persons requiring such a large amount of gain had profound hearing losses with substantial conductive components. Frequency response requirements were assessed mainly by examining the range of slopes required in each octave; these are given for the
entire sample in Figure 2. The required slopes range from about $-20$ dB/octave in the 4 kHz/8 kHz octave to about $30$ dB/octave in the 1 kHz/2 kHz octave.

The relative positions of the gain and slope distributions obtained with the new procedure are different from those obtained with the old procedure. The changes in the positions of the curves can best be seen by comparing the median gains and slopes (i.e., the 50 percent points on the cumulative frequency distributions of required gains and slopes) obtained with the two procedures. The median open-access (HA1) coupler gain requirements of the two procedures are shown in Figure 3. At 250 Hz, the median gain obtained with the new procedure is the same as that obtained with the old procedure. At 500 Hz, it is about 9 dB higher than that obtained with the old procedure. At 1 kHz, it is about 2 dB less, and at 2 kHz, about 4 dB less. At 4 kHz, it is about 2 dB less, and at 8 kHz, about 8 dB less.

The median open-access coupler slope requirements of the two procedures are shown in Figure 4. In the 250 Hz/500 Hz octave, the median required slope increases from about 1 dB/octave using the old procedure to about 10 dB/octave using the new procedure; in the 500 Hz/1 kHz octave, the median required slope is reduced from about 21 dB/octave to about 9 dB/octave. In the 1 kHz/2 kHz octave, it is reduced from about 8 dB/octave to about 6 dB/octave. In the 2 kHz/4 kHz octave, it is increased from about $-4$ dB/octave to about 1 dB/octave, and in the 4 kHz/8 kHz octave, it is reduced from about 0 dB/octave to about $-3$ dB/octave.

The question of whether there is any relationship between the required slopes in adjacent octaves was reexamined. Product moment correlations were performed between the required slopes in adjacent octaves for the complete sample of 697 clients. The correlation coefficients obtained and their statistical significance are given.

**Figure 1**
Cumulative frequency distributions of required open-access (HA1) 2-cc coupler gain.
in Table 3. Only the correlation of the slopes at 250 Hz/500 Hz with those at 500 Hz/1 kHz was significant, but was too small to be of any practical importance. The same conclusion is therefore reached as was reached using the Byrne-Tonisson procedure. For all practical purposes, the slope requirements in the different octaves are independent of one another and, ideally, a separate tone control is needed for at least each octave over which the hearing aid response is to be fitted.

While the cumulative slope distributions are useful, they do not enable the shapes of individual response curves to be seen. The clustering analysis was therefore performed to produce a reasonable number of representative frequency response curves. The 54 typical frequency responses are presented in Figure 5. The six responses within each section of the figure share similar maximum and minimum gains. The sections on the right hand side have greater low frequency gains than those on the left, whereas those at the top have greater high-frequency gains than those at the bottom. One limitation must be borne in mind when considering these curves: Each response curve shown is the mean of a cluster of individual responses and extreme slopes which only occur rarely and may not be apparent. The cumulative distributions presented earlier are therefore more useful for working out slope requirements in particular frequency regions. It is

<table>
<thead>
<tr>
<th>Correlation</th>
<th>Coefficient</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>250/500 with 500/1K</td>
<td>0.172</td>
<td>1% level</td>
</tr>
<tr>
<td>500/1K with 1K/2K</td>
<td>0.096</td>
<td>not significant</td>
</tr>
<tr>
<td>1K/2K with 2K/4K</td>
<td>0.076</td>
<td>not significant</td>
</tr>
<tr>
<td>2K/4K with 4K/8K</td>
<td>-0.093</td>
<td>not significant</td>
</tr>
</tbody>
</table>

Figure 2
Cumulative frequency distributions of required open-access (HA1) 2-cc coupler gain slopes.
clear from Figure 5 that some of the high-gain responses have very similar shapes to some of the low-gain responses. To facilitate specification of the required tone-control response variation, an additional clustering analysis of the responses with their gains normalized at 500 Hz was performed. The results for the three subpopulations, each grouped into 10 clusters, are shown in three charts in Figure 6.

The most striking difference between these clusters and those obtained using the Byrne and Tonisson procedure is the response slope below 1 kHz. The 250 to 500 Hz slope is now more steep and the 500 Hz to 1 kHz slope to less steep than before. While the Byrne-Tonisson procedure thus called for a relatively fixed, flat, low-frequency plateau, the Byrne-Dillon procedure calls for a relatively fixed, sloping response between 250 and 500 Hz. Note that for some individuals the slope will need to be less steep than in the higher octaves so that a simple, single slope electronic filter will still not suffice.

Turning now to BTE aid requirements: the standard 2-cc coupler hearing aid responses that hearing aid manufacturers provide for BTE aids are HA2 responses, so it is desirable to determine NAL’s requirements for BTE aids in terms of standard HA2 coupler responses. The correction figures given in Table 1 were therefore used to convert the HA1 gain, slope and frequency response requirements to HA2 requirements. The resulting cumulative frequency distributions of required HA2 2-cc coupler gain at the various frequencies, the cumulative frequency distributions of required HA2 slopes, and the 54 typical HA2 frequency responses are presented in Figures 7–9, respectively.

In 1984/85, approximately 2 percent of NAL hearing aid fittings were BL (body-level) hearing aids. These aids are fitted either to elderly clients who are unable to manage other types of aid or to clients who require very high gains. The elderly clients generally require low- and medium-gain aids. The clients who require very high gains generally have profound mixed-hearing losses. The gain, slope, and frequency response requirements for BL aids can be obtained from the HA2 2-cc coupler gain, slope, and frequency response requirements for BTE aids by use of the correction factors shown in Table 4.

There are some limitations inherent in the results presented that also merit discussion. The calculations com-
completed are based on the Byrne-Dillon fitting procedure
and on Lybarger’s rule for conductive overlays and may
therefore be affected by any shortcomings these proce-
dures might have. For instance, NAL clinical audiologists
regularly provide more gain to severely and profoundly
deaf children than is recommended either by the Byrne-
Tonisson or by the Byrne-Dillon procedures (10). This
fact was known to us at the time we completed the cal-
culations, and we considered whether we should allow
for it. We decided against doing so, for these reasons:
First, the rule which the audiologists appear to follow in
these fittings may not be correct. Research is currently
under way to establish an appropriate fitting procedure
for clients with severe to profound hearing loss and it
may turn out that the children require less gain than is
being provided at present. Second, even if this currently
used rule should prove to be correct, it may be that the
gain requirements of children with profound sensori-
neural deafness were accounted for in the cumulative
frequency distributions of required gain because individ-
uals with profound air-conduction hearing losses and sub-
stantial conductive overlays were included in the calcu-
lation of the gain requirements.

**MAXIMUM INTERNAL AID NOISE**

The internal-aid noise specification describes the max-
imum amount of internally generated noise that can be
emitted from a hearing aid before it becomes objection-
able to the hearing aid user. To compare the noise of an
aid with the specification described below, the equivalent
input noise of the aid has to be determined by subtracting
the gain of the aid (in dB) at each 1/3 octave center

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**Figure 6**
Ten clusters of open-access (HA1) 2-cc coupler frequency re-
sponses for each subpopulation, with gains at 500 Hz nor-
malized to 0 dB.

**Table 4**
Corrections for obtaining BL hearing aid
HA2 2-cc coupler gain and slope requirements
from HA2 2-cc coupler gain and slope requirements
for BTE hearing aids.

<table>
<thead>
<tr>
<th>Frequency, Hz</th>
<th>250</th>
<th>500</th>
<th>1K</th>
<th>2K</th>
<th>4K</th>
</tr>
</thead>
<tbody>
<tr>
<td>BTE to BL</td>
<td>-5</td>
<td>-7</td>
<td>0</td>
<td>+10</td>
<td>-1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Octave, Hz</th>
<th>250/500</th>
<th>500/1K</th>
<th>1K/2K</th>
<th>2K/4K</th>
</tr>
</thead>
<tbody>
<tr>
<td>BTE to BL</td>
<td>-2</td>
<td>+7</td>
<td>+10</td>
<td>-11</td>
</tr>
</tbody>
</table>

**Note:**
BL = body level
BTE = behind the ear
frequency from the output level of the noise (in dB SPL) measured in 1/3 octave bands.

**Basis of Noise Criterion**

The experiment used to derive the noise specification is described in detail in NAL Report No. 102 (5). Briefly, the specification reflects the signal-to-noise ratio (SNR) just acceptable to the majority of a panel of subjects while they were listening to continuous discourse. The derivation requires knowledge of the long-term average spectrum (LTAS) of speech; since the publication of NAL Report No. 102, additional measurements of LTAS have been performed. The results varied slightly from the previous ones, so a new LTAS based on 60 talkers has been determined by averaging the two sets of results. Consequently, the equivalent input noise level has been adjusted slightly, and the new specification is shown in Figure 10 and Table 5. (See page 52)

**Noise Criterion for High-Gain Aids**

In NAL Report No. 102, we stated that the noise criterion could be relaxed for high-gain hearing aids. This recommendation was based on the assumption that, in the case of severe hearing losses, internal noise outputs which met the criterion would be far from audible. This assumption is illustrated in Table 6, from which it can be seen that the output noise is more than 15 dB below threshold for HTL’s of 60 dB and greater. If we assume that there is no need for the noise to be more than about 15 dB below threshold, then we can allow the noise output level and the equivalent input noise level to increase for the higher HTL’s (as shown by the numbers in brackets),

![Figure 7](image-url)  
Figure 7  
Cumulative frequency distributions of required HA2 2-cc coupler gain.
given that the recommended gain is used. However, this relaxation does not apply in circumstances where significantly more than the recommended gain is used; it has recently been found that children with severe to profound sensorineural hearing losses are regularly fitted by NAL audiologists with considerably more than the recommended gain. The problem occurs when the gain provided to clients increases on a dB/dB basis with HTL for HTL's of 60 dB and greater (see Table 7), a strategy which is apparently used by the audiologists to ensure that a sufficient amount of the speech band at an overall level of 70 dB long-term RMS is heard. When this strategy is used, the equivalent input noise criterion cannot be relaxed. If it is, then the noise output level approaches and eventually exceeds threshold (as shown by the numbers in brackets in Table 7). It should also be noted that, even when the audiologist sets out to provide the recommended gain, some clients prefer to use as much as 15 dB more than the recommended gain. For these individuals, also, the equivalent input noise level cannot be allowed to increase. We are therefore obliged to reverse our previous decision and recommend that there be no relaxation of the equivalent input noise criterion.

**SUBDIVISION OF TOTAL RESPONSE REQUIREMENTS**

Response requirements can be divided into two categories: response shapes and absolute amount of gain and maximum output. Requirements for a family of aids are outlined in this way in the following two sections.

*Figure 9 (opposite page)*

Fifty-four typical HA2 2-cc coupler frequency responses.
Required Max. 2cc Coupler Gain (dB)

Frequency (Hz)
Figure 10
Maximum equivalent input noise (measured in 1/3 octave band levels) deemed to be acceptable when listening to a speech signal with a long-term RMS level of 65 dB SPL (curve), and equivalent input noise level of the normal ear (circles). [From Killion (8).]

Table 5
Maximum allowable 1/3 octave equivalent input noise levels.

<table>
<thead>
<tr>
<th>Frequency, Hz</th>
<th>I/p Noise, dB SPL</th>
<th>Frequency, Hz</th>
<th>I/p Noise, dB SPL</th>
<th>Frequency, Hz</th>
<th>I/p Noise, dB SPL</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>47.0</td>
<td>500</td>
<td>26.5</td>
<td>2,500</td>
<td>14.5</td>
</tr>
<tr>
<td>125</td>
<td>45.0</td>
<td>630</td>
<td>23.0</td>
<td>3,150</td>
<td>15.5</td>
</tr>
<tr>
<td>160</td>
<td>43.0</td>
<td>800</td>
<td>20.0</td>
<td>4,000</td>
<td>16.5</td>
</tr>
<tr>
<td>200</td>
<td>40.5</td>
<td>1,000</td>
<td>17.5</td>
<td>5,000</td>
<td>18.0</td>
</tr>
<tr>
<td>250</td>
<td>37.5</td>
<td>1,250</td>
<td>16.0</td>
<td>6,300</td>
<td>19.0</td>
</tr>
<tr>
<td>315</td>
<td>33.5</td>
<td>1,600</td>
<td>15.0</td>
<td>8,000</td>
<td>20.0</td>
</tr>
<tr>
<td>400</td>
<td>30.0</td>
<td>2,000</td>
<td>14.5</td>
<td>10,000</td>
<td>21.0</td>
</tr>
</tbody>
</table>

Table 6
Relationships at 1 kHz between HTL, equivalent input noise level, and sensation level of internal noise when recommended transmission gain is provided at all HTLs.

<table>
<thead>
<tr>
<th>HTL, dB</th>
<th>Threshold at Eardrum, dB SPL</th>
<th>Transm. Gain of Aid, dB</th>
<th>Equiv. Input Noise, dB SPL</th>
<th>Noise Output Level, dB SPL</th>
<th>Noise Sensation Level, dB</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>9</td>
<td>7.0</td>
<td>17.5</td>
<td>24.5</td>
<td>15.5</td>
</tr>
<tr>
<td>10</td>
<td>19</td>
<td>11.6</td>
<td>17.5</td>
<td>29.1</td>
<td>10.1</td>
</tr>
<tr>
<td>20</td>
<td>29</td>
<td>16.2</td>
<td>17.5</td>
<td>33.7</td>
<td>4.7</td>
</tr>
<tr>
<td>30</td>
<td>39</td>
<td>20.8</td>
<td>17.5</td>
<td>38.3</td>
<td>-0.7</td>
</tr>
<tr>
<td>40</td>
<td>49</td>
<td>25.4</td>
<td>17.5</td>
<td>42.9</td>
<td>-6.1</td>
</tr>
<tr>
<td>50</td>
<td>59</td>
<td>30.0</td>
<td>17.5</td>
<td>47.5</td>
<td>-11.5</td>
</tr>
<tr>
<td>60</td>
<td>69</td>
<td>34.6</td>
<td>17.5(19.4)</td>
<td>52.1(54)</td>
<td>-16.9(-15)</td>
</tr>
<tr>
<td>70</td>
<td>79</td>
<td>39.2</td>
<td>17.5(24.8)</td>
<td>56.7(64)</td>
<td>-22.3(-15)</td>
</tr>
<tr>
<td>80</td>
<td>89</td>
<td>43.8</td>
<td>17.5(30.2)</td>
<td>61.3(74)</td>
<td>-27.2(-15)</td>
</tr>
<tr>
<td>90</td>
<td>99</td>
<td>48.4</td>
<td>17.5(35.6)</td>
<td>65.9(84)</td>
<td>-33.1(-15)</td>
</tr>
<tr>
<td>100</td>
<td>109</td>
<td>53.0</td>
<td>17.5(41.0)</td>
<td>70.5(94)</td>
<td>-38.5(-15)</td>
</tr>
</tbody>
</table>

Frequency Response Requirements

The ideal response requirement, that of independent control of the response slope within each octave over which the aid is to be fitted, remains unchanged. As this ideal is still not technologically feasible in the immediate future, available space and power consumption in the aid must again be assigned to control over those frequency regions considered most important.

The lowest priority region for electronic response control is probably the 250 Hz to 500 Hz octave. First, the range of required slopes is less in this octave than in any other (see Figure 2). Second, at least half of all aids fitted are dominated by vent or earmold leak transmitted sound in this frequency region, so that electronic gain modifications would be ineffective or at best unpredictable. This second argument obviously does not apply to aids intended for those with substantial low-frequency losses.

The next lowest priority for control is the 4 kHz to 8 kHz octave, partly because it is usually difficult or impossible to obtain sufficient gain at 8 kHz and partly because speech cues above 4 kHz are less important than cues at lower frequencies (ANSI, S3.5–1969).

The octave from 2 kHz to 4 kHz receives the next lowest priority. Responses in this octave are amenable to control by earmold modification, although this makes aid fitting more expensive and time consuming than if electronic high-frequency tone control adjustment is available. A total response range of 22 dB/octave is required if 95 percent of NAL’s clients are to be exactly fitted in this octave. A range of 17 dB/octave can be achieved
acoustically, or 23 dB/octave if the more complex sound channel cavity molds (or earhooks) are included. A high-frequency (2 to 4 kHz) tone control can thus be a highly desirable but not essential option.

The two octaves with the highest priority, over which it is absolutely essential to have good electronic control of the frequency response, are the 500 Hz to 1 kHz and the 1 kHz to 2 kHz octaves. The range of response shapes required within these two octaves can be illustrated by the plot in Figure 11. If 95 percent of cases are to be fitted exactly within each octave, then any combination of the required range of slopes within each octave needs to be achieved. That is, the aid must be able to be configured to realize any point within the shaded area. The limits of this area have been determined from Figure 7 and so refer to slope as measured in an HA2 2-cc coupler. While it would be highly desirable to achieve this flexibility in a single aid with two independent tone controls, this does not seem technologically feasible at present. A more practical alternative is to have three models with different slopes in the 1 to 2 kHz octave, each model having a low-cut tone control with a knee point at, or slightly above, 1 kHz. These response shapes are shown in Figure 12, and if the variable tone control can be set at its two end points and two intermediate points, the obtainable response combinations are indicated by the circles in Figure 11. While a continuously variable control would allow all the intermediate slopes to be realized (horizontal lines in Figure 11), a switched control with a discrete number of rest positions is just as acceptable. (The latter is even preferable if it allows more precise selection of a response shape without the need to make confirming electroacoustic measurements.)

The complete response shape of each model can now be deduced. Below 500 Hz, all models have a fixed slope which should thus be the median required slope, 9 dB/octave above 250 Hz. Between 2 kHz and 4 kHz, if no electronic high-frequency tone control is included, the HA2 response should slope upward at 9 dB/octave. This

![Figure 11](image)

**Figure 11**
HA2 2-cc coupler response slope in 1 kHz to 2 kHz octave versus slope in 500 Hz to 1 kHz octave. Cross-hatched area: the required range of combinations.

<table>
<thead>
<tr>
<th>Table 7</th>
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<tr>
<td>Relationships at 1 kHz between HTL, equivalent input noise, level, and sensation level of internal noise when more than the recommended transmission gain is provided at higher HTLs.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>HTL (dB)</th>
<th>Threshold at Eardrum (dB SPL)</th>
<th>Transm. Gain of aid (dB)</th>
<th>Equiv. Input Noise (dB SPL)</th>
<th>Noise Output Level (dB SPL)</th>
<th>Noise Sensation Level (dB)</th>
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</thead>
<tbody>
<tr>
<td>0</td>
<td>9</td>
<td>7.0</td>
<td>17.5</td>
<td>24.5</td>
<td>15.5</td>
</tr>
<tr>
<td>10</td>
<td>19</td>
<td>11.6</td>
<td>17.5</td>
<td>29.1</td>
<td>10.1</td>
</tr>
<tr>
<td>20</td>
<td>29</td>
<td>16.2</td>
<td>17.5</td>
<td>33.7</td>
<td>4.7</td>
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<tr>
<td>30</td>
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<td>20.8</td>
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<td>38.3</td>
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</tr>
<tr>
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<td>42.9</td>
<td>-6.1</td>
</tr>
<tr>
<td>50</td>
<td>59</td>
<td>30.0</td>
<td>17.5</td>
<td>47.5</td>
<td>-11.5</td>
</tr>
<tr>
<td>60</td>
<td>69</td>
<td>36.0</td>
<td>17.5(19)</td>
<td>53.5(55)</td>
<td>-15.5(-15)</td>
</tr>
<tr>
<td>70</td>
<td>79</td>
<td>46.0</td>
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<td>63.5(71)</td>
<td>-15.5(-8)</td>
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<td>80</td>
<td>89</td>
<td>56.0</td>
<td>17.5(30)</td>
<td>73.5(86)</td>
<td>-15.5(-3)</td>
</tr>
<tr>
<td>90</td>
<td>99</td>
<td>66.0</td>
<td>17.5(36)</td>
<td>83.5(102)</td>
<td>-15.5(+3)</td>
</tr>
<tr>
<td>100</td>
<td>109</td>
<td>76.0</td>
<td>17.5(41)</td>
<td>93.5(117)</td>
<td>-15.5(+8)</td>
</tr>
</tbody>
</table>
enables HA1 2-cc coupler response slopes of −12 to 13 dB/octave to be obtained if the full range of earmold types is used. In addition, the simple, constant, inner-diameter tubing earmold then results in an HA1 2-cc coupler response slope of 2 dB/octave, which is close to the median (and most commonly required) slope of 1 dB/octave. The response shape in this octave is also influenced by the need to increase the gain at the normal ear canal resonance frequency to compensate for the loss of unaided gain at this frequency caused by the presence of the earmold. [This loss has already been allowed for at 2 kHz and 4 kHz (see Table 2), but the effect is greatest at frequencies between these two.] If a high-frequency tone control is included, then the HA2 2-cc coupler slopes from 2 to 4 kHz should be −1, 5, 11, and 17 dB/octave.

Above 4 kHz, the response should be equal to the median required slope of −8 dB/octave. The total response shape requirement for the three models is shown in Figure 13. In the absence of any data, the response slope below 250 Hz has been set to 0 dB/octave. In practice, the use of directional microphones with a response slope of 6 dB/octave will make the attainment of a slope of less than 6 dB/octave very difficult. A single fixed slope of 6 dB/octave for all frequencies below 500 Hz is considered a reasonable alternative. The three models A, B, and C will constitute approximately 24 percent, 56 percent, and 20 percent, respectively, of the total requirement within each power and gain range. The corresponding required response shapes for ITE and BL aids are shown in Figures 14 and 15. The attainment of these shapes in ITE and ITC aids is obviously a more difficult problem.

GAIN AND MAXIMUM OUTPUT

The considerations and requirements for different gain-maximum power output (MPO) combinations are essentially unchanged. Maximum output (or SSPL) requirements can be deduced on the assumption that the aid should not be capable of amplifying a sound to a level which exceeds a person’s loudness discomfort level. When MPO is set equal to loudness discomfort level (LDL) and maximum coupler gain is calculated from the Byrne-Dillon selection procedure, the resulting gain-MPO requirements are as shown in Figure 16. Each cross rep-

Figure 12
Required HA2 2-cc coupler response shapes for 3 models, each with 4 tone-control positions, in 500 Hz to 2 kHz frequency range.

![Figure 12](image_url)

Figure 13
Required HA2 2-cc coupler response shapes for 3 behind-the-ear hearing aid models (solid lines) and high-tone control variation (dotted lines) and low-tone control variation (dashed lines) required within each model. For clarity, low tone control variation is shown only for C model. Dashed-dotted line: a more easily achieved alternative for response below 500 Hz.
represents one client, with the basic data obtained as described in NAL Report No. 102. For clients with mild hearing losses but high LDL values, there is no necessity for MPO to be as high as LDL (in fact, there may be good reason, in the interests of safety, for MPO to be set well below LDL for these clients). The sloping line in the upper left of the figure limits the MPO to be no greater than the output level of speech peaks lying 12 dB above a 70 dB overall RMS level input speech signal.

The other lines comprising the six-sided figure similarly enclose the actual required range of combinations. This area can be adequately covered with six models, as shown in Figure 17. Each model has to cover a predicted gain range of up to 17 dB. As Byrne and Tonisson (4) have found that prediction of the overall gain level to be used by each subject is only possible to within ±15 dB, a volume control with a 35 dB usable range should be just sufficient to meet the needs of all clients without requiring an external gain trim control. (This recommendation has changed, largely because the range of gains required at 2 kHz is slightly less with the Byrne-Dillon procedure.)

In the nomenclature system shown in Figure 17, the first letter refers to the overall family, the second to the maximum output range, and the third to the gain range. It is expected that the XLL aids will be mainly ITE aids, although some BTE aids are also required in this category. The XML aids will be mainly BTE aids, with a small proportion of ITE aids. The XMH, XHL, and XHH aids will be almost entirely BTE aids. A very small number of BL aids will be required in all categories. Additionally, a very small number of super power—super gain BL aids will be required over and above the outlined categories. These aids, with peak gains of about 90 dB

Figure 14
Required HA1 2-cc coupler response shapes for in-the-ear hearing aids. For definition of symbols, see Key in Figure 13.

Figure 15
Required HA2 2-cc coupler response shapes for body-level hearing aids. For definition symbols, see Key in Figure 13.

Figure 16
Range of HA2 2-cc coupler gain-MPO combinations required at 2 kHz. Each cross: data from 1 aid wearer, but combinations considered desirable are limited by 6-sided figure.
Six models recommended to meet required range of gain-MPO combinations at 2 kHZ. Dashed lines: required range.

and powers of about 150 dB SPL, are required for clients who have profound hearing losses with substantial conductive components.

SUMMARY OF UPDATED REQUIREMENTS

The following summarizes the updated performance requirements for the family of hearing aids needed by NAL. Many of the previously published requirements have not changed and can be found in earlier publications (5,6).

Within each of the six gain-MPO combinations shown in Figure 17, the three response shapes shown in Figure 13 are required. A total of 18 hearing aid models are thus required, each with the following 4 fitter adjusted controls:

1) an MPO control providing a range of adjustment as shown in Figure 17;
2) an MPO shape control as discussed in sections 2.2.2 and 3.3.3 of NAL Report No. 102;
3) a low-tone cut control with a control range as shown in Figure 13;
4) a high-tone cut control with a control range as shown in Figure 13.

Internal noise in the hearing aids should be quantified by measuring the output noise in 1/3 octave bands (in dB) at the center frequency of each band. The acceptability of this equivalent input noise should be determined by comparing it with the criterion given in Figure 10 or Table 5 of this report. The criterion should be met for all combinations of tone control positions and with the volume control anywhere within 30 dB of maximum gain. Below 500 Hz, however, the criterion can be relaxed by 1 dB for every dB by which the aid gain falls below 0 dB gain. No relaxation of the criterion can be allowed for high-gain hearing aids.

REFERENCES

2. BYRNE D, DILLON H: The National Acoustic Laboratories' new procedure for selecting the gain and frequency response of a hearing aid. (Submitted for publication.)
3. BYRNE D, MURRAY N: Predictability of the required frequency response characteristic of a hearing aid from the pure tone audiogram. (Submitted for publication.)