

The 3 Types Of Sensorineural Hearing Loss: Loudness And Intelligibility Considerations

By MEAD C. KILLION & SELDA FIKRET-PASA

We differentiate three separate types of sensorineural hearing losses: Type I—those exhibiting normal or near-normal loudness sensations for all sufficiently intense sounds (complete recruitment); Type II—those exhibiting a loudness growth function that levels off below the normal-loudness curve but doesn't reach it (partial recruitment); and Type III—those exhibiting not only reduced loudness for high-intensity sounds and a reduced dynamic range of hearing, but also a severely reduced dynamic range for intelligibility; the latter requires operation near loudness discomfort for adequate intelligibility in difficult situations. Each of these three types requires a different method of hearing aid processing.

Type I and Type II losses are characterized by their loudness growth functions. Type III losses may or may not have abnormal loudness growth functions (although they typically do); they are characterized by their intelligibility-growth functions, which show that the individual must operate his or her hearing aids near discomfort levels in order to understand speech in difficult situations.

TYPE I HEARING LOSS

Figure 1 shows the loudness growth curve for a Type I sensorineural loss. A loss of 40 dB in sensitivity at threshold is illustrated; a mild-moderate sensitivity loss similar to this will typically be accompanied by the loudness response illustrated in Figure 1, with normal loud-

ness sensation or *complete recruitment* for the higher intensity sounds. Other aspects of hearing—e.g., frequency resolution, loudness resolution, ability to understand speech in noise, ability to perform in a musical group—will also be normal or near normal at the higher intensities.^{1,2} In short, the only real problem for a person with a Type I loss is a loss of sensitivity for quiet sounds; he or she often has no important loss of *anything* for loud sounds.

Gain

What gain should we prescribe for quiet sounds for this person? Our first reaction might be to provide 40 dB of gain. After all, the average person with normal hearing can hear a 0-dB HL tone. But the 40 dB(A)-45 dB(A) background noise level in most residences and offices produces a masking noise that prevents even a normal-hearing person from hearing tones in the sound field below 20 dB HL to 25 dB HL.³ Providing 40 dB of gain to the person in our example would be giving a fair amount of "empty gain." Just as with the normal-hearing person, the impaired individual's thresholds in a 40-dB(A) to 45-dB(A) noise level would be masked thresholds. In that environment, he or she couldn't detect sounds quieter than 20 dB HL to 25 dB HL any more than a normal-hearing person could, regardless of how much gain is provided; more gain just makes the background noise louder. Thus, a more reasonable answer to "how much gain?" would be about 20 dB, perhaps 25 dB at most to cover quiet conditions.*

For intense sounds—above 85 dB SPL—the answer to the "How much gain?" question is "none." As illustrated in Figure 1, an individual with Type I hearing loss has normal loudness for sounds above 85 dB SPL and needs no gain for such sounds. At the same time, there is no reason to give that individual a *loss* of hearing for intense sounds, as some compression-limiting and curvilinear-compression hearing aids do. Why shouldn't the fortissimo passages *sound* extremely loud? The musician's are blowing their heads off to achieve that result! (We refer here to events where the *musicians* make the sound, rather than 5000-watt amplifiers. We thus hasten to exclude rock and pop concerts, at which hearing protection is always a good idea.) This is not an argument against compression limiting, a type of circuit operation that is badly needed for Type III losses, only an argument against the *misuse* of compression limiting.

The question that remains is: "What gain should be used in the middle, for moderate-level sounds?" Taking conversational speech at typically 65-dB SPL (50-dB HL) as a reasonable benchmark, we see from Figure 1 that approximately 15 dB of gain is required to increase the 50-dB HL input—which produces a 50-dB perceived loudness for a normal ear—to the 65-dB HL presentation level that produces a 50-dB perceived loudness for this impaired ear.

Processing

Figure 2 shows both the unaided loudness function of a Type I loss, and the

Mead C. Killion, PhD is President of *Etymotic Research* and Adjunct Professor of Audiology, Northwestern University. **Selda Fikret-Pasa, PhD** is in the Department of Ear, Nose, and Throat, Section of Audiology, Hacettepe University, Ankara, Turkey. Correspondence to Dr. Killion at *Etymotic Research, Inc., 61 Martin Lane, Elk Grove Village, IL 60007*.

*A side comment: Misunderstanding of this phenomenon several decades ago led some university clinics to prescribe gain nearly equal to the individual's hearing loss, often leading to acrimonious discussions with more sophisticated hearing aid dealers who were required to fill the prescriptions. With the best of present-day hearing aid microphones, however, such a prescription *can* be filled: aided sound-field thresholds in the 0 dB HL to 5 dB HL region are readily obtainable, should they be desired.⁴ It probably *should* be filled if the individual needs to baby-sit in a very quiet home and hear the baby cry from several rooms away. Empty gain in more normal environments can always be removed by turning down the volume control.

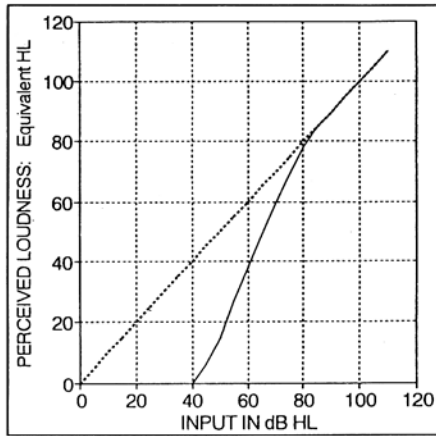


Figure 1. Example of Type I hearing loss. Dotted line is normal. (After Lyregaard⁸ and Lippmann et al.⁷).

aided loudness function that would be produced following the above guidelines. In circuit terms, the latter is the result of using a wide-dynamic-range compression circuit that has an approximately 2.2:1 compression ratio, with a lower threshold knee at 30 dB HL (approximately 45 dB SPL) and an upper threshold knee at 75 dB HL (approximately 90 dB SPL).

What would the popular conventional linear hearing aid produce in the way of an aided loudness growth curve? This is shown in Figure 3. Note that the correct gain for quiet sounds is produced. Note also that peak clipping or compression limiting has been used to limit the output to 95 dB HL (approximately 110 dB SPL), approximately 5 dB below the typical uncomfortable loudness level (UCL) of 100 dB HL reported by Pascoe for 40-dB sensorineural losses.⁵ Thus, the individual wearing this aid will be protected from discomfort.*

Note, however, that with the illustrated linear amplification all sounds between 40 dB HL and 90 dB HL will be abnormally loud; sounds between 60 dB HL and 70 dB HL (75 dB SPL and 85 dB SPL) will be amplified to 25 dB above normal loudness. Not surprisingly, people wearing linear hearing aids are often observed adjusting their volume controls.

Figure 4 illustrates two different adjustments of commercial compression circuits that produce what has been called "curvilinear compression" or "3:1 compression." These circuits are sometimes described as "equivalent to wide-dynamic-range-compression-with-treble-increases-at-low-level processing."¹¹ Note that the adjustment that gives a very low upper knee of compression (the x-x curve) does indeed give a reasonable aided loudness growth up to perhaps 70

*By "linear" in the present context, we mean fixed-gain operation until limiting sets in. The limiting itself may be highly nonlinear and full of unpleasant distortion such as that typically produced by starved Class A amplifiers.

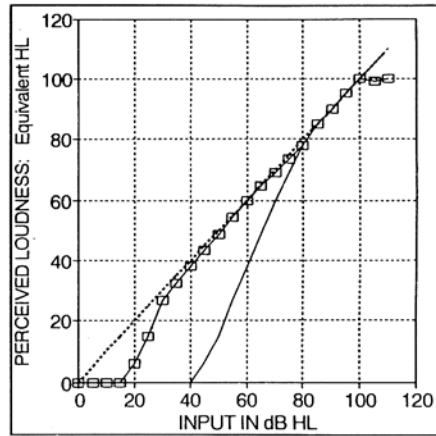


Figure 2. Type I hearing loss with WDRC processing with 2.2:1 compression ratio (□—□).

dB HL, but acts as a compression limiter above that level. It produces a loss in loudness for all inputs above 75 dB SPL. In effect, this hearing aid produces a hearing loss for intense sounds. This may be useful for a hyperacusic individual who finds all loud sounds intolerable, but it is the auditory equivalent of saying: "No more bright sunny days for you; only dark overcast days are allowed!" The top 40 dB of loudness experience, and the excitement of normal loudness contrasts, has been denied. The designer of these circuits saved money on the detector circuitry: Instead of using a wide-dynamic-range-logarithmic detector, which takes dozens of parts, the designer used a simple linear rectifier.

Intelligibility

How about intelligibility? Which one of these circuits produces the best intelligibility in noise? The answer depends on the range of presentation levels and whether or not the hearing aid user is allowed to adjust the volume control. But, assuming the volume control can be readjusted as required, the answer is that each of them can give identical intelligibility.

The overwhelming experimental evidence is that a wide bandwidth, an appro-

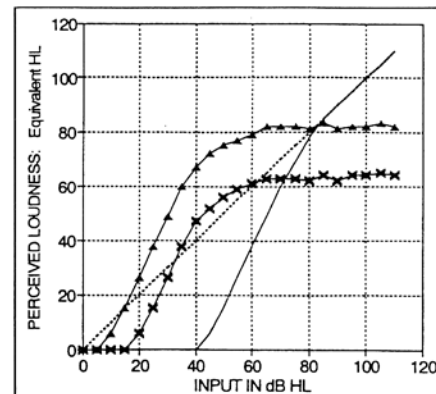


Figure 4. Type I loss with curvilinear compression processing. Two adjustments illustrated.

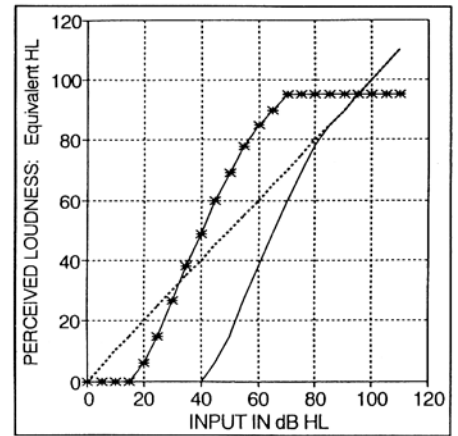


Figure 3. Type I loss with linear hearing aid (*—*).

priate frequency response (so that all speech cues are adequately audible), and low distortion (so that speech is clear) are all that is required to maximize intelligibility for a Type I hearing loss in either quiet or noise.⁶ Naturalness in loudness perception may be important to quality of life, but appears irrelevant to intelligibility for this type of loss.⁷

TYPE II HEARING LOSS

Figure 5 shows the loudness growth curve for a Type II sensorineural loss. A moderate-severe sensitivity loss of 60 dB is illustrated. Hearing loss of this degree will typically be accompanied by the loudness behavior illustrated in Figure 5, in which there is no region of completely normal loudness sensation, although what a mathematician might call a "displaced asymptotic behavior" is seen in the curve at high levels. The loudness sensation grows to within 10 dB of normal, but never gets any closer. This represents *partial recruitment* for the higher-intensity sounds. (Recall that *full* recruitment occurs when loudness has come completely back to normal; here it is 10 dB away.)

Other aspects of hearing, e.g., frequency resolution, loudness resolution, ability to

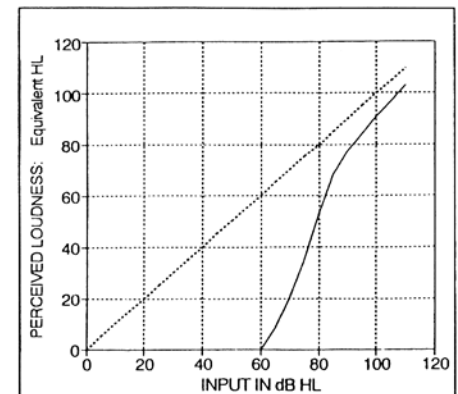


Figure 5. Example of Type II hearing loss.

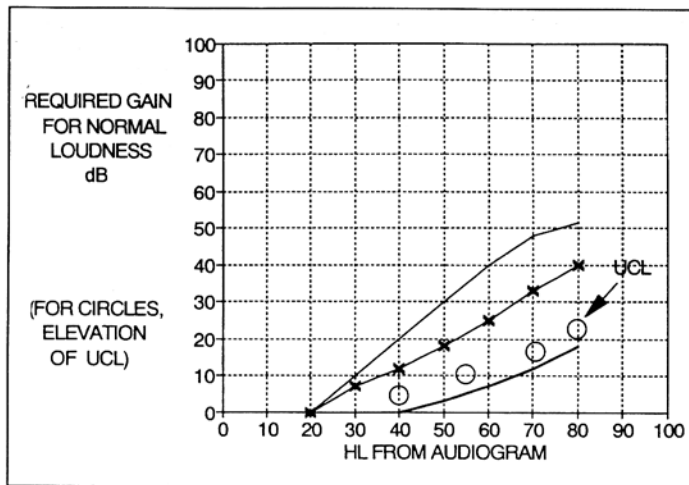


Figure 6. Gain required to restore loudness for low-level (—○—), comfortable-level (X—X), and high-level (—X—) sounds. UCL data indicate that the required high-level gain is safe (UCL and MCL data from Pascoe⁵)

understand speech in noise, ability to perform in a musical group, will probably not be completely normal, even at the higher intensities.⁹ A person with a Type II sensorineural loss has both a loss of sensitivity for quiet sounds *and* some loss of acuity for intense sounds.

Gain

What gain should we prescribe for quiet sounds for this person? Recognizing that gain equal to the hearing loss would be largely empty gain (not to mention largely impractical from the feedback standpoint), a reasonable goal might be 35 dB to 40 dB of gain for quiet sounds, as would be prescribed by the well-known 1/2 and 2/3 gain rules of Lybarger and Berger.

For intense sounds, 10 dB of gain is needed to restore normal loudness sensations for high-intensity sound. But what about loudness discomfort; shouldn't we be considering output limiting to prevent discomfort? The question is a good one, and can be rephrased as: "Does the amount of elevation in UCL that typically accompanies hearing loss permit sufficient gain to restore normal loudness for

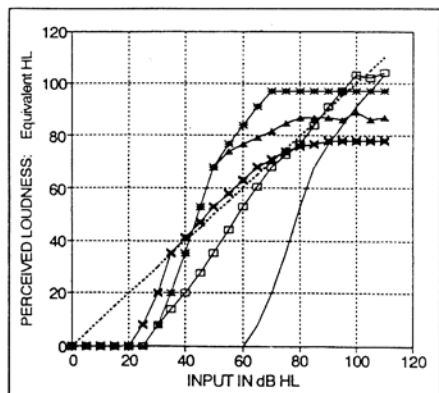


Figure 7. Type II loss with various signal processings.

all high-level sounds, or is some form of limiting required to prevent discomfort?" Fortunately, there are data that answer the question.

The curve with the circled points in Figure 6 represents the elevation of discomfort levels above normal, as a function of hearing loss, based on 500 ears as reported by Pascoe.⁵ Pascoe found little difference across frequency, so he pooled data

from 500 Hz, 1000 Hz, 2000 Hz, and 4000 Hz to arrive at the estimate. Note that a 60-dB loss is typically accompanied by a 12-dB elevation in UCL.

The heavy solid curve in Figure 6 represents the estimated loudness deficit for intense sounds accompanying partial recruitment, based on the data of Lippmann⁷ and Lyregaard.⁸ This is the gain required to bring intense sounds to normal loudness. The surprising experimental finding is that—on the average, at least—the elevation in discomfort levels exceeds loudness-restoration gain needed for intense sounds. For example, only 10 dB of gain is required to restore high-level loudness with the typical 60-dB loss. This is 2 dB less than the 12-dB UCL elevation found in the same loss.

Thus, a hearing aid that provides the gain required to restore normal loudness for high-level sounds should present no more of a discomfort problem to its wearer than a normal-hearing person

would experience in the presence of intense sound. This is consistent with widespread experience with wide-dynamic-range-compression (WDRC) hearing aids that can be adjusted to restore normal loudness for intense sound.¹ Discomfort complaints have been virtually nonexistent.

Processing

Figure 7 shows both the unaided and aided loudness function for several types of hearing aid circuits. Note that the 3:1 (adjustable) compression ratio available in one WDRC programmable circuit¹⁰ permits better loudness matching than either the 2.2:1 compression ratio of the other popular WDRC circuit or the behavior of "curvilinear" or "3:1" circuits.

Intelligibility

Both types of commercially available WDRC circuits with TILL (treble increases at low levels)¹¹ processing have been reported to be superior to the user's previous linear hearing aids in terms of word recognition in noise.¹² So too has curvilinear compression, as summarized elsewhere.¹² At the same time, previous research indicates that clean, wide-band linear amplification will nearly always provide just as good intelligibility for Type I and Type II losses—*provided the listener is allowed to adjust the volume control for each situation.*⁷ The data in Figure 8 can be taken as an indication of how often someone might need to adjust the volume control in real life, assuming real life included going to church.

TYPE III HEARING LOSS

Figure 9 shows word recognition scores versus presentation level for a subject whose word recognition scores in noise (four-talker babble) grow steadily until

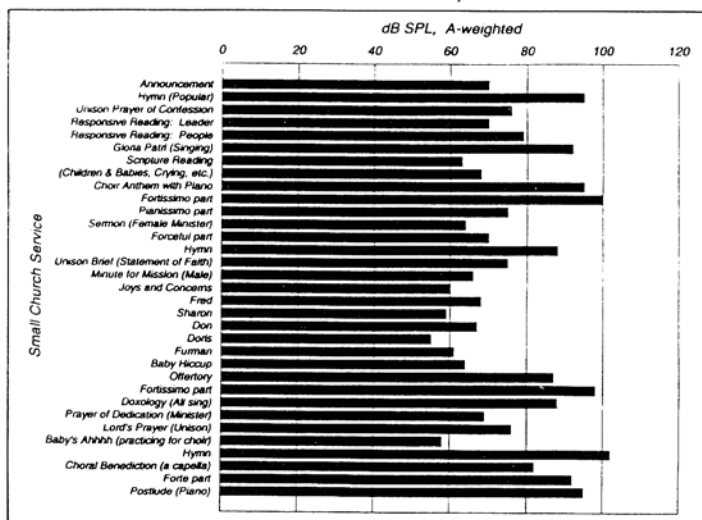


Figure 8. Range of A-weighted sound levels in one small church service (frequent peak readings FAST scale).

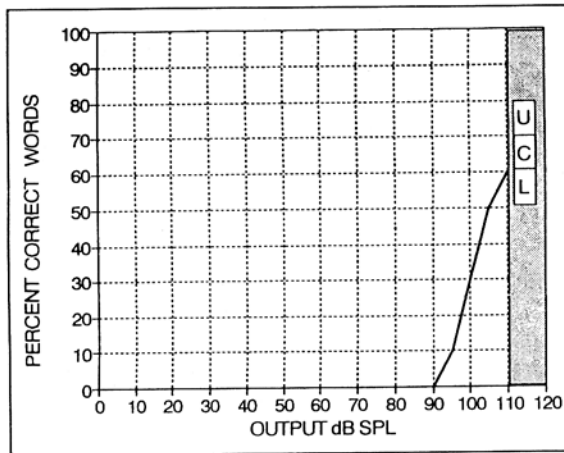


Figure 9. Intelligibility of speech in four-talker babble vs. SPL for Subject 1 (data from Fikret-Pasa, 1993).

discomfort is reached. (No data were obtained beyond discomfort.) This subject, the first of eight of Fikret-Pasa's "Type III loss" subjects, had a relatively flat hearing loss averaging about 70 dB HL.¹³

Gain

To even partially understand speech in noise, the subject in Figure 8 needs sounds presented near UCL. The only practical way to achieve this result is to provide a maximum gain that can exceed UCL for moderately loud sounds, combined with compression limiting set to just below UCL. When a difficult listening situation arises (a wedding party, for example), this individual can turn up the volume control and allow the compression-limiting circuit to hold all outputs at maximum-clarity-below-discomfort levels.

Although the type of limiting may be less important for persons with Type I and Type II losses, who may never need to operate in the limiting condition longer than it takes to readjust the volume control, Fikret-Pasa's data indicate that clipping as a means of limiting badly degrades intelligibility: The scores for her Subject 1 dropped nearly 70 percentage points when the circuit was driven 20 dB to 25 dB into clipping. Similarly, 50-msec-recovery-time compression limiting, which is the industry-standard, also resulted in significant degradation: Scores dropped about 40 percentage points for Subject 1 when the circuit was driven 20 dB to 25 dB into compression. Adaptive Compression[®] preserved intelligibility better: Scores for Subject 1 dropped only about 20 percentage points when the circuit was driven 20 dB to 25 dB into compression, a change that was not statistically significant.

Not surprisingly, Subject 1 scored much better across a range of input levels (70 dB SPL to 100 dB SPL) with com-

pression limiting (8:1 compression ratio) than with either WDRC (3:1 or 2:1 compression ratio) or with a linear operation for intense sounds. Somewhat surprisingly, however, only some of Fikret-Pasa's subjects showed the same results. One even performed significantly better with the above-mentioned WDRC-TILL circuit—linear operation for intense sounds—than with compression limiting. Nonetheless, compression limiting appears the most defensible choice for Type III individuals. They can always turn down the volume control and operate on the linear portion of the circuit function in the unlikely case that such operation is advantageous for them.

Notwithstanding this, some subjects with severe-to-profound hearing loss, which might be considered Type IV, appear to do best with peak-clipping limiting circuits.¹⁴

FREQUENCY-DEPENDENT HEARING LOSS

So far, we have ignored the fact that most hearing losses are frequency-dependent. Normal-to-mild loss at low frequencies and moderate loss or moderate-to-severe loss at high frequencies are most common. Thus, it is common to find a Type I loss at low frequencies and a Type II loss at high frequencies. Assuming we accept an approximation of normal loudness sensation as a reasonable goal, a circuit with either a frequency-dependent compression ratio or a level-dependent frequency response is required. In fact, either circuit approach can produce similar results: a TILL type of signal processing with linear operation at high levels. In either case, some gain for intense high-frequency sounds (in the region of Type II loss) can be provided.

It is satisfying to note that from either the intelligibility standpoint (Skinner¹⁵) or the modified-Zwicker-loudness-model standpoint (Leijon¹⁶), a study of the appropriate frequency response as a function of input-sound-pressure levels leads to that same conclusions.

Fortunately, the human auditory system is quite tolerant—especially after sufficient training—and so optimum choices are rarely required. Even linear hearing aids can prove quite satisfactory for many individuals.

The good news is that for persons with Type I and Type II losses, WDRC hearing aids with TILL processing can provide just as good speech intelligibility in both quiet and noise as can fast-finger-flicked

linear processing. Moreover, they can do this without producing the dull auditory monotony of stifled loudness and rigidly-fixed frequency responses—frequency responses that are truly appropriate to only a single output level. By using appropriate compression characteristics, it appears possible to provide both intelligibility and naturalness. In other words, it is practical to include "high fidelity to normal hearing" as one of the goals of a hearing aid fitting. ■

REFERENCES

1. Killion MC: *Design and evaluation of high fidelity hearing aids*. PhD thesis, Northwestern University. Ann Arbor, MI, University Microfilms, 1979.
2. Royster JD, Royster LH, Killion MC: Sound exposures and hearing thresholds of symphony orchestra musicians. *J Acoust Soc Am* 1987;89:2793-2803.
3. Killion MC, Studebaker GA: A-weighted equivalents of permissible ambient noise during audiometric testing. *J Acoust Soc Am* 1978;63:1633-1635.
4. Killion MC: Transducers and acoustic couplings. In Studebaker GA, Hochberg I (eds): *Acoustical Factors Affecting Hearing Aid Performance*. Boston: Allyn and Bacon, 1993.
5. Pascoe DL: Clinical measurements of the auditory dynamic range and their relation to formulas for hearing aid gain. In Jensen J (ed.): *Hearing Aid Fitting: Theoretical And Practical Views*. Proceedings of the 13th Danavox Symposium. Copenhagen, Danavox, 1988:129-152.
6. Skinner MW, Miller JD: Amplification bandwidth and intelligibility of speech in quiet and noise for listeners with sensorineural hearing loss. *Audiology* 1983;22:253-279.
7. Lippmann RP, Braida LD, Durlach NI: Study of multichannel amplitude compression and linear amplification for persons with sensorineural hearing loss. *J Acoust Soc Am* 1981;53:1646-1657.
8. Lyregaard PE: POGO and the theory behind. In Jensen J (ed.): *Hearing Aid Fitting: Theoretical And Practical Views*. Proceedings of the 13th Danavox Symposium. Copenhagen, Danavox, 1988.
9. Lutman ME, Clark J: Speech identification under simulated hearing-aid frequency response characteristics in relation to sensitivity, frequency resolution, and temporal resolution. *J Acoust Soc Am* 1986; 80:1030-1041.
10. Waldhauer F, Villchur E: Full dynamic range multiband compression in a hearing aid. *Hear J* 1988;41(9):29-31.
11. Killion MC, Staab WJ, Preves DA: Classifying automatic signal processors. *Hear Instr* 1990;41(8):24-26.
12. Killion MC, Villchur E: Kessler was right—partly: But SIN test shows some aids improve hearing in noise. *Hear J* 1993;46(9):31-35.
13. Fikret-Pasa S: *The effects of compression ratio on speech intelligibility and quality*. PhD thesis, Northwestern University. Ann Arbor, MI, University Microfilms, 1993.
14. Dillon H: Compression in hearing aids. In Sandlin RE (ed): *Handbook Of Hearing Aid Amplification*. Vol. 1 *Theoretical And Technical Considerations*. Boston: College Hill Press, 1988:121-145.
15. Skinner MW: Speech intelligibility in noise-induced hearing loss: effects of high-frequency compensation. *J Acoust Soc Am* 1980;67:306-317.
16. Leijon A: *Optimization of hearing-aid gain and frequency response for cochlear hearing losses*. PhD thesis and Chalmers University of Technology Technical Report #189. Göteborg, Sweden, 1989.