Variables Affecting the Use of Prescriptive Formulae to Fit Modern Nonlinear Hearing Aids

Francis K. Kuk*
Carl Ludvigsen

Abstract

It is routine for audiologists to fit nonlinear hearing aids by using one of several current prescriptive formulae. While such an approach might result in acceptable fittings for single-channel analog compression hearing aids, its direct application to fitting current multichannel compression hearing aids may result in less than an optimal fit. In this paper, the effects of filter bandwidth, number of channels, detector type, compression threshold, attack and release times, and distortion on the final output of a nonlinear compression hearing aid are discussed. The subjective results of such effects and its implications on our clinical practice will be explored as well.

Key Words: Attack and release times, compression thresholds, detectors, distortion, expansion processing, filter bandwidth, filter channels, prescriptive formulae

Abbreviations: CR = compression ratio, CT = compression threshold, DSL (i/o) = Desired Sensation Level (input/output), FFT = Fast Fourier Transform, HA = hearing aid, IHAFF = Independent Hearing Aid Fitting Forum, I/O = input/output, LGOB = Loudness Growth by Octave Band, RMS = root mean square, UCL = uncomfortable listening level, WDRC = wide dynamic range compression

Many clinicians use prescriptive formulae to estimate the optimal electroacoustic settings on linear and nonlinear hearing aids (HAs). Typically, the input data to the fitting formula include audiologic data such as thresholds at different frequencies (e.g., Fig. 6, Killion and Fikret-Pasa, 1993). Other input measures may include suprathreshold data such as uncomfortable listening level (UCL) (e.g., Desired Sensation Level [DSL(i/o)], Cornelisse et al, 1994) or loudness growth information at discrete frequencies obtained under conventional or insert earphones (e.g., Loudness Growth by Octave Bands [LGOB], Allen et al, 1990; Independent Hearing Aid Fitting Forum [IHAFF], Valente and Van Vliet, 1997). The output of the nonlinear fitting formula may be target insertion gain as a function of frequency at different input levels (e.g., low, medium, and high) or input/output (I/O) curves and compression ratios (CRs) for a number of frequency channels. The clinician adjusts the settings on the HAs to meet the prescriptive target. Alternatively, some programmable and digital HAs may also self-adjust to meet such prescription. Furthermore, real-ear/coupler measures can be used to verify if the prescribed target (gain/output) is achieved.

An implicit assumption behind all prescriptive formulae is that they are applicable to any brand of HAs. Furthermore, if the measured output of the HAs matches the prescribed target, one would expect that optimal performance in accordance to the fitting rationale could be guaranteed in real-life listening situations. In reality, few would agree that that is the case. Some HAs that meet a prescriptive target may be unacceptable, whereas others that deviate significantly from a target may be satisfactory. Such deviation can be partially explained by a difference in individual preference. However,
physical differences among nonlinear HAs may also contribute to such observation. In this paper, several factors that may affect the output and performance of nonlinear HAs beyond what current fitting algorithms have considered will be identified. These factors include the number of channels in the HA, their bandwidths, the type of detector used, the compression threshold (CT), the time constants, and the distortion characteristics of the HA. The authors believe that these factors can act in isolation or in combination to affect the final output of the HAs. Hence, it is important to consider them when applying a prescriptive formula to fit a specific nonlinear HA. This is especially true for some digital HAs because of the varied and complex signal-processing strategies involved. It must be pointed out that the following discussion is not exclusive of digital nonlinear HAs or a specific brand of HAs. Rather, the considerations would apply to any nonlinear multichannel (digital or analog) HAs.

**NUMBER OF FILTER CHANNELS AND FILTER BANDWIDTH**

Current digital HAs and many programmable HAs are multichannel devices. Depending on the design philosophy, these HAs differ in the number of channels and the bandwidth of each channel. The output represents the summed output from all of the contributing channels. The output power in each channel to a complex input signal such as speech, music, etc., is dependent not only on the gain within each channel but also on the bandwidth of the channel. This suggests that two nonlinear HAs with equal gain for sinusoids may provide different output to the same complex stimulus if they differ in the number of frequency channels.

Figure 1 illustrates the output difference between two hypothetical multichannel nonlinear HAs that differ in their bandwidths (and the number of channels). Both use a CR of 2:1. Hearing aid 1 uses a Fast Fourier Transform (FFT) based filter algorithm and has a bandwidth of 100 Hz. Hearing aid 2 uses a minimum-phase filter algorithm and has a bandwidth of 1000 Hz. Both are presented with a white noise that has a spectrum density level of 40 dB SPL/Hz. For simplicity, only consider the frequencies between 3000 Hz and 4000 Hz (i.e., 1000-Hz range). For HA 1, the total input level in each channel is the spectrum level integrated across all frequencies in that channel or 60 dB (i.e., 40 + 10*log [100 Hz]). At this input level, the I/O curve shown in Figure 1 would predict an output of 95 dB SPL from each channel. Because there are 10 channels for the considered frequency range of 1000 Hz (the bandwidth is 100 Hz), the overall output from the HA for the 3000-Hz to 4000-Hz region will be the sum of all 10 100-Hz channels. Thus, the sum is 105 dB SPL (i.e., 95 + 10*log [10]).

For HA 2, the total intensity level within the channel that covers the 3000-Hz to 4000-Hz region is 70 dB SPL (i.e., 40 + 10*log [1000]). At this input level, the I/O curve in Figure 1 would suggest an output of 100 dB SPL. This is 5 dB less than the case with the narrower bandwidth (but more channels). In other words, the narrower the bandwidth (and the more frequency channels), the higher the output of the compression HA in response to a complex signal.

The magnitude of the output difference varies with the CR. For example, Figure 2 shows that if one maintains the gain at the 60 dB SPL input level but changes the CR to 4:1 (dark line), (thus, the gain for the very soft sound, say, 20 dB SPL, is increased) the output from each channel of HA 1 would be 95 dB SPL. This results in a total output of 105 dB SPL (95 dB + 10*log [10]) from HA 1. On the other hand, output from HA 2 will be 97.5 dB SPL (97.5 dB SPL + 10*log [1]). This is 7.5 dB less than HA 1. In other words, the output difference increases as the CR increases.

Figure 2 also shows the output from these two HAs if they were linear (dotted line). Assuming that the gain in each channel is 30 dB, the output from each channel of HA 1 would be 90 dB SPL at the 60 dB SPL input level (40 dB +
have not considered the effect of bandwidth in their gain specification (i.e., most assume single-channel or linear processing), gain corrections for bandwidth effects must be made for nonlinear multichannel HAs when applying these formulae. Furthermore, corrections may also be necessary if the device allows variable bandwidths with adjustment of the crossover frequencies. Otherwise, even when a target is matched, the HA with more channels but narrower bandwidths may sound louder than the one with fewer channels and broader bandwidths. Differences in the order of 3 to 5 dB from the effect of filter bandwidth may be expected in real life.

## DETECTOR TYPE

In a compression HA, the instantaneous gain is typically determined by continuously estimating the short-term input level. To obtain such an estimate, the input signal is fed through a detector. Typically, analog HAs use a simple rectifier as a detector and the peak or the average amplitude of the input signal is used to control the gain. There are many more options in modern HAs. One example may be a true root-mean-square (rms) detector, which changes the gain of the HA according to the rms level of the input signal. Others may include a detector that adjusts gain according to the statistical properties of the input signal. In this way, the gain adjustment strategy takes into account the type of input signal (e.g., speech or noise).

The use of different detectors could also result in different outputs. For example, Figure 3 shows a sinusoid and a complex signal that has the same rms level. If a rms detector were used to regulate gain, both signals would likely activate the detector mechanism at the same time and to the same degree. On the other hand, the peak level of the sinusoid is 3.4 dB lower than that of the complex signal shown in Figure 3. This means that the complex signal will activate the detector sooner than the sinusoid if a peak detector is used instead. Consequently, the CT shown on the I/O curve, because it is derived from a sinusoid, will be effectively lower when a complex stimulus such as speech is used. This is shown in Figure 4. From this I/O curve, it follows that for a complex signal, a compression HA that uses a rms detector will sound louder than one using a peak detector if both match a prescriptive target and have the same static I/O curve.
COMPRESSION THRESHOLDS

The lowest level at which a compressor is activated is commonly known as the CT or knee-point. In current input-compression type HAs, such thresholds can vary from 40 dB SPL to 65 dB SPL. In one digital HA, this threshold can be as low as 20 dB SPL in some frequency regions.

The effect of the CT can be significant on the output of a compression HA. Figure 5 shows a compression HA with two CTs, but the same CR above the threshold. When the CT is at 60 dB SPL, output of the HA at an input of 50 dB SPL is 75 dB SPL (or 25-dB gain). However, as the CT is decreased to 50 dB SPL, output at the 50 dB SPL input becomes 80 dB SPL (or a gain of 30 dB). There is no difference in the gain or output above the 60 dB SPL input. Consequently, two HAs may both meet the same gain targets for conversational (65 dB SPL) and loud (80 dB SPL) inputs but differ in their output for low (below 60 dB SPL) input sounds. Subjectively, the one with the lower CT may yield improved audibility for soft sounds, resulting in higher intelligibility for low-input speech (Valente et al, 1998). Intelligibility for conversational speech will be similar to the HA with the higher CT. On the other hand, the wearer may perceive more ambient or environmental noise with the lower CT. Dillon et al (1998) showed that adult hearing-impaired persons preferred a higher CT than a lower CT in single-channel fast-acting compression HAs. In addition, the HA with a low CT may result in feedback more easily.

One may argue that the audibility advantage of a low CT may be achieved simply by increasing the overall gain of the HA that has the higher CT (or turn up its volume control). This is shown as the dotted I/O curve in Figure 5, which, despite the higher CT at 60 dB SPL, has the same output below 50 dB SPL as the HA with the CT at 50 dB SPL. However, it should also be clear that the output above an input of 50 dB SPL, including conversational and loud speech, is also higher.

The use of digital signal processing in HAs allows a way to minimize the negative effect of the extra gain below the CT. Linear processing below the CT, an approach used by almost all of today’s analog and programmable HAs, provides the same gain for all sounds below the CT. This increases the audibility of both wanted and unwanted sounds. On the other hand, an expansion circuit below the CT can provide the desired amplification to sounds at input levels around the CT but less to sounds below the CT. The assumption is that sounds around the CT are desirable, whereas those below the CT may not be as meaningful. Subjectively, a person with normal low-frequency hearing may object more to circuit and ambient noises from a compression HA that uses linear processing below the CT than one that uses expansion processing. The difference in output between linear and expansion processing below the CT is shown in Figure 6.

ATTACK AND RELEASE TIMES

The response time of a compression HA is indicated by its attack and release times. Earlier compression HAs typically employed single fixed attack and release times. Adaptive
release time in which the release time is dependent on the duration and intensity of the input signal gained popularity in the late 1980s and is used widely today. Nowadays, some digital HAs use multiple attack and release times that reflect not only the intensity and duration characteristics of the recent inputs but also the history of the inputs entering the HA.

The attack and release times reflect the amount of time that the HA takes to reach a steady-state output. Intuitively, a short attack time means that following a sudden increase in input level, the compressed signal stabilizes quickly to its steady-state output, as reflected on the I/O curve. By contrast, a long attack time (typically longer than 15–20 msec) means that the HA takes longer to stabilize to the steady, reduced-gain state. In other words, immediately after the input level increases, there is less gain reduction (i.e., more output) than is indicated on the I/O curve. Along the same line, a short release time means that following a sudden decrease in input level, the HA returns to the predetermined static gain level quickly. A long release time (typically longer than 1 to 2 sec) means that the HA takes longer to return to the static high-gain level. In other words, less gain is available for sounds occurring after a loud sound (i.e., less output) than is indicated on the I/O curve. Figure 7 shows the output of a digital compression HA that uses a long attack/release time as a function of input levels. The static or long-term I/O curve that is typically reported on the specification sheet is indicated in solid line. This is also the curve that is obtained when a short attack/release time is used. The dotted lines are the dynamic or short-term I/O curves for a 30-dB range of input within the compression region. Note that the dynamic I/O curve has a slope of 1:1 (or linear processing), whereas the static I/O curve has a slope of 2:1 (or nonlinear processing).

The ratio between the attack and release times is a major determinant of the output level when speech or other complex signals are the input. This is illustrated by the two dotted I/O curves in Figure 7. When the attack and release times are similar, output modification made to the static I/O curve would be similar for input levels above and below a particular input level. The consequence is a dynamic I/O curve that has a slope of 1:1 and with an average output similar to that shown on the static I/O curve (labeled as dynamic 1). On the other hand, if the attack time is substantially shorter than the release time, the average output would be lower than that shown on the static I/O curve, despite a similar slope of 1:1. This is indicated as “dynamic 2” in Figure 7. For a quantitative explanation of how the I/O curves are generated, see Kuk (1998).

One would conclude from the I/O curve in Figure 7 that the real-world dynamic output of a compression HA would differ greatly from its predicted static I/O curve unless very short attack and release times are used in the circuit. It would seem important that any

Figure 6 Differences in output between linear processing and expansion processing below the compression threshold.

Figure 7 Differences in the static (solid) and dynamic (dotted) I/O curves when different attack/release times are used. For a nonstationary input like speech, the static curve will result only if short attack/release times are used. The curve “dynamic 1” results when equal attack and release times are used; “dynamic 2” results when the attack time is much shorter than the release time.
Prescriptive formulae would also consider the effect of the attack and release times in its gain formulation. Otherwise, two compression HAs using different response times would sound very different to the wearer even if both match the same prescriptive target. Unfortunately, none of the prescriptive formulae have considered that in their gain formulation.

The effect of the release time can be examined in the output waveform. Figure 8 shows the output of a three-channel wide dynamic range compression (WDRC) HA when the input is a 30-second speech sample in a moderate party noise background. The upper tracing is obtained with a release time exceeding 1 sec and the lower tracing with a release time of 30 msec. A fixed attack time of 10 msec is used for both release times. One notes that the long release time results in a waveform that is more clearly demarcated. The intensity difference between the “peaks” and the “valleys” (noise floor, pauses between speech) remains distinct. Subjectively, wearers report less interference with the background noise and that the speech is more pleasant.

The long-term amplitude spectra of these two speech samples would also be different. Figure 9 shows that the short release time reduces the spectral peak-to-valley differences and the overall level around the 1000-Hz and 6000-Hz regions. The longer release time maintains more of the spectral peak-to-valley amplitude difference and provides a higher long-term rms output in the mid and high frequencies. The longer release time is rated generally higher in regard to its perceived sound quality (Neuman et al, 1995). Despite such dramatic perceptual and spectral differences, clinical studies (e.g., Lynn and Carhart, 1963; Schweitzer and Causey, 1977) failed to demonstrate any significant effects on intelligibility with various release times.

The total effect of the above-mentioned parameters on the output of a compression HA raises several questions regarding our current practice for fitting nonlinear HAs. First, one may question the rationale of determining individual loudness growth function for the purpose of setting compression parameters. Second, one may question the value of strict adherence to matching prescriptive targets.

**Questionable Rationale for Individual Loudness Growth Measure**

The purpose of individual loudness growth measure is to determine gain for various inputs so that an appropriate CR can be determined. The previous discussion suggests that such CR (or the recommended gain) will not be achieved unless the HA uses short attack and release times. Otherwise, the real-world or effective CR becomes lower than the static CR that is predicted from individual loudness growth measurement. Several researchers (e.g., Stone and...
Moore, 1992; Verschuure et al, 1996) had shown that the effective CR of a HA decreases (i.e., becomes more linear) as the release time increases. Unfortunately, because of the negative perception associated with a short release time (e.g., pumping, breathy, noisy, etc.), most of the current WDRC HAs use release times that are longer than that required to achieve the static CR. This means that the real-world CR of most WDRC HAs is lower than that indicated on the static I/O curve. Additionally, loudness summation across frequencies, which has been shown to differ between normal-hearing and hearing-impaired individuals (Launer, 1995), is often not considered thoroughly in most loudness scaling procedures. In other words, the effort spent in individual loudness scaling may not result in “normal loudness” in the real world. Indeed, in a recent article, Byrne (1996) questioned the utility of individual loudness scaling for the fitting of nonlinear HAs. The authors feel that if the goal for a WDRC HA is only to achieve more gain for soft sounds and less gain for loud sounds, such can be more efficiently achieved with predictive measures (Pascoe, 1988; Hellman and Meiselman, 1990). The predictive accuracy can be further improved with in-situ threshold measurement (Ludvigsen and Topholm, 1997) and integration of specific knowledge of the characteristics of the particular HA into the gain formula (e.g., filter bandwidth, release time, etc.). Individual differences in loudness functions or preferred listening levels may be compensated in subsequent finetuning.

Target Matching

With speech input, it is necessary to use short attack and release times (attack time and release times less than 20–30 msec) if one were to achieve the output that is indicated on the static I/O curve from a compression HA. This means that even if one disregards all of the aforementioned variables like filter bandwidth, CT, etc., nonlinear prescriptive formulae can only be used with fast-acting WDRC HAs. Such formulae cannot be used for nonlinear HAs using slow-acting compression, adaptive compression, or those with waveform-dependent release time. Matching the output of these HAs to a target that has not considered such release time effect may lead to spurious outcome in the real world. Indeed, Lechtenberg (1998) noted that satisfied wearers of a digital HA reported excessive loudness when the device was adjusted to match the DSL (i/o) target.

A related precaution is the choice of attack and release time and fitting formulae in some programmable and digital HAs. Because the fitting formulae are based on short attack and release times, the choice of a longer attack/release time to be used with a prescriptive fitting target may require corrections to the fitting targets to avoid spurious results.

DISTORTION PROPERTIES

Distortion perceived at the output of a HA is the resultant distortion occurring at its various stages: microphone, preamplifier, filters, power amplifier, and receiver. In the 1970s and 1980s, most HAs used class A amplifiers or simple push-pull amplifiers, often with peak clipping as output control. These types of amplifiers are likely to generate distortion products at moderate and high input levels. In recent years, the introduction of digital technology led to the development of new amplifiers (e.g., Digital Output Drives and Class D amplifiers) that minimize such distortion.

Several authors (Kuk, 1996; Agnew, 1998) have summarized the effect of distortion on wearer satisfaction. Briefly, it has been shown that distortion negatively affects sound quality judgment, speech intelligibility, and even the preference between monaural and binaural fittings (Naidoo and Hawkins, 1997). Furthermore, distortion was used to account for the lower loudness discomfort level (LDL) measured through a HA than headphones (Fortune et al, 1991). These effects would suggest that two HAs could both match a prescriptive target equally well but the wearer might prefer less gain in the HA that has higher distortion than one with lower distortion.

CONCLUSION

Prescriptive fitting formulae have made significant contributions to the fitting of HAs. Although their use on single-channel, fast-acting compression HAs may be acceptable, their use on current (and future) HAs with more complex signal processing may need to be modified to reflect the component characteristics of the specific HA. Specifically, the number of channels (and their bandwidths), detector characteristics, and time response characteristics of the HA must be considered so that proper corrections can be made to the targets for optimal response. Furthermore, such targets may need to be revisited to reflect the advancement in technology. In
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a sense, unless all HA manufacturers follow the same design philosophy and choose the same components in their HAs, the use of generic prescriptive formulae to fit all modern HAs may be problematic. A possible scenario in the future is that HA manufacturers would develop their own HA specific fitting approach based on their knowledge of the unique design of their HA. This would involve significant research effort on the part of the manufacturers. This would also mean, as a clinician, that one should follow specific verification guidelines from the manufacturers to avoid misinterpretation of the measurement results. If one were to match the output of a HA to a general-purpose prescriptive target using conventional verification technique, one must validate with additional subjective measures like sound quality judgment to ensure that the final settings are indeed appropriate. As indicated earlier, simply matching a target does not guarantee a successful fitting.

REFERENCES


