Comparison of Sound Quality and Clarity with Asymmetrical Peak Clipping and Output Limiting Compression

David B. Hawkins*
Sharmala V. Naidoo*

Abstract
This study compared the preferences of 12 subjects with mild-to-moderate hearing losses for a linear circuit when the type of output limitation could be changed between asymmetrical peak clipping and output limiting compression. Through a paired-comparison paradigm, subjects rated the sound quality and clarity of speech in quiet, speech in noise, and music when the output levels were well below saturation and when slight saturation and high saturation occurred. A significant preference was found for the output limiting compression for each of the three stimuli for both sound quality and clarity. The preference became stronger with increases in saturation. The results suggest that if linear hearing aids are being used, the output should be limited with compression rather than peak clipping.

Key Words: Hearing aids, output limiting compression, peak clipping, sound quality

Selection of the maximum output capabilities of a hearing aid has traditionally focused on the avoidance of loudness discomfort. If the SSPL90 of the hearing aid is less than the user’s loudness discomfort levels (LDLs), then it has typically been assumed that the maximum output has been dealt with appropriately. However, the method used to limit the output may also be important. It has been known for years that significant distortion can be introduced when peak clipping is employed to limit the output of a hearing aid (Davis et al., 1947). Indeed, audiologists who perform listening checks on hearing aids often notice the dramatic increase in distortion with a peak clipping hearing aid when their voice is intense enough to saturate the hearing aid. In contrast, when a hearing aid using compression to limit the output is saturated, far less distortion is created (Krebs, 1972; Walker and Dillon, 1982).

Despite the clear difference in measurable and perceptual distortion between peak clipping and compression when the two types of circuits are saturated, peak clipping appears to be the most common method of output limitation in hearing aids in the United States. A survey by the present authors completed in 1991 addressed this issue. A questionnaire was mailed to 20 major American hearing aid manufacturers asking the number of hearing aids sold during the previous year and what percentage used peak clipping versus some type of compression. The reply was anonymous and data were returned on approximately 900,000 units, representing 56 percent of the 1.6 million units sold during 1990 (Kirkwood, 1990). Although specific manufacturers varied in the amount of their use of peak clipping versus compression, 82 percent of the 900,000 units used peak clipping. These data indicate that peak clipping is presently the predominant method used to limit the output of hearing aids in this country.

While there is a large literature comparing linear amplification to various types of compression, we have found no published studies comparing linear hearing aids with peak clipping and output limiting compression when the hearing aid is saturated. Situations in which the hearing aid would be saturated most likely occur when input levels are high, such as often happens with the person’s own voice or when he
or she is in a noisy situation. If the increased distortion produced by peak clipping were objectionable to the hearing aid user, then it could be hypothesized that at least one contributing variable to the common "difficulty in noise" complaint could be related to the high percentage of hearing aids fit with peak clipping (Van Tasell and Crain, 1992). Some evidence for a preference for output limiting compression over peak clipping is found in a study by Dawson, Dillon, and Battaglia (1990), where 76 subjects were switched from a peak clipping to a linear output limiting compression hearing aid. Those with a moderate or severe hearing loss had a "positive reaction" to the change to compression; those with profound losses were divided in their preferences.

An unpublished study by May, Dillon, and Battaglia (1989) directly compared speech intelligibility and sound quality of peak clipping and output limiting compression hearing aids with 12 subjects having mild-to-moderate sensorineural hearing losses. Various stimuli were tape recorded through the two hearing aids at different levels relative to saturation and played back to the subjects. While speech discrimination scores were better for the output limiting compression at high saturation levels, sound quality judgments were not different between the two hearing aids. The authors found these latter results "surprising" and "inconsistent with our previous listening experience."

The purpose of this study was to examine further the issue of peak clipping versus output limiting compression for linear hearing aids and to determine which type of output limiting is preferred by subjects with mild-to-moderate sensorineural hearing losses when the hearing aid is in saturation. To this end, a special purpose multiamplifier hearing aid was used so that all electroacoustic characteristics were the same except the type of limiting (peak clipping versus output limiting compression) and allowed for rapid switching between the circuits conducive to a paired-comparison methodology. A design similar to that of May et al (1989) was employed in which the two limiting methods were compared on sound clarity and quality for differing amounts of saturation for several different stimuli.

**METHOD**

**Subjects**

Twelve adults with a mean age of 61 years (range of 37 to 85 years) with sloping mild-to-
The noise consisted of the 12-talker babble from the revised Speech Perception in Noise test. For the speech-in-noise condition, the signal-to-noise ratio was +10 dB. The music passage was a taped segment of classical music.

Each of these stimuli was presented at three different intensities from a loudspeaker. These differing input levels to the hearing aid microphone, in combination with specific volume control and SSPL90 settings, were chosen to produce three differing amounts of saturation for both the peak clipping and output limiting compression circuits. The three conditions were labelled -12 dB, +5 dB, and +20 dB. In the -12 dB condition, the rms output of the hearing aid with a composite speech-weighted noise input (the noise signal from the Frye 6500 system) of 58 dB SPL was 12 dB below the level at which the hearing aid’s input-output function departed from linearity. The point of departure from linearity was defined as the level at which the output SPL first increased 4 dB or less with an increase in input of 5 dB. In other words, the hearing aid was functioning in its linear operating range, and the peaks of the speech should theoretically not be saturating the hearing aid.

In the +5 dB condition, 5 dB of saturation was occurring. A 65 dB SPL input, when combined with the gain of the circuit, would have been 5 dB above the limiting level of the hearing aid. In the +20 dB condition, an input of 80 dB SPL plus the gain of the hearing aid would have been 20 dB above the limiting level. For all three conditions, the overall rms output levels for a composite speech-weighted noise were similar. These levels were 100, 103, and 104 dB SPL for -12, +5, and +20 dB, respectively.

### Electroacoustic Measurements

Figure 2 shows the SSPL90 curves (obtained with pure tones) and frequency response curves (obtained with a composite speech-weighted noise) for the peak clipping and output limiting compression circuits for the -12 dB condition. Input-output curves for a composite speech-weighted noise are shown in Figure 3. As the output levels in this condition during data collection were 100 dB SPL, it is clear that the circuits were operating in their linear range and were not in saturation. Total harmonic distortion values at 500, 800, and 1600 Hz measured with 55 dB SPL pure-tone signals with the peak clipping circuit were less than 2 percent for both circuits. The attack and release times for the output limiting compression circuit as measured by a Frye 6500 hearing aid test box were 10 and 100 msec, respectively.

The SSPL90 for the +5 and +20 dB conditions was approximately 105 dB SPL for both the peak clipping and output limiting compression circuits. This value is lower than the SSPL90 in the -12 dB condition, as it was necessary to saturate the circuits for the +5 and +20 dB conditions. This reduced output was accomplished through output control trimmers on the master unit. The frequency response curves for the peak clipping and output limiting compression circuits for the +20 dB condition are shown in Figure 4. They were obtained with a composite speech-weighted noise of 80 dB SPL, equal to the speech input level used in that condition. Notice the irregularity in the peak clipping response curve due to the distortion products being generated by the clipping. Total harmonic distortion values obtained with 80 dB SPL pure-tone signals with the peak clipping circuit were...
Figure 4 Frequency response curves (obtained with composite speech-weighted noise of 80 dB SPL) for the peak clipping (PC) and output limiting compression (COMP) circuits in the +20 dB condition.

49 percent, 32 percent, and 31 percent at 500, 800, and 1600 Hz, respectively. For the output limiting compression circuit, the distortion was 4 percent, 2 percent, and 1 percent for the same frequencies. The input-output functions for the two circuits for the +5 and +20 dB conditions were obtained with a composite speech-weighted noise and are shown in Figure 5.

With speech rms inputs of 65 and 80 dB SPL, both circuits were saturated by approximately 5 and 20 dB, respectively.

Procedures

The tone controls on both the peak clipping and output limiting compression circuits were adjusted for each subject to best match the NAL recommended frequency response slope from 500 to 2000 Hz.

All testing was done in a 3.7 m by 6.4 m room having a mean reverberation time of 0.4 sec (average of 250, 500, 1000, 2000, 4000, and 8000 Hz). Taped speech, noise, and music stimuli were routed through an audiometer, amplified, and delivered to a single loudspeaker located 1 m from the subject at a 0-degree azimuth.

Before data collection began, subjects listened to each stimulus at an amplified level of approximately 105 dB SPL, the highest presentation level in the study, and were asked if any of the stimuli were uncomfortably loud. Two subjects reported uncomfortable loudness and were thus excluded from the study; two additional subjects were recruited to maintain the pool of 12 subjects.

Subjects listened to 18 conditions: the three stimuli (speech in quiet, speech in noise, and music) at three levels re: saturation (-12, +5, and +20 dB), with judgments being made of both sound quality and clarity. Each condition was repeated three times, yielding a total of 54 trials. The order of the 54 conditions was randomized for each subject. Specific definitions of “sound quality” and “sound clarity” were not given to the subjects; they were simply asked to compare the two circuits on the basis of the “quality of the sound” and the “clarity of the sound.”

A paired-comparison task was utilized to obtain subject preferences for peak clipping and output limiting compression. In front of the subject were placed two cards with the letters A and B. Subjects were instructed to point to A or B and alternate back and forth between A and B until they had formed a preference. From behind the subject, the experimenter alternated between the peak clipping and output limiting compression circuits through a switch on the multiamplifier box. The peak clipping and output limiting compression circuits each occurred randomly in the A or B interval across the conditions. After the subject decided on a preference for either A or B, they were asked to assign a strength to that preference through a method described by Dillon (1984). Subjects indicated the strength of their preference by choosing one of the choices on the following rating scale:

1. A is much better than B.
2. A is moderately better than B.
3. A is slightly better than B.
4. B is slightly better than A.
5. B is moderately better than A.
6. B is much better than A.

Subjects were given practice trials until they indicated that they felt comfortable with the task. All aided listening was done monaurally with the unaided ear occluded with a foam earplug.
RESULTS

Following the recommendations of Dillon (1984), the subjective preferences were assigned numerical values for data analysis. A “slightly better” response was designated as 1, “moderately better” as 3, and “much better” as 5. Preferences for output limiting compression were given positive values and negative numbers were assigned to preferences for peak clipping. The results for sound quality and clarity were analyzed separately. An analysis of variance for repeated measures for both sets of data indicated a significant preference for output limiting compression over peak clipping (F = 2.91, p < .0001 for quality; F = 2.88, p < .0001 for clarity). The results are discussed separately for sound quality and clarity.

Sound Quality Preference Data

The mean preference data are shown in Figure 6 for sound quality for each stimulus at the three levels relative to saturation.

The significance of each preference was determined by examining whether the mean preference was significantly different from zero. Each of the nine comparisons shown in Figure 6 yielded a significant preference for output limiting compression. There was a significant effect of saturation level (F = 74.4, p < .0001), indicating that the preference for output limiting compression became greater as the amount of saturation increased. Given the large increase in harmonic distortion that occurred as the amount of saturation increased, it is not surprising that the preference for output limiting compression became greater as more saturation occurred. It is clear that the subjects perceived a difference between the two circuits. It was not anticipated that the two circuits would be judged as different in the -12 dB condition, as theoretically both were operating in their linear range. It is possible that some of the signal peaks were reaching the maximum output of the hearing aid, and some peak clipping was occurring, which may have been perceived by the subjects. This would appear to be the most logical explanation, as the frequency responses and input-output functions of the two circuits were closely matched.

If the mean preferences are expressed in terms of the subjective scales, one would categorize the output limiting compression preference at -12 dB as slightly better, slightly to moderately better at +5 dB, and moderately better at +20 dB. Examination of the individual subject data showed that all subjects preferred output limiting compression for each of the three stimuli in the +5 dB and +20 dB conditions.

The effect of stimulus type was also significant (F = 6.2, p = .002), with the preference for output limiting compression being greater for speech in quiet and speech in noise than for music, especially in the +5 dB condition.

Sound Clarity Preference Data

Figure 7 shows the data for the sound clarity judgments. The results are virtually identical, descriptively and statistically, to those for the sound quality preference judgments. The preference for output limiting compression was again significant for each stimulus at each of the three saturation levels. These results would suggest that either both clarity and quality are equally affected by the parameters that were

Figure 6  Mean preference data for sound quality for music, speech in quiet, and speech in noise at each of the three levels relative to saturation.

Figure 7  Mean preference data for sound clarity for music, speech in quiet, and speech in noise at each of the three levels relative to saturation.
varied, or that the two concepts were interpreted by the subjects as being equivalent.

**DISCUSSION**

The results of this study indicate that persons with mild-to-moderate hearing loss do prefer output limiting compression to asymmetrical peak clipping as a method of output limitation when the two circuits are saturated. The fact that all subjects preferred the sound quality and clarity of output limiting compression in the +5 and +20 dB conditions further strengthens this conclusion. Presumably this preference is based upon detection of the greater saturation-induced distortion associated with peak clipping. Preves (1990) has suggested that coherence measurements may be useful in assessing this phenomenon and that compression can reduce the distortion. He stated that "...if the peaks in the frequency response cause saturation, thus forming nonlinear distortion components, the coherence will be degraded. Coherence and signal-to-distortion ratio may be improved by the use of compression in the hearing aid amplifier to prevent the occurrence of saturation (Kates, 1989, pp. 57–58)." To examine this relationship further, coherence measurements were made on the circuits in this study with the input levels and VCW positions that were employed in the actual conditions. Figure 8 shows the coherence curves obtained for the three conditions (−12 dB, +5 dB, and +20 dB) with both peak clipping and output limiting compression. A qualitative comparison of the coherence differences between the two circuits to the sound quality and clarity judgment differences shown in Figures 6 and 7 reinforces Preves' suggestion that coherence values may correlate well with sound quality judgments, as he stated that "preliminary listening tests demonstrate that the coherence measurement may be a good indicator of hearing aid sound quality."

Preventing saturation-induced distortion has generated interest in increasing headroom in hearing aids (Preves and Newton, 1989; Fortune and Preves, 1992a,b). The availability of Class D receivers with increased headroom has made the provision of lower gain hearing aids with higher SSPL90s possible. By having a higher SSPL90, the possibility of more intense inputs saturating the hearing aid is decreased. Indeed, Fortune and Preves (1992b) have shown that even LDLs are affected by saturation-induced distortion, with aided LDLs being lower (thus causing reduced headroom) when linear circuits are saturated. However, arbitrarily increasing the headroom without regard to LDLs...
may create discomfort for some individuals and result in reduced acceptance of the hearing aid. An alternative to simply increasing headroom to avoid saturation-induced distortion would be to utilize a low-distortion method of limiting the output, such as output limiting compression. The results of this study indicate that listeners with mild-to-moderate hearing losses prefer this type of limiting to asymmetrical peak clipping.

Given the survey results mentioned earlier indicating that 82 percent of hearing aids sold in 1990 utilized peak clipping, it is tempting to speculate that a portion of the problems mentioned by hearing aid users in noisy situations may be due to saturation-induced distortion products. This same hypothesis was mentioned by Teder (1990), who stated that “...the wide range of speech and noise levels leads one to wonder whether the inability to understand speech in noise, so common among hearing instrument wearers, is not, in many cases, simply caused by overload of a linear hearing instrument? ...A properly designed compression limiter should function significantly better in such circumstances...” (p. 33). In a similar vein, Van Tasell and Crain (1992) speculated that some of the purported benefits of adaptive frequency response hearing aids may be related to the fact that many of these hearing aids limit the output with less distortion than the standard peak clipping circuit. They concluded that “if it can be shown that peak clipping adversely affects wearability of the hearing aid, by reducing either speech intelligibility or the acceptability of the quality of hearing aid-processed sounds, then peak clipping hearing aids should be avoided” (p. 121). The results of this study, while not confirming that part of the “speech-in-noise problem” is due to peak clipping, do suggest that peak clipping should be avoided as a method of output limitation.

The conclusion that peak clipping should be avoided must be tempered by two limitations in the design of this study. First, the peak clipping circuit we used may represent the worst case for this type of output limitation. Asymmetrical peak clipping was employed, and although this does appear to be a common form of clipping, it generates distortion products at odd multiples of the fundamental. Since these distortion products are closer in frequency to the fundamental than when symmetrical clipping is used, it is possible that symmetrical peak clipping or diode clipping would have resulted in smaller differences between peak clipping and output limiting compression. A second limitation is that specific volume control wheel (VCW) positions were chosen, along with known input levels, to produce certain amounts of saturation. It is not known if subjects would set their VCWs in real environments to allow such levels of distortion. It may be the case that users would never allow the +20 dB of saturation situation used in this study to occur in real life. While it is common knowledge that most users of linear hearing aids do reduce their VCWs in noisy situations and when the input levels are high, we are not aware of any data showing where the actual output levels are in relation to the SSPL90. It is not uncommon, however, to have hearing aid users report that they remove their hearing aids in very noisy situations because they offer no benefit or that hearing is better unaided. Whether this type of report is due to the inherent limitations of the impaired auditory system to process signals in noise, saturation-induced distortion, lack of appropriate packaging of the input signal into the dynamic range, or all of the above, is not clear.

It is interesting to note that nearly all of the newer programmable hearing aids, some of which are claimed to have made rather dramatic improvements in noisy conditions, have incorporated some type of compression. It is important to remember, however, that this study only investigated the rather limited condition of linear amplification with output limiting compression. Very different types of compression for different purposes are utilized in some of these devices. This study did not address the types of compression found in these and some other nonprogrammable circuits, such as those having lower compression thresholds, variable compression ratios, wide-range dynamic range compression, and adaptive compression. Along with this trend of the programmable line of hearing aids to incorporate compression of some type, it is possible that the percentage of peak clipping hearing aids being sold in this country has decreased since the survey mentioned earlier in this article was completed.

In summary, the results of this study would suggest that, at least for listeners with mild and moderate hearing losses, peak clipping (at least asymmetrical) should not be the preferred method of output limitation. Better sound quality and clarity will be perceived by the hearing aid user with output limiting compression when input levels are such that saturation is reached. This entire issue of how to best limit output is intricately entwined with the desired location of output limitation, concepts of loudness discomfort, headroom, and packaging of the input signal into the residual dynamic range. More
research is needed in each of these difficult areas before the characteristics of the "optimal" hearing aid can be better defined.

Acknowledgment. The authors gratefully acknowledge the assistance of Dr. David Preves and Brian Woodruff of Argosy Electronics who provided the multiamplifier device and performed the coherence measurements. Dr. Preves also provided valuable comments on an earlier version of this manuscript.

Portions of the paper were presented at the 1992 American Academy of Audiology Convention, Nashville, Tennessee.

REFERENCES


