Fitting a Wide Dynamic Range of Speech into a Narrow Dynamic Range of Hearing

Introduction

Sounds around us extend over a huge dynamic range—from below the normal threshold of hearing to above the normal level of discomfort or even pain. Most of the time, people with normal hearing can arrange things so that sounds are between their threshold and discomfort levels. This becomes difficult to achieve for people with hearing loss; the difficulty in achieving it increases with the size of the loss.

There is an obvious need for hearing aids to employ some form or forms of dynamic range compression to make as many sounds as possible audible and comfortable. This problem is commonly viewed in the following way, although it is not necessarily laid out in these discrete steps:

- Realize that speech is inaudible, or partly inaudible, at many frequencies (figure 1a).
- Apply linear amplification, with the amount of amplification at each frequency calculated to make speech as audible as possible, but without exceeding the person’s loudness discomfort level (figure 1b).
- Recognize that the full 30 dB range speech may still not be audible at some frequencies, so apply fast-acting, wide dynamic range compression with a compression ratio sufficient to fit all the speech range within the person’s dynamic range. This may require two or more channels of compression (figure 1c).
- Recognize that perfect audibility has been achieved only for the overall level of speech (e.g., 65 dB SPL) assumed in the calculation. Therefore, apply additional compression, which can be either fast acting or slow acting, sufficient to ensure that full audibility is achieved for a wide range of overall speech levels. If fast compression were to be used with a large number of channels, the audibility picture for the original speech level would then look like that shown in figure 1d.

Although pictures like figure 1d give the impression that all of the speech is now potentially understandable, this is far from the truth. This chapter will outline three
ways in which the mismatch between the dynamic range of sounds and the dynamic range of hearing can be examined. Some of the evidence reviewed suggests that we should sometimes aim for parts of the speech signal to be inaudible!

Here are the three broad approaches to the problems caused by a restricted dynamic range:

1. Reduce the dynamic range of the most intense parts of signals with compression limiting or peak clipping, as appropriate.
2. Reduce the dynamic range of a wider range of input signals with some combination of fast- and slow-acting wide dynamic range compression that has a low compression ratio. Important questions to consider include: How fast should the compression be? How wide is the dynamic range that should be compressed? To what degree should it be compressed?
3. Aim for a low sensation level in some situations, and accept the consequence that some of the speech signal will be inaudible.

I will outline these, then examine whether findings that appear to be true for adults should be varied for children.

Limiting the Maximum Output

Maximum output is limited in every hearing aid. The two questions faced by clinicians are these:

1. What type of limiting should be used—peak clipping, compression limiting, or a combination of the two?
2. How should the maximum output level be adjusted?

Let us first examine what happens when a speech signal reaches the maximum output of a hearing aid and what consequences it has for the aid wearer. The processes are different for compression limiters and peak clippers.

Compression Limiting

A compression limiter is an amplifier whose gain is reduced once the output of the amplifier exceeds a certain limit. When the compressor is limiting, every 1 dB increase in input level causes an additional 1 dB gain reduction, so that the output level remains unchanged. If the hearing aid has just one limiter that is shared by all the frequencies within a speech signal, limiting causes the gain to be reduced for all components in the signal.

Similarly, all components within the signal contribute to the level coming out of the limiter and hence jointly determine whether or not limiting is occurring.

Look at the amplified speech spectrum shown in figure 2. Will limiting occur in this case? At first sight it might seem that it should not because the speech “peaks” are below the saturated sound pressure level (SSPL) of the hearing aid. This is not correct, however, for two reasons. First, speech “peaks” that are usually shown 12, or 15 dB above the long-term rms levels of speech are close to the maximum short-term rms levels of the speech signal. The true peaks of the speech signal are 20 to 30 dB above the one-third octave long-term rms levels (Byrne et al. 1994). The shorter the attack time and the longer the release time, the more fully will the compressor react to these brief peaks. The second reason why the hearing aid will already be limiting originates in the way we measure SSPL. This is measured with a swept pure tone so that at any moment, all the power of the hearing aid is available to amplify just one frequency. When we put a broadband signal, such as speech, into the hearing aid, the available power has to be divided among all the speech components present. In other words, when the hearing aid limits, every component will be some amount below the pure-tone SSPL at the corresponding frequency. The implication of this is that limiting can occur even if there is an apparent gap between the maximum short-term rms levels and the SSPL curve.

What are the implications of compression limiting? They depend on the attack and release times:

- For release times less than 30 to 50 ms, some distortion of vowels is likely to be evident because the gain of the compressor varies within each pitch peri...

Figure 2. The amplified speech spectrum before and after limiting by a hearing aid with the maximum output curve shown. Limiting (i.e., saturation of the hearing aid) reduces the speech peaks by the amount shown by the thin lines.
od of the vowel. The problem is worse for male speech because the pitch period is approximately twice as long as for female speech.

- For release times longer than about 30 ms, gain may not increase quickly enough following an intense vowel. Any short, weak consonant following such vowels will be made less audible by the effect of the preceding vowel on the compressor.
- The gain for weak formants will be reduced if a strong formant is sufficiently intense to cause limiting. Strong and weak have to be interpreted in light of how the hearing aid tone controls affect the amplitude of each formant prior to limiting.

In short, an excessive amount of compression limiting should be avoided. A small amount of limiting is, however, almost imperceptible (Hawkins and Naidoo 1993). As a rule of thumb, if the calculated long-term rms levels are within about 5 dB of SSPL for several one-third octave bands, the effects of limiting will be easily audible to people with normal hearing and probably those with a mild or even moderate hearing loss. People with normal hearing will notice that limiting of this degree degrades speech quality if attack and release times are short enough for the limiter to be effective. It is likely that people with severe and profound loss will find the quality degradation less noticeable. For these people the effect of limiting on loudness is much more significant than its effect on quality (Storey et al. 1998).

The quality degradation can be minimized if the compression limiter includes a combination of fast-acting and slow-acting compression limiting (Roe et al. in preparation). In an experimental evaluation of speech quality with different limiting systems, addition of a slow-acting compression limiter to either a fast-acting limiter or a peak clipper was liked by many subjects and disliked by none.

### Peak Clipping

For peak clipping, the conclusions are similar, although the mechanisms are different and the effect of clipping on speech quality is more pronounced (Hawkins and Naidoo 1993; Storey et al. 1998). Figure 3 shows a complex signal (comprised of two pure tones) after it has been amplified and clipped. Although the large amplitude of the low-frequency tone has caused clipping to occur, the smaller, high-frequency tone has also been affected by the clipping. Its level will be reduced because the tone, in effect, disappears whenever clipping occurs. Just as with compression limiting:

- When signal components in one frequency band are clipped, all signal components that are present simultaneously are clipped.
- Wide band speech will be clipped even though individual components of the signal are at a level lower than the SSPL at that frequency.

The consequences of peak clipping are more audible. Clipping adds new frequencies to the signal, and this is heard as distortion, at least by people with mild and moderate loss, and by some people with severe and profound loss (Storey et al. 1998). Because saturation is more audible when it is caused by peak clipping than when it is caused by compression limiting, SSPL selection is less critical for compression limiting than for peak clipping. In particular, the minimum acceptable value of SSPL is lower for compression limiting (Storey et al. 1998).

There is, however, an advantage for peak clipping for some people. For a given technology (battery size, receiver size) hearing aids can produce a greater output level for peak clipping than for compression limiting. Figure 4 shows the differences in output level that were measured between two compression limiting hearing aids and two peak clipping hearing aids with otherwise similar technology (Dawson, Dillon, and Battaglia 1991). Although there appears to be only a 3 dB difference in the maximum outputs if one examines their performance with pure tones, there is a 10 dB difference if one considers the long-term rms level (Leq) at the output when a speech signal saturates the hearing aid. It is not surprising that people with hearing impairment sometimes describe aids with compression limiting as soft. The solution is to
increase the SSPL control, but when no further increase is possible, and there are no higher power models from which to choose, peak clipping is more likely to produce a successful outcome.

**Adjusting SSPL**

A threshold-based procedure (NAL-SSPL) for prescribing SSPL has been published (Dillon and Storey 1998). This procedure is intended for hearing aids that have a single limiter, or clipper. That includes all single-channel hearing aids and some multichannel aids. The SSPL is prescribed as the three-frequency average (500, 1000, and 2000 Hz) SSPL in a 2cc coupler. This can be converted to a real-ear saturation response (RESR) prescription by adding 6 dB. The RESR prescription is most useful for children and infants because of their small ear canal volumes, as discussed in several other chapters in this book. If the child’s individual three-frequency average real-ear-to-coupler difference (RECD) is subtracted from the prescribed RESR, the result is a 2cc coupler prescription of SSPL for that individual child.

For hearing aids that limit independently in each of a number of channels, a different version of the NAL-SSPL procedure has been published (Dillon 2000). In this case, maximum output is prescribed as a set of RESR values, as shown in table 1. To use it, one has to subtract a constant that depends on the number of independent channels in the hearing aid. This reduction is necessary for two reasons. First, the total loudness is greater than the loudness of any individual channel, so to avoid discomfort, each channel has to be limited to a lower value than would be necessary were it to be the only channel present. Second, as a signal is divided into more and more channels, less speech power falls into any one channel, thus decreasing the SSPL needed to avoid an excessive amount of limiting. The amount by which RESR should be reduced is shown in table 2. This frequency specific SSPL prescription procedure is built in to the NAL-NL1 prescription software for nonlinear hearing aids.

**Summary**

In summary, part of our goal of fitting a wide range of speech into a narrow range of hearing can be accomplished by allowing the top part of the speech range to partially saturate the hearing aid. This limiting will have no adverse consequences, provided the amount of limiting is not excessive. The likelihood of adverse consequences will be minimized if compression limiting, rather than peak clipping, is used wherever possible. Peak clipping is preferred for people with hearing impairment who need more loudness and sensation level than can be provided by

---

**Table 1.** Real-ear saturation response needed at each frequency to avoid excessive discomfort and limiting. Note that the values in table 2 must be subtracted for hearing aids that limit independently in more than one channel. Reprinted from Dillon (2000), by permission.

<table>
<thead>
<tr>
<th>Frequency</th>
<th>HTL250</th>
<th>500</th>
<th>1k</th>
<th>2k</th>
<th>4k</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>85</td>
<td>90</td>
<td>90</td>
<td>90</td>
<td>87</td>
</tr>
<tr>
<td>5</td>
<td>86</td>
<td>91</td>
<td>91</td>
<td>92</td>
<td>89</td>
</tr>
<tr>
<td>10</td>
<td>87</td>
<td>92</td>
<td>93</td>
<td>93</td>
<td>90</td>
</tr>
<tr>
<td>15</td>
<td>89</td>
<td>94</td>
<td>94</td>
<td>94</td>
<td>91</td>
</tr>
<tr>
<td>20</td>
<td>90</td>
<td>95</td>
<td>95</td>
<td>96</td>
<td>92</td>
</tr>
<tr>
<td>25</td>
<td>91</td>
<td>96</td>
<td>97</td>
<td>97</td>
<td>93</td>
</tr>
<tr>
<td>30</td>
<td>92</td>
<td>98</td>
<td>98</td>
<td>99</td>
<td>95</td>
</tr>
<tr>
<td>35</td>
<td>94</td>
<td>99</td>
<td>100</td>
<td>100</td>
<td>96</td>
</tr>
<tr>
<td>40</td>
<td>95</td>
<td>101</td>
<td>101</td>
<td>101</td>
<td>97</td>
</tr>
<tr>
<td>45</td>
<td>96</td>
<td>102</td>
<td>103</td>
<td>103</td>
<td>98</td>
</tr>
<tr>
<td>50</td>
<td>97</td>
<td>103</td>
<td>104</td>
<td>104</td>
<td>99</td>
</tr>
<tr>
<td>55</td>
<td>99</td>
<td>105</td>
<td>105</td>
<td>105</td>
<td>101</td>
</tr>
<tr>
<td>60</td>
<td>100</td>
<td>106</td>
<td>108</td>
<td>107</td>
<td>102</td>
</tr>
<tr>
<td>65</td>
<td>103</td>
<td>110</td>
<td>110</td>
<td>109</td>
<td>105</td>
</tr>
<tr>
<td>70</td>
<td>107</td>
<td>113</td>
<td>113</td>
<td>112</td>
<td>107</td>
</tr>
<tr>
<td>75</td>
<td>111</td>
<td>116</td>
<td>115</td>
<td>114</td>
<td>110</td>
</tr>
<tr>
<td>80</td>
<td>114</td>
<td>120</td>
<td>118</td>
<td>117</td>
<td>112</td>
</tr>
<tr>
<td>85</td>
<td>118</td>
<td>123</td>
<td>121</td>
<td>120</td>
<td>115</td>
</tr>
<tr>
<td>90</td>
<td>121</td>
<td>126</td>
<td>123</td>
<td>122</td>
<td>117</td>
</tr>
<tr>
<td>95</td>
<td>125</td>
<td>130</td>
<td>126</td>
<td>125</td>
<td>120</td>
</tr>
<tr>
<td>100</td>
<td>128</td>
<td>133</td>
<td>129</td>
<td>127</td>
<td>122</td>
</tr>
<tr>
<td>105</td>
<td>132</td>
<td>136</td>
<td>131</td>
<td>130</td>
<td>125</td>
</tr>
<tr>
<td>110</td>
<td>135</td>
<td>140</td>
<td>134</td>
<td>133</td>
<td>127</td>
</tr>
<tr>
<td>115</td>
<td>139</td>
<td>143</td>
<td>136</td>
<td>135</td>
<td>130</td>
</tr>
<tr>
<td>120</td>
<td>143</td>
<td>146</td>
<td>139</td>
<td>138</td>
<td>132</td>
</tr>
</tbody>
</table>
compression limiting. This choice is therefore much easier to make for an adult or verbal child than it is for a pre-verbal child.

Wide Dynamic Range Compression

In wide dynamic range compression (WDRC), the hearing aid gradually reduces gain as input level rises above a mid input level and gradually increases gain as input level decreases below a mid input level. We will first review the advantages and disadvantages of this type of compression relative to linear amplification and then review some evidence concerning adjustment of the compression parameters.

Advantages of WDRC

While compression limiting can prevent sounds from being so loud as to cause discomfort, a hearing aid that has limiting as its only form of compression will cause signals to be very loud very often. A more comfortable result can be obtained with WDRC. Figure 5 shows the input-output (i-o) curves for a linear hearing aid and a hearing aid with WDRC. The gains of the hearing aids have been adjusted so that for a 65 dB SPL input signal, both hearing aids have the same gain and output level, and we will further assume that this output level is in the middle of the aid wearer's comfortable range. As the input level rises above 65 dB SPL, the WDRC aid reduces its gain and so produces a more comfortable output signal than does the linear aid. Similarly, as the input level decreases below 65 dB SPL, the WDRC aid increases its gain and so produces a more audible signal than does the linear aid. These comfort and audibility advantages of the WDRC aid are thus most evident for very high and very low input levels, respectively. In fact, for typical input levels around 65 dB SPL, the WDRC aid has no advantages at all (Dillon 1996).

Disadvantages of WDRC

A compressor increases its gain whenever the input level decreases. Unfortunately, the compressor cannot tell the difference between a weaker sound that the aid wearer would like to hear and a weaker sound that the aid wearer would rather not hear. Consequently, if background noise has a level lower than speech, the compressor will amplify the noise (when it is present without the speech) more than it amplifies the speech. The extent to which this happens is reduced if the attack and release times are very long or if the hearing aid is able to recognize that the sound is indeed noise and instruct the compressor not to increase the gain. Because an aid wearer may consider a sound to be noise on one occasion, but a signal of some interest on another occasion, there is obviously a limit to how well the hearing aid can judge whether gain should be increased for soft sounds.

A second disadvantage is that whenever the gain of a hearing aid is increased, so is the potential for feedback oscillation. This does not represent a problem if the hearing aid has a sufficiently high feedback margin, but otherwise can result in the hearing aid whistling whenever the aid wearer is in a quiet environment.

Prescription of Compression Threshold

One solution to these disadvantages is to make the compressor active only for medium- and high-level signals, and to revert to linear amplification for low-level signals. That is, the compression threshold is set to a medium level (e.g., 60 dB SPL) rather than a low level (e.g., 40 dB SPL). Although this removes one of the advantages of WDRC, many patients prefer these medium compression thresholds to lower ones. This has been experimentally evaluated in two studies using single-
channel compression with a 2:1 compression ratio. In one study, 14 out of 16 subjects preferred a compression threshold around 66 dB SPL to one around 40 dB SPL (Barker and Dillon 1999). In the second study, 84 out of 140 subjects preferred a compression threshold of 66 dB SPL to one of 50 dB SPL. The lower compression threshold was preferred by 43 subjects, and 13 subjects had no preference (Dillon et al. 1998). In both studies, the subjects wore multichannel hearing aids, with one compression threshold in each memory, in their own environment for at least a month before deciding on which amplification option they preferred. It is possible that different results would have been obtained with multichannel compressors, but at the very least, we should not assume that a low-compression threshold would be better for patients than a medium-compression threshold. For adults and older children, it seems reasonable to start with a compression threshold between 50 and 60 dB SPL, and be prepared to vary this depending on their subjective reports. For younger children, where no useful reports can be obtained, it seems wisest to avoid very low or very high compression thresholds. This is discussed later in this chapter.

A complex issue is the effect of signal type on compression threshold. Compression thresholds are usually measured with narrow band signals, but we are more interested in the level of speech at which compression commences. These signals differ in bandwidth, spectral shape, and dynamic characteristics. Because speech is weighted to low frequencies, pure-tone compression thresholds have to be less for high-frequency sounds than for low-frequency sounds if all components of speech are to go into compression at the same overall level of speech. The filtering of speech into separate channels before compression causes an additional complexity in multichannel hearing aids. Pure-tone compression thresholds must therefore depend on the bandwidth of each channel if the aim is to achieve a certain compression threshold for speech. Yet another complexity is the effect of microphone location. We are interested in what happens when the aid is worn, but compression threshold is usually referred to measurements in a 2cc coupler, or ear simulator. In the NAL-NL1 prescription procedure, allowances are made for these effects, and the basic assumption is that all frequencies of speech should just go into compression when the overall level of speech is 52 dB SPL and the aid is being worn (Dillon 1999). The pure-tone compression thresholds that accomplish this vary with the type of hearing aid (BTE, CIC, etc.), the number of channels, and the crossover frequencies between channels. Pure-tone thresholds are, however, usually less than 50 dB SPL for high-frequency sounds, and between 55 and 60 dB SPL for low-frequency sounds.

**Prescription of Compression Ratio**

The compression ratio(s) selected for a WDRC hearing aid are a direct result of the rationale behind the use of compression and of the specific prescription procedure used. All nonlinear prescription procedures are to some extent based on the concept of normalizing loudness—that is, enabling the person with a hearing impairment to hear any sound at the same loudness at which it would be perceived by someone with normal hearing. Complete loudness normalization would result in a sound at threshold for a person with normal hearing to also be at threshold for every person with a hearing impairment. Similarly, a sound that just caused discomfort to a person with normal hearing would also just cause discomfort to a person with a hearing impairment.

Most procedures include some variation from loudness normalisation within either their philosophy or their implementation.

- Figure 6 does not attempt to make audible sounds that lie within 20 dB of normal threshold (Killion and Fikret-Pasa 1993). This decreases the compression ratio needed for low-level sounds, relative to that required for loudness normalization.
- International Hearing Aid Fitting Forum (IHAF) does not require a compression threshold any lower than that needed to amplify soft speech to normal loudness (Cox 1995). Amplification thus reverts to linear for low-level sounds.
- DSL(i/o) maps an extended dynamic range of inputs rather than a normal dynamic range into the dynamic range of the person with a hearing impairment (Cornelisse, Seewald, and Jamieson 1995).¹ This increases the compression ratio relative to loudness normalization. As with IHAF, amplification reverts to linear amplification below whatever compression threshold is chosen by the clinician.
- ScalAdapt decreases the gain applied to low-frequency signals, relative to that required for loudness normalization, to decrease the dominance of low-frequency sounds and upward spread of masking that would otherwise occur (Kiessling, Schubert, and Archut 1996).
All of these procedures apply their variation of loudness normalization to all narrow band sounds. The first three procedures mentioned should therefore approximately re-create the normal relationship between the loudness of low-frequency sounds and high-frequency sounds for both narrow band and complex sounds. That is, low-frequency sounds will be louder than high-frequency sounds.

The NAL-NL1 procedure applies loudness normalization to the overall loudness of sound, but balances loudness between the frequencies in such a way that the calculated speech intelligibility index is maximized. The effect is to prescribe lower compression ratios than are prescribed by the other procedures. There are other differences between the prescriptions (Byrne et al.; Dillon 2000 in press).

There is, as yet, little experimental evidence as to what compression ratios should be. We know it is possible to make them too high. If compression ratios are high enough to fit the full 30 dB dynamic range of speech into a narrower dynamic range of hearing, and if this is done with multiple narrow bands in the hearing aid, speech intelligibility suffers (De Gennaro 1986). It is not hard to see why this happens. In the extreme case of very high compression ratios and many narrow bands, all speech sounds are compressed into the same spectral shape, thus destroying spectral shape cues that help identify the place of articulation of speech sounds.

**Prescription of Attack and Release Times**

Hearing aids are now available with release times shorter than 30 ms and longer than 10 sec. There are also hearing aids with dual release times and hearing aids with adaptive release times. These two variable release times have similar effects in that a long release time dominates when there is a sustained high-level input to the hearing aid, but a short release time dominates when there is a brief high-level input. There is some evidence that the combination of fast and slow release times is beneficial, at least when used for limiting (Roe et al. in preparation). It seems likely that similar advantages would exist in WDRC compressors, but otherwise there is very little evidence as to how quickly compression should operate. While the attack and release times undoubtedly affect quality and amplification of background noise, and possibly intelligibility, it seems likely that the major advantages of compression are obtained no matter what attack and release times are used.

**Who Will Benefit?**

Although WDRC has mostly been used for adults with mild-to-moderate hearing loss, there are several other important groups who are likely to gain even more benefit. Because WDRC (however wide it might actually be) reduces dynamic range, it will provide most benefit to those who have no other way to reduce dynamic range and those who are most in need of dynamic range reduction:

- Infants and children who are too young to operate a volume control
- People who cannot operate a volume control because they have limited manual dexterity and/or because of the small size of a hearing aid
- People who have a severe or profound sensorineural hearing loss, and who therefore have a very narrow dynamic range of hearing

One recent study has investigated the benefits of single-channel compression with a 2:1 compression ratio, compared to linear amplification for people with severe and profound hearing loss (Barker, Dillon, and Newall submitted). Subjects preferred the 2:1 compression to linear amplification. A complication with these subjects is that a low compression threshold often cannot be achieved because of the influence of feedback. If compression threshold is reduced, with gain for mid-level sounds held constant, the gain for low-level sounds increases, and this makes feedback oscillation more likely. The practical outcome is that clinicians should use WDRC for patients with severe and profound hearing loss, but more than ever they have to take feedback into account when setting the compression threshold of the hearing aid. Hearing aids without an adjustable compression threshold might therefore not be suitable for these patients unless sufficient gain from mid-level sounds can be achieved.

**Keeping Sensation Level Low—Aiming for Partial Audibility**

If we cannot allow too much limiting to occur for intense sounds, and if we cannot compress sufficiently to make all speech audible, what is left? Surprisingly, the best option may be to leave inaudible the least intense parts of speech.

---

¹This statement is true of DSL (i/o) in its default settings. The user can select a normal rather than an extended input dynamic range in the advanced mode of operation.
To make speech audible for someone with a severe hearing loss, speech has to be amplified to a high SPL, even to achieve a low sensation level. Unfortunately, the ability of the ear to analyze speech diminishes as the absolute level of speech increases. The Speech Intelligibility Index (SII), previously known as the articulation index, is a method by which the intelligibility of speech can be predicted based on the amount of speech energy that is audible at each frequency. Even for application to people with normal hearing, the SII method contains a term called the level distortion factor (LDF). This multiplicative factor decreases once the overall level of speech increases above 73 dB SPL, as shown in figure 6.

For people with hearing impairment, there are additional difficulties, possibly caused by their reduced frequency and temporal resolution abilities. Whatever the reason, people with hearing impairment are less able than people with normal hearing to extract information from an audible signal. Furthermore, this deficit is most evident at high sensation levels. Indeed, when the peaks of speech are only a few dB above hearing threshold, people with hearing impairment may be just as able to extract information as people with normal hearing listening at the same sensation level. Figure 7 shows data for one subject from the experiment described by Ching, Dillon, and Byrne (1998). For this subject, there is no point in amplifying the maximum short-term rms levels more than about 18 dB above threshold; further increases in level contribute to loudness, but not to intelligibility.

At each frequency, it is a good idea not to increase loudness any more than is necessary for good intelligibility. The loudness “saved” may enable the sensation level to be further increased at some other frequency where perhaps the extra level contributes to intelligibility.

In summary, one should not assume that more audibility is always better than less audibility. Of course, the results upon which this statement is based were obtained...
with linearly amplified speech. We should thus be more specific and say that increasing the sensation level of the short-term rms levels does not always increase intelligibility. Holding the sensation level of the speech maxima constant, while increasing the audibility of lower level speech components, can be achieved with fast-acting wide dynamic range compression. As we saw earlier, this is beneficial, provided it is not done too much. Again, increasing audibility beyond a certain point (i.e., making the compression ratio too high) can cause intelligibility to decrease.

Special Considerations for Children?

Most of the direct evidence concerning what type of amplification works best has been obtained with adults. Is this applicable in general to children and in particular to infants who have not yet acquired language?

Differences in Ear Geometry

There is no doubt that infants have different-sized ears from adults, and that this causes higher SPLs to be generated in the real ear for a given coupler gain and maximum output. In other words, ear size and real-ear-to-coupler difference (RECD), in particular, have to be taken into account when a hearing aid is selected and adjusted on the basis of its coupler performance. This is covered in detail elsewhere in this book (Moodie, Sinclair, Fisk, and Seewald 2000). Let us make the question more explicit: Are the desired real-ear electroacoustic characteristics different for infants than for adults?

Differences in Speech Identification Ability

There is also no doubt that, given the same acoustic information, infants will not be able to extract as much speech information from the acoustic waveform as would an adult with knowledge of the language. Several examples are given by Nozza (2000) and Stelmachowicz (2000) in this book. Does this imply that infants should be given hearing aids that have a real-ear performance different from those that would be given to an adult with the same hearing loss? Not necessarily. We need to consider more closely the nature of the differences between infants and adults.

Signal-to-Noise Ratio

Infants will require a better signal-to-noise ratio (SNR) than adults if they are to perform as well as adults. (This assumes that the infants have sufficient linguistic and other skills to do the task at all.) Although all people with a hearing impairment will benefit from devices that improve SNR, it seems that there is a stronger imperative to use such devices for infants. Otherwise, there will be a range of listening situations in which adults will assume that understanding is possible, but in which the SNR will be too poor for an infant to identify speech sounds. The practical conclusion is that infants should be given remote transmission systems (e.g., FM systems) or directional microphones whenever it is possible and whenever noise or reverberation is likely to affect speech perception. The SNR advantage provided by remote transmission systems is substantial, but even the 5 dB advantage provided by good directional microphones is very worthwhile. A note of caution is necessary. Both devices work by suppressing the sensitivity to sounds coming from certain directions or places. The devices should not be worn if the infant or child needs to hear danger or warning sounds that come from unexpected directions or places in order to stay safe. In this regard, a switchable directional microphone (e.g., a dual microphone system) is excellent; directional and omnidirectional performance can then each be obtained when the advantages of each are required.

Signal Level

Infants with normal hearing require a higher level than adults in order to achieve the same intelligibility (Nozza 2000; Stelmachowicz 2000). The same is true of young children (Byrne 1983). Does this mean they should be given a higher gain? Possibly, but there are two caveats. First, the experimental evidence shows that for children with normal hearing, soft sounds should be amplified more than for adults in order for the children to get maximum intelligibility. We should certainly not assume that medium- or high-level sounds should also be amplified to a greater degree than is best for adults. Given what we know about the adverse effect that high sound pressure levels have on intelligibility for people with normal hearing, and the further limitation that hearing loss places on increasing sensation level, using additional gain for medium- and high-level signals may well have the opposite effect and decrease performance. This is an area urgently requiring further research for adults as well as for children. Second, even if additional amplification of medium- to high-level inputs (relative to those preferred by adults) did increase intelligibility for children, should this be done? Comfort is presumably just as important for children as it is for adults. Furthermore, chil-
Children face a lifetime of hearing aid use, so the risk of the hearing aid exacerbating their hearing loss by noise exposure is greater than it is for adults in general and for the elderly in particular. The risk of causing further loss is primarily determined by the initial degree of hearing loss, the input levels experienced, and the amount of gain provided to medium- and high-level input sounds (Macrae 1994). Avoidance of noise-induced hearing loss induced by the hearing aid is a strong motivation for using compression that gradually reduces the gain as input levels rise above the typical level of 65 or 70 dB SPL.

Ability to Manipulate a Volume Control

One way that infants differ from adults is in their ability to manipulate a volume control. Infants cannot do it all! This has two obvious consequences:

1. If sounds get too soft, infants cannot compensate by increasing the volume control. To avoid the possibility of this, infants should perhaps be given more gain than adults for soft sounds.
2. If sounds get too loud, infants cannot compensate by decreasing the volume control. To avoid the possibility of this, infants should perhaps be given less gain than adults for loud sounds.

These two deductions are speculative, but seem reasonable. If both are true, the inevitable consequence is that infants should be given a higher compression ratio than is optimal for adults. Of course, this same argument seems to be true for adults fitted with hearing aids that do not have a volume control. The difference is that if the adult considers loudness to be inappropriately low or high, he or she can pick up the phone and request an appointment to have the hearing aid adjusted.

Screaming Children

It is sometimes said that children have different expectations regarding how loud sounds should be. Children frequently scream and shout at each other, and parents often resort to a raised voice to obtain and maintain children’s attention. Although these observations may well be true, they cannot be used to justify different loudness goals for children compared to adults. The world of high sound pressure levels inhabited by a child does not disappear once the child puts on hearing aids. When a child is screamed at by another child, this causes a higher than normal input to the eardrum. Using higher than normal gain (in a linear aid) will expose the child to doubly high output levels from the hearing aid in noisy environments. This is much more likely to be harmful than beneficial.

Direct Experimental Evidence

It is difficult to compare these conclusions with direct experimental results on the gain and frequency response experimentally found to be best for children. The first complication is that all the experimental data relate to linear hearing aids, whereas this chapter contends that different answers will be found for weak than for intense signals. The second complication is that it is extraordinarily difficult to find out either what works best or what is preferred for very young children, but if any children require different amplification from adults, it is most likely to be the very young.

Three studies have directly or indirectly found that the gain and response shape preferred by children with hearing impairment is the same as that preferred by adults with the same pure-tone hearing loss (Byrne, Parkinson, Newall 1990; Ching, Newall, and Wigney 1997; Snik et al. 1995). Byrne and colleagues reached this conclusion by directly comparing the experimentally determined optimum amplification characteristics for adults to those for children. Ching and colleagues found that on average, the NAL-RP response neither under- nor over-predicted the children’s preferred gain or response slope. Snik et al. (1995) found that the NAL-RP prescription neither under- nor over-predicted the gain that children chose and that the response slope (up to 2 kHz) agreed closely with the response slope that the children’s clinicians considered to be best for the children.

By contrast, Snik and Hombergen (1993) found that the gain used by older children and the gain considered by clinicians to be optimal for younger children was 7 dB higher than that used by adults.

Conclusions

Although this chapter has offered some recommendations for fitting hearing aids, we do not know how critical it is to select a specific set of compression parameters. When hearing aids with different types of

²How much should the compression ratio be increased? Suppose we wished infants to have 5 dB more gain for a 50 dB input, and 5 dB less gain for a 90 dB input, than we would prescribe for an adult with the same hearing loss. A few calculations show that this is approximately the same as squaring the compression ratio that we would use for an adult.
compression have been experimentally compared, the usual finding is that some subjects prefer each type of hearing aid compared! That is, despite the growing number of procedures for prescribing hearing aids, we do not know what is best for adults, let alone for children. Given our uncertainty over what is best, the clinician should not be too concerned if the performance prescribed by any selection procedure cannot be accurately obtained with any particular hearing aid.

Our studies have, however, convinced us of the importance of three aspects of the use of compression in hearing aids.

1. In the absence of WDRC, compression limiting will give a much cleaner sound than peak clipping (Storey et al. 1998). (The advantage is minimal if the hearing aid includes WDRC and has a compression ratio high enough that the hearing aid rarely limits.)

2. The use of WDRC, with any compression threshold less than about 70 dB SPL, will give comfort advantages in noisy places for most hearing aid wearers (Barker and Dillon 1999; Dillon et al. 1998; Ridgway 1998).

3. There is no point in presenting speech at high sensation levels in an attempt to achieve high intelligibility scores (Ching, Dillon, and Byrne 1998). Wide dynamic range compression is the key weapon in preventing excessively high sensation level and loudness without requiring the aid wearer to constantly operate the volume control.

Although there is no direct evidence, using compression must decrease the need for a volume control, and because infants are unable to use a volume control, compression should be even more valuable for infants and children than it is for adults.

Acknowledgments

The support of the Cooperative Research Centre for Cochlear Implant, Speech and Hearing Research is gratefully acknowledged.

References


Barker, C., Dillon, H. and Newall, P. Submitted. Fitting low ratio compression to people with severe and profound hearing losses.

Byrne, D., Dillon, H., Katsch, R., Ching, T., and Keidser, G. Submitted. The NAL-NL1 procedure for fitting non-linear hearing aids: characteristics and comparisons with other procedures.


Hawkins, D., and Naidoo, S. 1993. Comparison of sound quality and clarity with asymmetrical peak clipping and


Roe, I., Dillon, H., Byrne, D., and Baechler, H. In preparation. An experimental evaluation of different methods of limiting the maximum output of hearing aids.


