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Preferred Real-Ear Insertion Gain on a Commercial Hearing Aid at Different Speech and Noise Levels

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Abstract

In the present study, we measured preferred real-ear insertion gain (REIG) under different levels of speech and noise to assess whether current automatic gain control (AGC) and automatic signal processing (ASP) hearing aids are operating optimally. Preferred REIG for optimal speech clarity was determined under seven speech and noise conditions. In four conditions, speech (discourse passages) was varied from 55 dB SPL to 85 dB SPL in 10-dB steps at a fixed signal-to-noise ratio (S/N) of +5. In the remaining conditions, speech was fixed at 65 dB SPL while the noise level was varied in 5-dB steps to yield S/Ns from +10 to –5. The results showed that subjects selected less gain as speech or noise levels were increased. In general, less overall gain was selected as speech level was increased, and less overall gain, especially in the low-frequency region, was selected as the S/N ratio became progressively poorer. These results are discussed in relation to how hearing aids with adaptive frequency/gain responses should respond to varying input levels to achieve optimal clarity of speech.

Key Words: Adaptive frequency/gain responses (AFR), automatic gain control (AGC), automatic signal processing (ASP), hearing aids, paired comparison, preferred real-ear insertion gain (REIG)

Hearing aids with automatic gain control (AGC) and automatic signal processing (ASP) circuitries adaptively change frequency/gain characteristics as the sound pressure level (SPL) of the listening environment varies. AGC hearing aids adaptively change overall gain as input or output SPL varies, while ASP hearing aids adaptively change low-frequency gain as input SPL varies. Manufacturers of these devices claim that adaptive gain reduction and/or high-pass filtering would alter the signal-to-noise ratios (S/N) of the listening environment and could result in better recognition of speech in noise. The reduction of the upward spread of masking (e.g., Danaher and Pickett, 1975) has been cited as one argument for incorporating ASP circuitry.

Currently, several commercial versions of AGC and ASP circuits are available. Each circuit operates in a specific manner, resulting in potentially different outcomes. For example, AGC hearing aids could vary by: (1) the stage of compression (i.e., input versus output); (2) compression threshold (CT); (3) compression ratio (CR); (4) fixed (same CR for all input levels) or level-dependent (CR varies according to input levels) CR; (5) attack and release times; (6) fixed or adaptive release time; and (7) number of channels available for compression and whether compression is equally applied across the entire frequency response or only applied in the low-frequency region (below 1000 Hz).

There are also variations in the design and operating characteristics of ASP hearing aids. Although most ASP hearing aids reduce low-frequency gain as a function of the input SPL

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regardless of the nature of the input stimulus (i.e., speech or noise), some devices sample the signal waveform and analyze its spectrum to determine the extent and frequency region for gain reduction. In addition, the activation threshold of the ASP circuit, the magnitude of low- and/or high-frequency attenuation, could also differ among devices. Some hearing aids have combined both AGC and ASP designs within the same device.

Despite the various designs of ASP and AGC circuits, the fundamental question of whether the adaptive changes in frequency/gain responses provided by these circuits reflect the user's preference remains largely unaddressed. Intuitively at least, user satisfaction with the hearing aid may increase if the result of the adaptive change in electroacoustic characteristics matches the user's preference for the given listening environment. On the other hand, if the adaptive change is insufficient, or if it is in the opposite direction of the user's preference, a decrease in satisfaction may result. Because of the differences among various hearing aids with adaptive frequency/gain responses, direct measure of the efficacy of a device would limit the conclusion to that device alone. An indirect method, that of determining how individual preference for real-ear insertion gain (REIG) varies with stimulus level, may yield more generalized results for one to evaluate how hearing aids with adaptive frequency/gain responses (i.e., ASP and AGC hearing aids) should operate in order to achieve maximum user satisfaction.

User satisfaction can be measured in many ways, such as improved speech recognition (either subjective or objective), improved speech clarity, and improved listening comfort. Unfortunately, these criteria may be exclusive to each other, in that the frequency/gain setting selected with one criterion may be markedly different from the use of another criterion (e.g., Kuk and Tyler, 1990). Such limitation must be recognized to avoid overgeneralization of results.

The present study was designed to quantify changes in preferred REIG for optimal clarity of speech as a function of changes in the levels of speech and noise. A task involving judgments of speech clarity in noise was used as the criterion. Subjective task was employed because of its reliability, efficiency, and validity (Studebaker, 1986). Judgment of clarity was chosen because hearing-impaired adults ranked speech clarity as the most important factor in determining the overall quality of hearing aids (Hagerman and Gabrielsson, 1985). The results may be compared to the action of AGC and/or ASP hearing aids for one to evaluate if their adaptive actions would optimize speech clarity under specific test conditions.

METHOD

Subjects

Twelve subjects ranging in age from 34 to 74 years (mean = 62 years) participated in the study. All subjects had bilaterally symmetrical (±10 dB), mild to moderately severe sensorineural hearing loss. They were grouped a posteriori according to their hearing thresholds at 250 Hz and 500 Hz. Group A subjects had average thresholds of less than 40 dB HL at these two frequencies (n = 7). Subjects in group B had average thresholds equal to or greater than 40 dB HL at these two frequencies (n = 5). Although not used as a criterion for grouping, the average threshold at 1000 Hz also differed between the two subject groups (group A = 45 dB HL, group B = 60 dB HL). Subjects' mean audiometric thresholds are shown in Table 1. Five group A and four group B subjects had at least 1 year of experience with linear amplification. The remaining subjects were new hearing-aid users. The average speech-recognition score using the CID W-22 word list was 76 percent for group A subjects and 85 percent for group B subjects.

Hearing Aids

The Starkey Trilogy I in-the-canal programmable hearing aid was used to select preferred REIG. A commercial linear hearing aid was used in order to reflect real-life hearing-aid use and to focus the study to only static changes (i.e., gain and frequency changes) in electroacoustic parameters. This hearing aid was chosen because of: (1) increasing popularity of canal instruments; (2) flexibility in low-frequency slope and overall gain adjustments; and (3) availability of three memories to allow for pairwise comparison of different frequency/gain responses.

There are three parameters for adjustment: low-frequency slope, overall gain, and resonant peak frequency. Low-frequency slope can be adjusted in 10 discrete steps to allow more than 30 dB of change in gain when measured at 500 Hz. Overall gain can be varied in 6 discrete 5-dB

Table 1 Subject Thresholds

Group	*Mean Age (yr)*	*Mean Audiometric Thresholds/Test Ear* Frequency (Hz)*					
		250	*500*	*1000*	*2000*	*4000*	*8000*
A	64	20	21	45	51	61	70
B	59	44	54	60	57	60	70

*dB HL re:ANSI, 1989.

steps from 20-dB to 45-dB peak gain. Although four resonant frequencies (peaks at 2500 Hz, 2800 Hz, 3100 Hz, and 3400 Hz) are available to accommodate variations in ear canal resonance, the default peak of 2800 Hz was used in this study. Saturation sound pressure level (SSPL90) on the hearing aid varies with volume control setting, with a maximum at 110 dB SPL. A Class D amplifier is used in the output transducer to reduce potential distortions at high input levels. It has been demonstrated that Class D amplifiers improve the sound quality of amplified sound over Class A amplifiers (Kochkin and Ballad, 1991). Figure 1 shows the range of low-frequency slope and overall gain adjustments when the device is set to maximum (solid curve) and minimum (circled curve) gain. The arrows indicate the directions in which a prescribed response can be adjusted to meet individual preference.

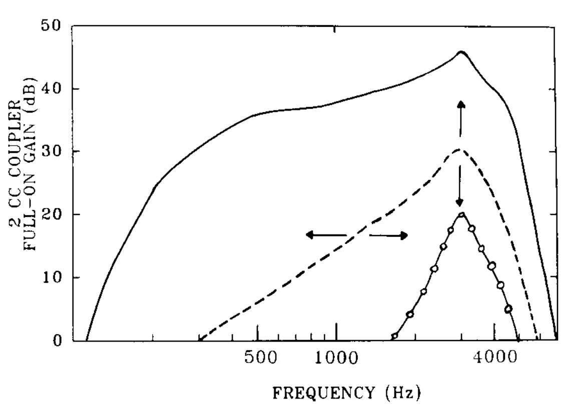

Figure 1 The 2-cc coupler full-on gain of the experimental hearing aid showing the range of low-frequency slope and overall gain adjustments at an input level of 60 dB SPL. Solid curve is obtained with maximum low-frequency slope and overall gain while the circled curve is obtained with minimum low-frequency slope and overall gain. The dashed curve is a hypothetical response corresponding to target NAL-R. Arrows indicate the directions in which NAL-R gain curve can change during the modified simplex comparison.

Programming was accomplished with a desktop programmer. This unit is linked to a remote control via a programming cable. The remote control is capable of storing three memories (i.e., electroacoustic settings) of the hearing aid. These memories are transmitted to the hearing aid via an ultrasonic signal. Because of directional restrictions of ultrasonic transmission, all subjects practiced extensively with the remote control device to ensure efficient and consistent transmission of settings to the hearing aids during the experimental session. In addition, all comparisons were performed only after subjects indicated a perceptual difference between frequency/gain settings when the remote control was activated.

Stimuli

Fifteen short passages of connected discourse having a duration of about 10 seconds were used to evaluate subjective judgments of speech clarity. The manner in which these passages were recorded has been reported previously (Kuk and Pape, 1992). Briefly, a male speaker read aloud these passages at a monitored voice level (approximately 65–70 dB SPL-lin) in an anechoic chamber. The passages were recorded on a Sony PCM recorder and stored on a 44 Mbyte Bernoulli cartridge for digital playback. All passages were judged by the experimenters and two other listeners with normal hearing to be neutral in meaning, of good sound quality, and to have minimal inflection changes.

The noise stimulus was a multitalker cocktail party noise distributed by the Widex Hearing Aid Company. Figure 2 reports the spectra of noise and discourse passages measured with the Ariel Hyperception spectral analysis software. The input was sampled at a 20-kHz sampling rate and measured using ⅓-octave band filters. Speech spectrum was the average of the spectra for each discourse passage, while the noise spectrum was averaged over the duration

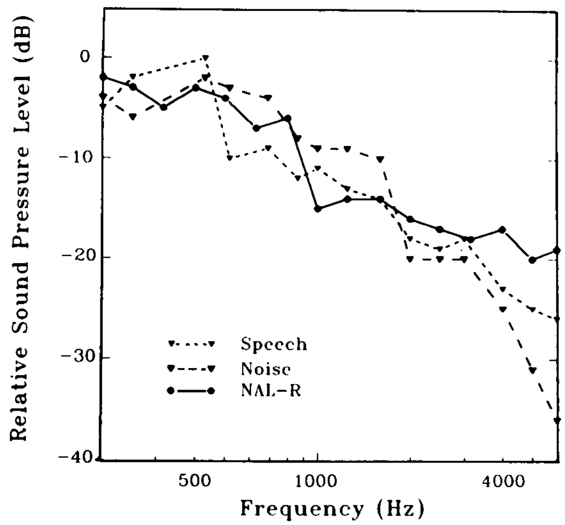

Figure 2 Speech and noise spectra measured over the duration of the signal sources (speech: closed, inverted triangles; noise: open, inverted triangles). The spectrum used in the calculation of NAL-R target was also included for comparison (closed dots).

of the multitalker party noise. The average speech spectrum used by Byrne and Dillon (1986) in formulating the revised NAL formula was also included in the same figure for comparison. In general, the speech signal has slightly more energy below 500 Hz and less energy between 500 and 2000 Hz than the noise stimulus. The average speech spectrum used by Byrne and Dillon (1986) approximated the noise spectrum to about 1000 Hz but showed less energy from 1000 Hz to 2000 Hz and more energy from 2000 Hz to 5000 Hz than the noise spectrum. These differences are not unexpected, given that the NAL-R spectrum is an average spectrum of male and female speakers while the speech spectrum is that of a single male speaker.

Speech materials were presented from an IBM-compatible (CompuAdd 325) computer while the multitalker party noise was played back on a Technics RS-TR313 cassette player. These two outputs were mixed at appropriate levels and were presented through a single loudspeaker, which was placed directly in front of the subject at a distance of 1 meter. Stimulus levels were calibrated with a Bruel & Kjaer sound level meter (type 2235) placed at the ear level of a mannequin situated in the same position as the subject in the sound field.

Procedure

Preferred REIG for optimal listening under different speech and noise levels was determined using a pairwise adaptive procedure. Speech clarity was used as a criterion in the selection of preferred gain. Only one ear was tested. The nontest ear was occluded with an E-A-R earplug. All hearing aids were custom-made in a conventional manner (with typical canal lengths) and were vented using a parallel Select-A-Vent (SAV) system. A 2-mm or 3-mm diameter vent plug was used for group A subjects. A 1-mm or 1.5-mm diameter vent plug was used for group B subjects. A screw-set volume control was ordered on all hearing aids, to avoid accidental change of gain during the experiment.

Initial Estimate of Preferred Insertion Gain

The screw-set volume control was initially adjusted to approximately ¾ to ⅘ of its maximum range. Afterwards, the low-frequency slope, the resonance peak, and the overall gain settings on the hearing aid were adjusted so that the measured REIG approximated the NAL-R prescriptive target. A Fonix 6500 real-ear measurement system was used to measure real-ear gain. Speech-shaped noise, presented at 65 dB SPL and at about 45 degrees to the side of the aided ear, was used as the stimulus. For all measures, the probe tube was placed underneath the hearing aid and the depth of insertion was approximately 5 mm past the sound bore of the hearing aid. A marker was made on the probe tube to ensure same insertion depth during aided and unaided measurements.

Determination of Preferred Insertion Gain at Various Speech and Noise Levels

Preferred REIG for subjective judgment of speech clarity was determined at seven speech and noise levels. For four conditions, the speech-to-noise ratio was held constant at +5 while the speech level changed from 55 dB SPL to 85 dB SPL in 10-dB steps. For the remaining conditions, the speech level was held constant at 65 dB SPL while the noise level was varied in 5-dB steps, resulting in S/Ns from +10 to –5. Test conditions were counterbalanced across subjects.

The low-frequency slope and overall gain settings were individually adjusted when selecting optimal REIG. An adaptive procedure similar to the modified simplex procedure (Neuman, Levitt, Mills, and Schwander, 1987; Kuk and Pape, 1992) was used. There were two distinctions between the present procedure and the modified simplex procedure utilized previously. First, because of device limitations, the present study utilized an uneven number of intervals along each electroacoustic dimension. There were six 5-dB intervals on the overall gain dimension (20 to 45 dB) and 10 intervals on the low-frequency slope dimension. Second, adaptive step size was used in comparing the low-frequency setting while fixed step size (at 5 dB) was used in overall gain comparison. Step size for the low-frequency dimension was initially set to two intervals (each representing 3- to 5-dB gain change at 500 Hz). It was reduced to one interval after the first reversal. These modifications shortened the time required to select optimal low-frequency and overall gain settings. Approximately 10 to 15 minutes were required to complete gain selection for one listening condition.

The three memories on the remote control device were programmed manually for the purpose of paired comparison. For the first round of comparison, one memory (#1) stored the overall gain and low-frequency slope settings that corresponded to NAL-R insertion gain. This served as the base setting to which settings that deviated from NAL-R would be compared. The second memory (#2) stored the gain settings for NAL-R, but with less low-frequency gain (about 10 dB below the prescribed NAL-R gain at 500 Hz). The third memory (#3) stored the gain settings for NAL-R, but with 5 dB less overall gain than the NAL-R prescription. Memory assignment was randomized. Memory #1 was compared to memory #2 in order to examine preference in the low-frequency slope dimension. The same memory (#1) was compared to memory #3 to examine preference for overall gain.

Instructions to the subjects are reported in the Appendix. Specifically, subjects were instructed to choose the memory providing the clearest perception of speech while listening to the passages embedded in noise background. Subjects were instructed to minimize their vocalization during comparisons and not to make clarity judgments based on amplification of their own voice. Each pair of memories (i.e., #1 with #2 and #1 with #3) was compared three times in random order. The memory that won two of three comparisons was identified as the winner.

Figure 3 is a matrix representation of the sequence of comparisons in one typical trial. The x-axis represents low-frequency slope dimension and the y-axis represents overall gain

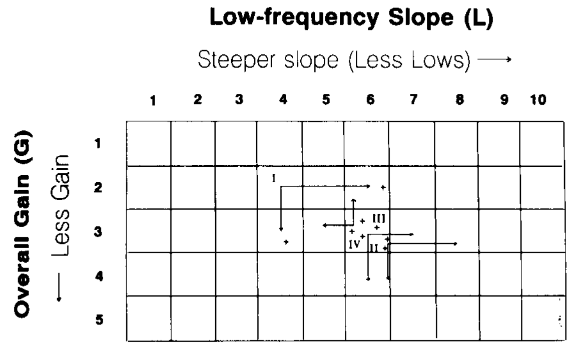

Figure 3 Matrix representation of the sequence of comparisons in one typical modified simplex trial.

dimension. Each cell represents a combination of low-frequency slope and overall gain settings. Let us assume that a low-frequency slope setting of "4" and an overall gain setting of "2" on the hearing aid yielded REIG recommended by NAL-R. Consequently, cell 4L, 2G was chosen as memory #1. In the first round of comparison (designated by numeral I), this cell was compared to cell 6L, 2G in the low-frequency slope dimension and to cell 4L, 3G in the overall gain dimension. If cell 6L, 2G wins over cell 4L, 2G, and cell 4L, 3G wins over cell 4L, 2G, (the winning cells are identified by a "+" symbol), this suggests that the subject would prefer less gain in both the low-frequency slope and overall gain dimensions for optimal speech clarity. The direction of comparison will move towards cells with less low frequency and less overall gain. The new base setting for comparison would move to cell 6L, 3G, and the comparison settings become cell 8L, 3G and 6L, 4G. This is the second round of comparison (II).

Memories on the remote control were reprogrammed with the new combinations of low-frequency slope and overall gain. Comparison with the same step size continued in the low-frequency dimension until subjects changed their preference (e.g., from preferring the setting with less gain to the setting with more gain). This signaled a reversal in preference (after comparison II), and the step size for the low-frequency dimension was reduced to one interval. The step size for the overall gain dimension remained constant. Comparisons continued until three reversals were encountered in both dimensions. In this example, the settings represented by cell 6L, 3G were chosen as the preferred frequency/gain setting.

The same passage was used for each triad of memory comparison. A new passage was used with each new triad of comparison. In this example, four different passages were used. The choice of passage was randomized. The order of stimulus presentation was counterbalanced.

RESULTS

Comparison between Prescribed and Measured NAL-R REIG

Figure 4 shows the mean measured and prescribed NAL-R REIG for both groups of subjects. Group A subjects reported less than 2-dB deviation between measured and target NAL-R REIG to 2000 Hz. At 4000 Hz, the average difference increased to approximately 6 dB. Group B subjects also deviated by about 2 dB between measured and prescribed NAL-R REIG up to 1000 Hz. The average difference increased to 4 dB and 7 dB at 2000 Hz and 4000 Hz, respectively.

Insertion Gain at Different Speech Levels (Constant S/N)

Figure 5 reports the REIG curves measured from group A and group B subjects at speech levels of 55, 65, 75, and 85 dB SPL and at a constant signal-to-noise ratio (S/N = +5). The mean prescribed NAL-R REIG was also included for comparison.

At an input level of 55 dB SPL, the average group A subject preferred 7 dB more REIG at 500 Hz and 3 dB less REIG at 2000 Hz than that recommended by NAL-R. It is unclear if subjects would prefer less than prescribed NAL-R

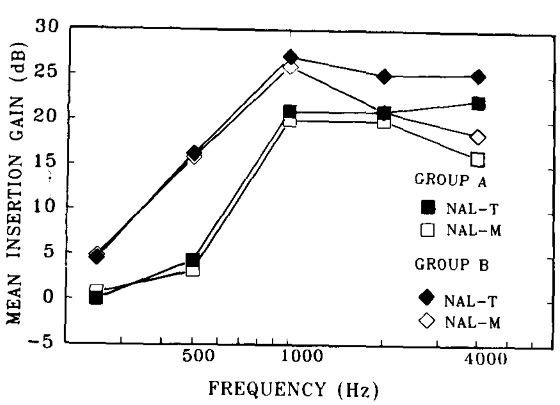

Figure 4 Comparison of mean target NAL-R (NAL-T) insertion gain and measured NAL-R (NAL-M) insertion gain for group A (open square) and group B (open diamond) subjects. The filled symbols are the target gain while the unfilled symbols are the measured gain.

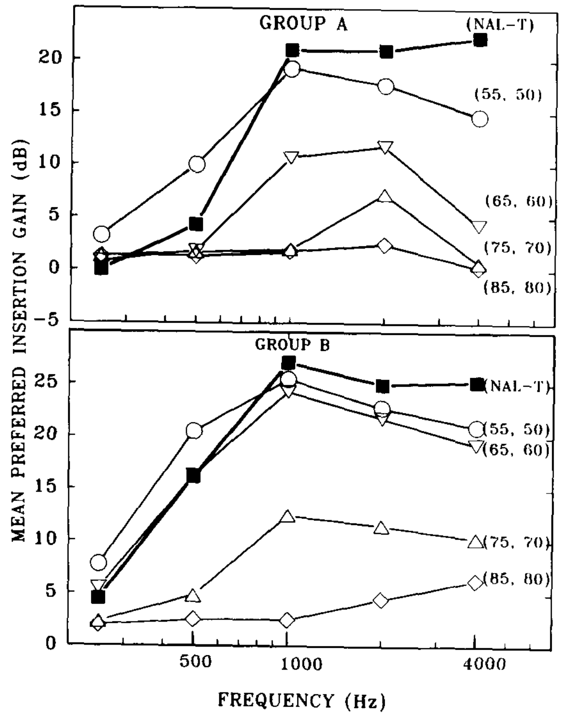

Figure 5 Mean preferred REIG for group A (upper) and group B (lower) subjects at four different signal levels while keeping a constant signal-to-noise ratio (+5). Numbers in parentheses represent the speech and noise levels employed to determine preferred REIG.

insertion gain at 4000 Hz, because prescribed gain was not achievable. Given the preference seen at 1000 and 2000 Hz, it is likely that group A subjects would also prefer less than the prescribed NAL-R gain at 4000 Hz.

Difference between prescribed NAL-R REIG and preferred REIG increased as the overall signal level increased. Preferred REIG decreased by an average of 6–8 dB across frequencies for every 10-dB increase in stimulus level above 55 dB SPL (or approximately 56.2 dB SPL overall, when speech SPL was added to noise SPL). Negligible REIG was selected by the subjects for speech levels at or above 75 dB SPL. Although the magnitude of the decrease in preferred REIG varied across subjects, all seven subjects in group A showed the same pattern of gain reduction as the overall input speech level increased above 55 dB SPL.

Group B subjects also preferred greater REIG below 500 Hz and less REIG above 1000 Hz than that prescribed by NAL-R when speech was presented at 55 dB SPL. In contrast to group A subjects, who preferred 6–8 dB less REIG for every 10-dB increase in input level above 55 dB SPL, four of five group B subjects showed only a 2- to 4-dB decrease in preferred

REIG when the speech stimulus increased from 55 to 65 dB SPL. Further increase in the overall signal levels from 65 to 75 dB SPL, however, resulted in 10- to 12-dB reduction in preferred REIG. This magnitude of preferred REIG reduction continued to the highest level of stimulus presentation (i.e., 85 dB SPL speech). The remaining subject reported a 6- to 8-dB decrease in preferred REIG for every 10-dB increase in input level.

Figure 5 can be redrawn into mean input-REIG functions to better illustrate the mean differences in preferred REIG as a function of the level of the input signal between the two subject groups. Figure 6 reports such functions for 500, 1000, and 4000 Hz. It is clear that these subject groups differed in mean REIG preferences in three aspects: the stimulus level at which REIG preference changed (i.e., compression thresholds, indicated with arrows); the rate of REIG change; and the level at which unity gain was indicated. Group A subjects revealed a steady decrease in REIG when the speech level exceeded 55 dB SPL. In most cases, unity gain was indicated at a speech level of 75 dB SPL (or overall level of 76.2 dB SPL). Group B subjects did not reveal large difference in preferred REIG until the input speech level was at or above a level of 65 dB SPL. Unity gain was not indicated even at 85 dB SPL speech level.

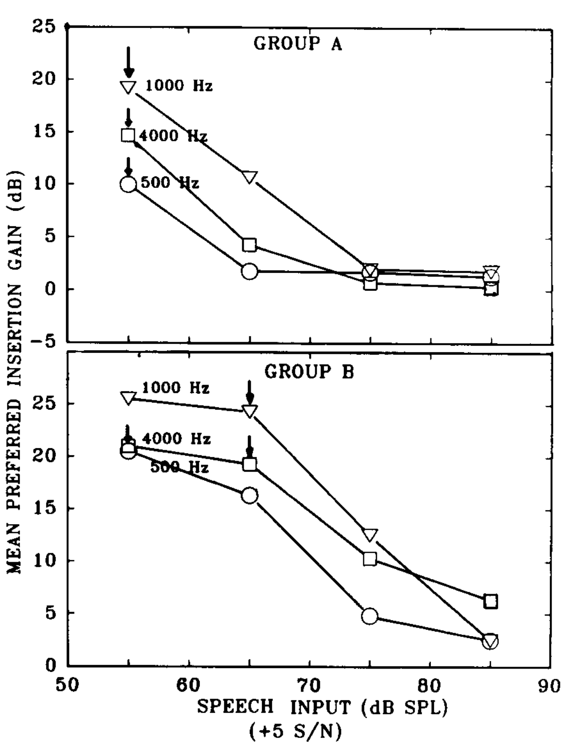

Figure 6 Mean preferred input-gain functions replotted from Figure 5 for 500 Hz, 1000 Hz, and 4000 Hz at different speech input levels. Upper panel represents group A while lower panel represents group B subjects. Arrows indicate input level at which significant gain reduction occurred (i.e., compression thresholds).

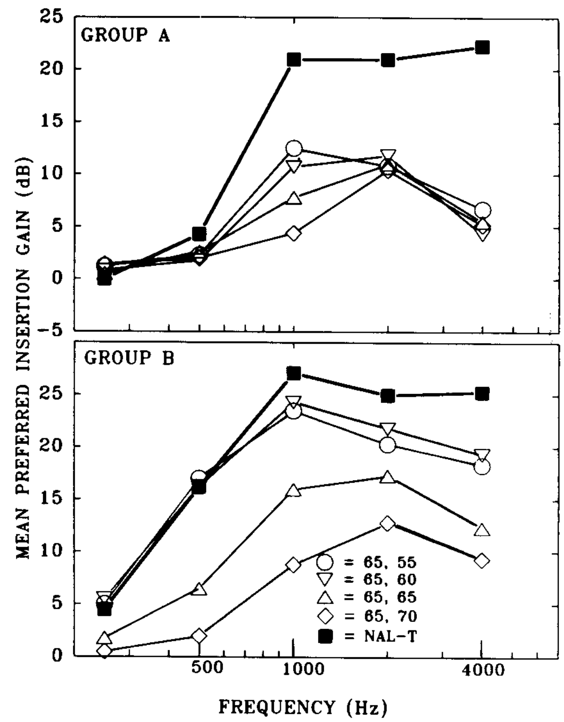

Figure 7 Mean preferred REIG at different signal-to-noise ratios (at fixed speech level of 65 dB SPL) for group A (upper panel) and group B (lower panel). Numbers in lower panel represent the speech (fixed at 65 dB SPL) and noise levels employed to determine preferred insertion gain.

Preferred REIG at Different Signal-to-Noise Ratios (Speech Level Constant)

Figure 7 reports preferred REIG at four signal-to-noise ratios when speech level was fixed at 65 dB SPL. Two observations can be made about the preferred REIG on group A subjects. First, preferred REIG at a speech input level of 65 dB SPL (regardless of S/N) was lower than target NAL-R REIG. Second, noticeable decreases in preferred REIG were only observed at 1000 Hz as the noise level increased. One observed approximately 3-dB decrease in REIG for every 5-dB increase in noise level above 60 dB SPL. Preferred REIG above and below 1000 Hz remained the same for the range of noise levels used.

Group B subjects selected similar amounts of REIG when the signal-to-noise ratios were at +10 (65 speech, 55 noise) and +5 (65 speech, 60 noise). Unlike the subjects in group A, who revealed no reduction in REIG in the high-frequency region as S/N became poorer, group B subjects selected less overall REIG across all frequencies as the noise level was increased above 60 dB SPL. The 10-dB increase in noise level from 60 to 70 dB SPL resulted in a 16-dB decrease in preferred REIG below 1000 Hz and approximately 10-dB decrease in preferred REIG above 2000 Hz. Unlike the uniform decrease in REIG across frequencies with increasing speech levels, both groups of subjects demonstrated preference for more decrease in REIG in the low-frequency region and less decrease in REIG in the high-frequency region as noise level was increased.

DISCUSSION

The present study examined the effects of signal and noise levels on preferred REIG using subjective speech clarity as a criterion. The results showed a general decrease in preferred REIG as the input level increased. The change in preferred REIG, however, was dependent on whether the speech or noise level was varied and on the configuration of the listener's hearing loss. These results provide one avenue to evaluate how a hearing aid with adaptive frequency/gain response circuitry (i.e., ASP and AGC) should respond to changing input levels. These results, however, must be considered preliminary, as more definitive specification in the design and/or fitting of an adaptive frequency/gain response circuit would require data from more subjects, as well as data collected under more test conditions.

Difference in Preferred REIG between Subject Groups

Listeners in both subject groups preferred more REIG in the lower frequencies than prescribed by NAL-R when speech was presented at 55 dB SPL (S/N = +5). The average listener selected REIG that approximated to 20 percent of their hearing loss at 250 Hz and 40 percent of their hearing loss at 500 Hz. This finding may be useful as an initial estimate to select optimal low-frequency REIG for soft speech.

Subjects in groups A and B differed in the input level that resulted in significant reduction in preferred REIG, the rate of reduction of REIG, the stimulus level yielding unity gain, and reactions to changes in noise levels. Such differences could be related to the better low- to mid-frequency hearing sensitivity of group A subjects and the use of a larger diameter vent. These subjects would require minimal or no REIG in the low- and mid-frequency regions. Furthermore, because listeners typically prefer more low-frequency emphasis and less high-frequency emphasis during a subjective clarity judgment task than during a syllable identification task (e.g., Kuk and Pape, 1992), subjects in this experiment would probably prefer less high-frequency REIG than prescribed by NAL-R while listening to discourse passages that were presented at or above average conversational level. Because group A subjects selected minimal low-frequency gain (below 1000 Hz) in the favorable S/N conditions (i.e., +10 and +5), gain reduction with increase in noise level was necessarily restricted to the lowest frequency region where some gain was selected (i.e., 1000 Hz).

Comparison with AGC Hearing Aids

The decrease in preferred overall REIG across frequencies with increasing input level (at a fixed S/N) is reminiscent of the action of an AGC circuit. The observation of greater attenuation of preferred REIG in the low-frequency region and less attenuation of preferred REIG in the high-frequency region with increasing noise levels reminds one of the combined action of an ASP and AGC circuit. These preferred gain changes affirm the need for hearing aids that can adaptively adjust their frequency/gain responses with changing input levels. This could be beneficial, at least for the optimization of speech clarity. The question that is raised in this study is whether the adaptive changes seen in current hearing aids reflect listener preference for such change. A direct comparison between the results of this study and the actions of each commercially available AGC and ASP circuits is beyond the scope of the manuscript. Rather, the following discussion will focus on the implications of the findings, with references to available hearing-aid technology only when deemed necessary.

Figure 6 shows that the preferred REIG decreased as the input levels increased. The stimulus level at which this decrease occurred, however, (i.e., compression thresholds) is different between frequencies and between the two subject groups. In addition, compression circuits with fixed compression ratios (CR) may not be optimal for subjective clarity judgment at all input levels. This becomes evident when

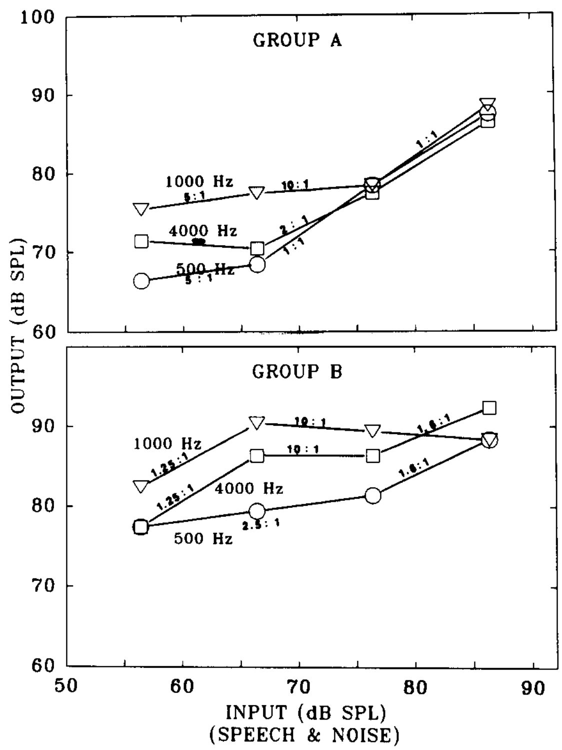

Figure 8 Input-output functions replotted from Figure 5 for group A (upper panel) and group B (lower panel) at 500 Hz, 1000 Hz, and 4000 Hz. Calculated compression ratios for each segment of the curve are also indicated.

one examines the input-output functions in Figure 8. These functions relate the preferred output level as a function of combined input level. The output SPL is calculated by adding the combined speech and noise levels to the gain (shown in Fig. 6) selected at that input. For example, the 76.2 dB SPL output reported at 1000 Hz for group A subjects at an input level of 56.2 dB SPL (the sum of 55 dB SPL speech and 50 dB SPL noise) is the sum of the input level and the 20-dB gain reported earlier for that input level. If CR is calculated as the change in input level to the change in output level, the 2-dB increase in output level at 500 Hz and 1000 Hz and 1-dB decrease in output level at 4000 Hz seen in group A subjects as the combined input level was increased from 56.2 dB SPL to 66.2 dB SPL would suggest a CR of 5:1 for 500 Hz and 1000 Hz. At 4000 Hz, assuming that the observed decrease actually reflects no increase in output with input change, one would need an AGC circuit with an infinite CR in order to match the listener's preference. Between an input level of 66.2 dB SPL and 76.2 dB SPL, a CR of 1:1 or unity gain may be desirable at 500 Hz; a CR of 10:1 may be desirable at 1000 Hz, and a CR of 2:1 may be desirable at 4000 Hz. Above 76.2 dB SPL, unity gain is preferred at all three frequencies. Subjects in group B may also prefer different CRs at different input levels. These CR values are also indicated on the figure.

While the absolute values of the CR indicated would likely change with different response criteria or different test conditions, the input-output functions revealed in Figure 8 suggest that different compression ratios are needed in order to optimize speech clarity when discourse passages are presented at various intensity levels (but at a constant S/N). The fairly constant output seen in group B subjects as the input varied from 56.2 to 86.2 dB SPL can be achieved with a compression circuit that has a wide range of compression thresholds and ratios. Such flexibility is needed in order to accommodate: (1) individual variations in hearing loss and gain preference; and (2) variations in gain preference as input levels in various listening environments change. Some current programmable hearing aids with compression and multiple memories can accomplish this goal. Each memory on the device may be adjusted with CR settings appropriate for a specific range of input levels. Alternatively, a compression hearing aid with appropriate level-dependent compression ratios may accommodate the level variations. In both cases, the selection of CR settings must be performed on an individual basis in order to ensure optimal results.

Comparison with ASP Hearing Aids

Kuk and Pape (1992) reported similar preferred REIG selected with discourse passages in quiet (70 dB SPL) and in noise (S/N = +5). This was observed in this study when the signal-to-noise ratios were favorable (i.e., S/N ≥ +5). In addition, this study showed that less low-frequency gain would be selected as the S/N becomes poorer (i.e., S/N ≤ 0) (Fig. 7).

The signal-to-noise ratio of the input signal also affected the preferred REIG. At a favourable S/N (≥ +5), changes in S/N led to a uniform decrease in REIG across all frequencies. At a poor S/N (≤ 0), decreasing S/N led to more gain reduction in the low-frequency region than in the high-frequency region. An additional confirmation of dissimilar preferred REIG for favorable and unfavorable S/Ns is revealed in Figure 9. This figure includes all the preferred REIG curves reported in Figures 5 and 7 for group B subjects. Of special interest is the

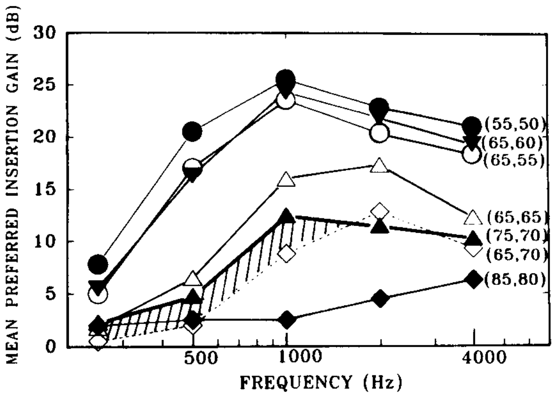

Figure 9 Mean preferred REIG for group B determined at fixed signal-to-noise ratio while varying overall input level (from Fig. 5) and at fixed speech level while varying the noise level (from Fig. 7). Numbers in parentheses represent the speech and noise levels used to determine preferred insertion gain. The shaded area represents the reduction in preferred REIG when the S/N was changed from +5 to −5.

preferred REIG selected with a speech signal of 65 dB SPL and a noise level of 70 dB SPL (dotted line) and the preferred gain selected with a speech level of 75 dB SPL and a noise level of 70 dB SPL (darkened line). Despite the higher overall level in the 75 dB SPL speech condition, the average group B subject preferred less low-frequency gain (below 1000 Hz) and similar high-frequency gain in the 65 dB SPL speech condition than in the 75 dB SPL speech condition (see shaded area).

This observation confirms that high-pass filtering may enhance clarity judgments when speech is presented in noise, but only when the signal-to-noise ratios are poorer than +5. It further suggests the possibility that the adaptive action (AGC and ASP) of the hearing aid will need to differ, depending on the S/N of the input signal. This requires the adaptive circuit not only to respond to the overall rms or peak level of the input signal (which is the approach on which most if not all ASP and AGC circuits operate), but also to decide if the input signal has a favorable S/N, in order to apply the appropriate amount of attenuation. Although attempts were made to utilize the statistical properties of speech and noise in designing ASP circuitry (Graupe, Grosspietsch, and Taylor, 1986), implementation may be difficult, because for most hearing-aid wearers, the most bothersome background noise is speech babble, which has similar spectral characteristics to the speech signal. Filtering of the noise spectrum will lead to concomitant degradation of the speech signal. Alternative strategies to enhance hearing-aid use in noise are necessary.

Group B subjects also selected less high-frequency gain as the noise level was increased. This contrasts the action of the typical ASP circuit and suggests that some high-frequency gain reduction may be necessary for some hearing-aid wearers. Although AGC and ASP circuits can be designed into a single hearing aid to yield more low-frequency attenuation and less high-frequency attenuation with increasing input level, such combinations may not yield the desired results at this time. Conceptually, if both circuits are activated by the peak or rms SPL of the input signal, one may overattenuate the low-frequency region of the input signal when it is primarily speech (i.e., favorable S/N) and overattenuate the high-frequency region of the input signal when the signal-to-noise ratio is poor.

At this point, hearing aids are not effectively designed to handle speech/noise determination. In order to ensure optimal clarity of speech, one may have to involve the hearing-aid wearer in adjusting the hearing aid to meet changing environmental needs. There may be three approaches to consider. In all these approaches, the wearer decides if the input signal has a favorable signal-to-noise ratio (i.e., whether it is primarily speech or noise). First, wearers of conventional hearing aids will need to turn the volume control down for loud speech and switch the N-H tone control to the H-position (and possibly reduce the VC) for loud, noisy speech. The second approach is to use a multimemory hearing aid and instruct the wearer to select the appropriate memory that is programmed for the specific condition. For example, if the input signal is loud but clear (i.e., favorable S/N), the wearer may use a memory that is programmed with a moderately intense input at a favorable S/N (e.g., input between 65 and 70 dB SPL at +5 S/N). On the other hand, if the external signal is noisy but not too loud, the wearer may use a memory programmed with a typical or moderately intense signal presented at a poor S/N ratio (i.e., 65 dB SPL speech at S/N = −5). The third approach is to use an AGC hearing aid (with appropriate compression ratios and thresholds) with user-activated, adaptive, high-pass control. In this case, the AGC circuit would handle the level variation while the user determines if additional filtering is necessary to improve speech clarity.

In summary, the preferred REIG exhibited by subjects in this study would suggest that an adaptive frequency/gain response hearing aid would need to possess features of both AGC and ASP circuits in order to enhance speech clarity in various combinations of speech and noise. In addition, it needs to be flexible enough so that it can finetune its adaptive responses to the listeners' needs and be "intelligent" enough to recognize speech from noise in order to self-adjust to the appropriate setting for optimal processing. These considerations have not yet included the temporal changes in the waveform brought about by the AGC action of the hearing aid (e.g., release time) or the change in preferred REIG with changes in response criteria (i.e., clarity versus intelligibility). Such considerations would also be critically important in defining the operations of such hearing aids.

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APPENDIX

Instructions for paired comparison.

This short passage will be processed by two different hearing-aid settings. As you listen, I will indicate to you which is hearing aid #1 and which is hearing aid #2. Your task is to indicate which hearing aid yields clearer speech by raising the appropriate number of fingers. That is, raise one finger if the sound quality of the short passage processed by hearing aid #1 is clearer and raise two fingers if the sound quality of the passage processed by hearing aid #2 is clearer. Please refrain from speaking as much as you can during the comparison. Base your impression of the hearing aid on the clarity of the short passages only. Do not base your decision on the quality of your own voice if and when you speak. If you need the passage repeated, please circle your index finger in the air to indicate such needs. Do you have any questions before we start?