Efficacy of 3 Commonly Used Hearing Aid Circuits

A Crossover Trial

Vernon D. Larson, PhD
David W. Williams, MS
William G. Henderson, PhD
Lynn E. Luethke, PhD
Lucille B. Beck, PhD
Douglas Noffsinger, PhD
Richard H. Wilson, PhD
Robert A. Dobie, MD
George B. Haskell, PhD
Gene W. Bratt, PhD
Janet E. Shanks, PhD
Patricia Stelmachowicz, PhD
Gerald A. Studebaker, PhD
Allen E. Boysen, PhD
Amy Donahue, PhD
Rinaldo Canalis, MD
Stephen A. Fausti, PhD
Bruce Z. Rappaport, PhD
for the Participants of the NIDCD/VA Hearing Aid Clinical Trial Group

Context Numerous studies have demonstrated that hearing aids provide significant benefit for a wide range of sensorineural hearing loss, but no carefully controlled, multicenter clinical trials comparing hearing aid efficacy have been conducted.

Objective To compare the benefits provided to patients with sensorineural hearing loss by 3 commonly used hearing aid circuits.

Design Double-blind, 3-period, 3-treatment crossover trial conducted from May 1996 to February 1998.

Setting Eight audiology laboratories at Department of Veterans Affairs medical centers across the United States.

Patients A sample of 360 patients with bilateral sensorineural hearing loss (mean age, 67.2 years; 57% male; 78.6% white).

Intervention Patients were randomly assigned to 1 of 6 sequences of linear peak clipper (PC), compression limiter (CL), and wide dynamic range compressor (WDRC) hearing aid circuits. All patients wore each of the 3 hearing aids, which were installed in identical casements, for 3 months.

Main Outcome Measures Results of tests of speech recognition, sound quality, and subjective hearing aid benefit, administered at baseline and after each 3-month intervention with and without a hearing aid. At the end of the experiment, patients ranked the 3 hearing aid circuits.

Results Each circuit markedly improved speech recognition, with greater improvement observed for soft and conversationally loud speech (all 52-dB and 62-dB conditions, $P \leq .001$). All 3 circuits significantly reduced the frequency of problems encountered in verbal communication. Some test results suggested that CL and WDRC circuits provided a significantly better listening experience than PC circuits in word recognition ($P = .002$), loudness ($P = .003$), overall liking ($P = .001$), aversiveness of environmental sounds ($P = .02$), and distortion ($P = .02$). In the rank-order ratings, patients preferred the CL hearing aid circuits more frequently (41.6%) than the WDRC (29.8%) and the PC (28.6%) ($P = .001$ for CL vs both WDRC and PC).

Conclusions Each circuit provided significant benefit in quiet and noisy listening situations. The CL and WDRC circuits appeared to provide superior benefits compared with the PC, although the differences between them were much less than the differences between the aided vs unaided conditions.

JAMA. 2000;284:1806-1813 www.jama.com

Sensorineural hearing loss is one of the most prevalent disabling conditions reported in the United States, affecting some 20 million to 26 million people.[1-3] Hearing loss is present in 35% to 42% of individuals older than 65 years.[4-6] It adversely affects physical, cognitive, behavioral, and social function, as well as the general quality of life,[7] and has been linked to depression and dementia.[8-10]

While hearing aids are the main form of treatment, only about 20% of those who could benefit from hearing aids wear them.[2,3,11] Moreover, surveys have suggested that about 50% of hearing aid users are dissatisfied with their instruments.[12] A recent survey, however,

Author Affiliations and a complete list of the members of the NIDCD/VA Hearing Aid Clinical Trial group are listed at the end of this article.
Corresponding Author and Reprints: Vernon D. Larson, PhD, Howard Leight Industries, 7828 Waterville Rd, San Diego, CA 92154 (e-mail: vlarson@howardleight.com).

suggested that because of improved technology, approximately 65% of hearing aid users are satisfied with their devices.[13]

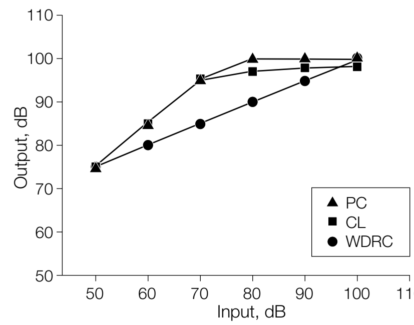
A vast array of hearing aid technologies is available, ranging from simple and relatively inexpensive analog circuits to complex and expensive digital devices that require sophisticated fitting procedures. Whereas numerous studies have demonstrated that hearing aids provide significant benefit compared with unaided listening for persons with hearing losses ranging from mild to severe,[14-17] carefully controlled, multicenter clinical trials of the relative benefit provided by different types of hearing aids have not been conducted. Laboratory studies and small-scale field studies have been designed in ways that make them difficult to compare and have failed to show consistent superiority for any type of signal processing.[18,19]

Choices among available hearing aids must be made without the benefit of data from well-designed clinical trials. This report presents the results of a double-blind, multicenter clinical trial to compare the efficacy of 3 different hearing aid circuits. Efficacy was measured in a variety of listening situations using tests of speech understanding, sound quality, and patient rank-order ratings. The 3 hearing aid circuits jointly account for 70% of the US hearing aid market.

The clinical trial compared 3 commonly used hearing aid circuits: the linear peak clipper (PC), the compression limiter (CL), and the wide dynamic range compressor (WDRC). The PC and CL circuits amplify input sounds linearly up to a predetermined level (usually set relative to loudness discomfort levels). Above that level, the output is limited using 2 different electronic methods. FIGURE 1 illustrates the major difference among the 3 circuits. For the PC, as the input signal level increases by 10 dB, so does the output level up to its maximum output capabilities when the instrument is said to be in "saturation." The CL operates similarly in that the output increases linearly up to a certain point. After that, however, the output is reduced by circuitry that automatically turns down the gain of the hearing aid by a fixed ratio. In this instance, the output is allowed to increase by 1 dB for each 10-dB increase in the input sound level. Finally, the WDRC behaves similarly to the CL circuit except that the automatic gain function begins at lower input sound levels and allows, in this instance, the output to increase 1 dB for each 2 dB increase in input sound level up to its point of maximum output.

The PC removes the positive and/or negative peaks of the amplified signal, whereas the CL uses automatic volume control circuitry. A disadvantage of PC circuitry is that some acoustic distortion results when the output limit is exceeded.[20,21] Far less distortion is created by CL circuitry.[22] The WDRC circuit allows input signals that vary in level over a wide range to be amplified as a narrower range of output signals,[23,24] which is associated with the reduced dynamic range found in the majority of sensorineural hearing loss. Although theoretically beneficial to listener comfort and speech understanding, a disadvantage of compression circuits (eg, CL and WDRC) is that they alter the temporal characteristics of signals in a way that can be apparent to the listener.[25,26]

Figure 1. Performance Characteristics of 3 Hearing Aid Circuits



PC indicates linear peak clipper; CL, compression limiter; and WDRC, wide dynamic range compressor.

METHODS

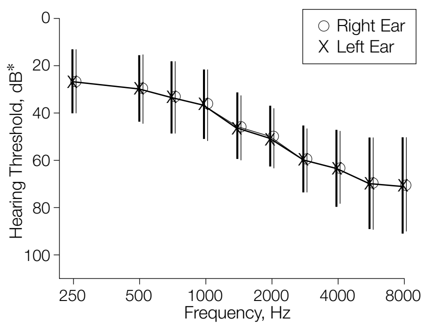
Trial Design

Eight audiology laboratories located within Department of Veterans Affairs (VA) medical centers participated. The experimental design was a 3-period, 3-treatment crossover design. Baseline measurements were made using a battery of tests in the unaided condition (no hearing aids). Patients were then stratified by center and randomized to 1 of 6 sequences of the 3 hearing aid circuits. Six sequences were used so that each hearing aid circuit had approximately an equal number of patients who used the circuit first, second, and third. Each block of 6 consecutive patients within each center was balanced so that each sequence was represented once. The actual frequencies for the 6 sequences in the trial ranged from 59 to 61. In each of the 3 periods, the patients were fit binaurally and used 1 circuit (aided condition) for 3 months. At the end of each period, the battery of outcome tests was repeated in both the unaided and aided conditions. The protocol was conducted in double-blind fashion. Neither the audiologist who administered the tests nor the patient could identify the circuit being worn because all 3 hearing aid circuits resided in the same casement and because a different audiologist programmed the device.

Patient Sample

The protocol was approved by the National Institute on Deafness and Other Communication Disorders (NIDCD) Hearing Aid Advisory Committee, the Hines VA Cooperative Studies Program Coordinating Center's Human Rights Committee, and by the institutional review board of each participating center. All patients provided informed consent, were fluent speakers of English, and had bilaterally symmetrical sensorineural losses with no evidence of retrocochlear pathology. Average audiometric thresholds for 500, 1000, 2000, 3000, and 4000 Hz were no better than 25-dB hearing level in either ear, with no threshold from 500 to 2000 Hz exceeding 70-dB hearing level. FIGURE 2 shows the mean (±1 SD) audiogram. To ensure that the sample included patients who were typical of the majority of adult hearing aid users, monaural word recognition scores

Figure 2. Mean Audiogram of Patient Sample (N=360)



Error bars for each ear indicate the range from 1 to −1 SD; the darker error bar on the left in each pair corresponds to the left ear. Asterisk indicates values based on American National Standards Institute guidelines for 1996.

on a recorded version of the Central Institute for the Deaf W-22 test[27] were required to be at least 28%, with a difference no greater than 26% between ears.

Experimental Apparatus

Each participant was fit binaurally with single channel, programmable, full-concha in-the-ear hearing aids (Dyna P2, Phonak, Stäfa, Switzerland) that contained all 3 circuit options. The National Institute of Standards and Technology evaluated prototypes to ensure that characteristics of the hearing aid conformed to the manufacturer's specifications.

The 3 programmable options were PC, CL, and WDRC. The CL had an 8:1 compression ratio (above compression threshold, an 8-dB increase in the input level resulted in only a 1-dB increase in the output) and duration-dependent release time capability. The WDRC had a fixed-compression threshold (approximately 52-dB input sound pressure level [SPL]), a compression ratio that ranged from 1.1:1 to 2.7:1 and a short, fixed release time (50 milliseconds). The maximum output levels of the 3 circuits were programmable over approximately the same range of SPLs.

Electroacoustic measurements[28] were made at each visit to ensure that hearing aid characteristics remained stable. Acoustic gain targets were established using the NAL-R method,[29] and probe microphone procedures were used to verify that targets had been achieved. Maximum output targets were obtained using loudness discomfort levels[30] and were subsequently held constant across visits and circuit types.

Outcome Test Battery

All testing was carried out in audiometric test rooms using identical equipment for test presentation and data collection at each site. Three categories of outcome measures were used: speech recognition tests, category ratings of perceived sound quality, and self-assessed subjective ratings of hearing aid benefit.

Speech Recognition

Two tests of speech recognition were used. A recorded version of a monosyllabic word-recognition test, the NU-6,[27] was presented using a single loudspeaker (positioned at 0°; ie, patients faced the loudspeaker) at an SPL of 62 dB (conversational speech level). Each of the 4 NU-6 lists contains 50 scoreable items with each item having a value of 2%. At conversational speech levels, listeners with normal hearing obtain perfect monosyllabic word recognition scores. The second test, a recorded version of the Connected Speech Test (CST),[31,32] consists of 48 passages with 8 to 10 sentences that approximate everyday, connected discourse. Because it was unlikely that a single laboratory condition could represent the range of possible listening conditions, we conducted this test in a variety of presentation and background-noise levels. The CST was presented via the loudspeaker (located at 0° azimuth) at a level of 74-dB SPL (loud speech) in quiet and then again at 74 dB in 3 background noise conditions. For SPLs of 52 dB (soft) and 62 dB (conversational loudness), the speech materials were presented in 3 conditions of background noise.

The background noise used was an uncorrelated multitalker babble,[31] which was delivered from loudspeakers located at azimuths 45° left and right at nominal signal-to-babble (S/B) ratios of −3 dB, 0 dB, and 3 dB. The S/B ratio refers to the relationship of the SPL of the speech to the SPL of the background babble. The nominal 0-dB S/B condition was estimated during the baseline visit prior to conducting tests for each patient by presenting CST practice materials at 62-dB SPL in the "unaided" condition using a bracketing procedure in which the binaural babble level was varied for each subject to produce 50% intelligibility. (The mean [SD] level of the babble was 55 [5.4] dB.) This relationship for each subject was designated as the 0-dB condition. The same S/B ratio for each subject was used for the −3-dB and 3-dB conditions, and for all tests conducted over the 9-month protocol, the same ratios were used. Normal listeners typically receive perfect scores at loud and conversational levels in a quiet background, but their performance at softer levels and in the presence of background noise varies as a function of the difficulty of the listening situation.

Category Ratings

The Quality Rating Test, was used to assess 3 aspects of patients' perception of sound quality: loudness, noise interference, and overall liking of the listening experience. The patients rated each dimension on a 10-point scale. On the loudness scale, 1 was too soft; 10, too loud; and 5, comfortably loud. For overall liking, 1 was very poor or terrible and 10 was excellent. In this task, the patients were instructed to ignore the loudness of the speech and consider only the overall sound quality. For noise interference, they assigned a 1 if noisiness completely interfered with quality and understanding of the speaker and 10 if noisiness did not interfere. Intermediate integer ratings could be assigned for all tests. Sentences designated as practice sentences of the CST[31] served as the stimuli for the Quality Rating Test. Patients were presented 5 different sentences and provided a rating after each presentation, which were were then averaged. The sentences were presented at an SPL of 52 dB, 62 dB, and 74 dB in a quiet background and then in the multitalker babble (S/B ratio, 10 dB).

Subjective Ratings

Two measures were used to elicit expressions of the quality of hearing aid performance from the patients. One was the Profile of Hearing Aid Performance/Profile of Hearing Aid Benefit (PHAP/PHAB), which quantifies 2 major aspects of hearing aid performance: speech communication in a variety of daily life situations and reactions to the loudness and quality of environmental sound.[33] For the PHAP/PHAB, 7 subscale scores were derived from the 66 items of the inventory that were completed by the patient in written format. The scales quantify problems in communication in favorable and unfavorable listening conditions as well as the aversiveness and distortion of a variety of sounds. The 7 subscales include communication with familiar talkers, ease of communication, reverberation, reduced cues, background noise, aversiveness of sound, and distortion of sound. At the end of each of the 3 trial periods, the patients completed the PHAP/PHAB inventory in the unaided and aided conditions using a 7-point scale that ranged from always to never. The PHAP scores quantify the scale scores in terms of aided performance, while PHAB scores quantify the scale scores in terms of benefit (ie, the difference between the aided scores and unaided scores). Hence, in the PHAP, scores for all subscales are reported in terms of percentage of time a problem is experienced and scores for the PHAB are reported in terms of the change in percentage of time a problem is experienced.

The second subjective assessment procedure was used at the final visit only. After having completed each of the 3 treatments, the patients provided, from memory, a rank-order rating of the 3.

Statistical Methods

A crossover design was chosen for this study instead of the more traditional randomized, parallel group design because it required fewer patients, eliminated between-patient variation, and it increased power for other objectives of the trial (eg, to determine which patient characteristics predict success with the different hearing aid circuits). In addition, some of the known disadvantages of the crossover design (eg, large dropout rate, instability of the patient's condition, and a large carryover effect) were not expected in this study. The 3 circuits were compared using aided scores and aided minus unaided scores (benefit scores) with a repeated measures analysis.

The sample of 360 patients provided at least 80% power to detect a small-to-medium effect size for the patients' rank-order rating among the 3 circuits. This sample size also provided greater than 95% power to detect a 7.2% difference in the NU-6 test, greater than 95% power to detect a 3.6% difference in the CST, greater than 90% power to detect a 20% difference in the Quality Rating Test, and 90% power to detect a 16.6% difference in the PHAB.

A mixed, repeated measures model was used to compare the 3 hearing aid circuits for the individual outcome variables. If the overall test was statistically significant, then pairwise comparisons were made between the groups using the Bonferroni procedure to adjust the α level for multiple tests. No adjustment was made for multiple outcomes. For this reason, P values close to .05 should be interpreted with caution. Sample sizes reported for specific tests and conditions departed somewhat from 360 because some patients did not complete the study, some were unable to perform the task, or, occasionally, the examiner was unable to follow the study's protocol.

RESULTS

Patient Sample

Four hundred forty-six patients were screened for inclusion in the trial and 360 (80.7%) were randomized. Of the patients who were not randomized, 15 were excluded on the basis of a single criterion, but most failed to meet 2 or more of the inclusion criteria. The main reasons included: air conduction thresholds exceeded 70 dB in either ear (20); a difference in pure tone averages between ears of more than 10 dB (17); mean air-bone gap exceeded 5 dB in either ear (13); or routine otoscopy did not reveal clear ear canals (13). In 7 instances, the audiologist did not feel that the patient was capable of performing the tasks required by the trial.

Of the 360 patients enrolled, 69.7% were military veterans. The mean age of the group was 67.2 years (range, 29-91 years). The racial/ethnic distribution approximated that of the US population: 78.6% were white; 12.2% black; 6.1% Hispanic; 1.9% Asian; and 1.1% Native American. Fifty-seven percent were men; women were mainly nonveteran patients who were authorized to be treated at VA medical centers for the purposes of this trial because the study grant funded the cost of the hearing aids and the time of the treating and evaluating audiologists. The most common self-reported causes of the patient's hearing loss were noise exposure and aging. About half (46.7%) had never used a hearing aid.

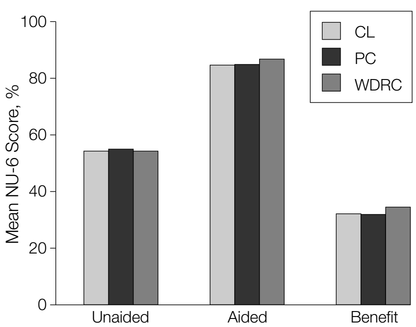
The number of patients from each center was nearly equal (range, 44-46). None of the groups representing the 6 randomized orders were statistically different in terms of age, age at onset of hearing loss, sex, race, previous hearing aid usage, and degree of hearing loss ($P \geq .11$ for all comparisons). Twenty-nine of the 360 patients did not complete the trial due to illness, relocation of residence, or other reasons (eg, withdrawal of patient consent, illness unrelated to hearing, death, sudden change in hearing). Three hundred thirty-seven patients completed the 90-day trial with the PC circuit, 338 with the CL, and 333 with the WDRC. The average reported hearing aid use time for the 3 circuits did not differ significantly and averaged about 9.8 (SD, 4) hours per day.

Speech Recognition Tests

FIGURE 3 provides a summary of the mean percentage correct results for the unaided and aided conditions for the

NU-6 test for each of the 3 circuits together with the benefit scores (aided minus unaided). For statistical testing, percentage correct scores for the NU-6 test were arcsine transformed to stabilize the error variance.[34] Comparison of the unaided means with the aided means showed that each of the 3 circuits improved the mean word recognition score by a substantial amount (approximately 29% in absolute score differences; $P<.001$). The overall statistical test comparing the 3 circuits was significant ($P=.002$ for the aided scores and $P=.002$ for the benefit scores). Pairwise comparison tests showed that the WDRC circuit was superior to the other 2 circuits for the aided scores and superior to the PC circuit for the benefit scores.

Figure 3. Mean Percentage of Correctly Recognized Monosyllabic Words



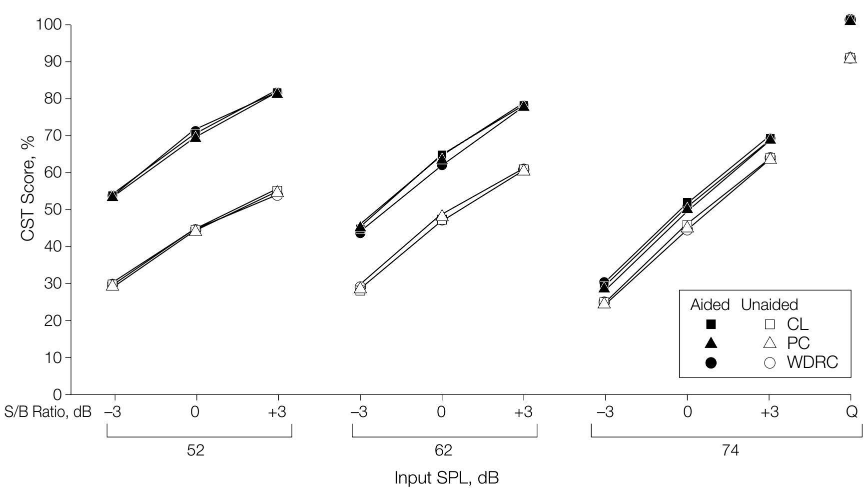
CL indicates compression limiter; PC, linear peak clipper; and WDRC, wide dynamic range compressor. The unaided values were obtained in the same test session as the aided values. Sample sizes varied slightly across conditions (320 to 324 for the aided conditions and 288 to 291 for the unaided conditions).

FIGURE 4 summarizes the findings for the aided and unaided CST results. Percentage correct scores were arcsine transformed to stabilize the error variance.[34] As expected, there were no differences among unaided means. However, significantly higher CST scores ($P<.001$) were achieved for all aided conditions relative to the unaided conditions. The overall statistical test comparing the 3 circuits for aided CST scores was significant for 1 condition (62/0; $P=.006$). Pairwise comparisons showed that the WDRC circuit was inferior to the CL and PC circuits.

The mean CST benefit scores (aided minus unaided) are shown in FIGURE 5. Comparison of the 3 circuits showed significant differences for the 62/0 ($P=.04$) and 74/0 conditions ($P=.02$). Pairwise comparison tests showed that for the 62/0 condition, the WDRC circuit was inferior to the CL circuit; and for the 74/0 condition, the WDRC circuit was superior to the CL circuit.

The data presented in Figures 4 and 5 also show that the 3 circuits provided similar amounts of improvement in test scores, but all showed successively less benefit as a function of signal level when background noise was present. A marked decrease in CST benefit scores from about 26% for the 52-dB conditions to approximately 6% for the 74-dB conditions was observed, suggesting that the hearing aids were less helpful at higher than at lower and moderate input levels. Furthermore, the Figures show that all 3 circuits provide measurable benefit in noisy conditions.

Figure 4. Connected Speech Recognition of Different Ratios of Signal to Ambient Noise



CL indicates compression limiter; PC, linear peak clipper; WDRC, wide dynamic range compressor; and SPL, sound pressure level. Mean unaided and aided scores on the Connected Speech Test (CST) shown for 10 test conditions for the 3 circuits. The abscissa labels the conditions by signal/babble levels (dB) for 9 conditions (52/-3 through 74/+3). S/B indicates signal-to-babble; Q, that the test was performed in quiet. Sample sizes varied across conditions (from 280 to 322 for unaided conditions and 320 to 336 for aided conditions).

Quality Rating Test

The Quality Rating Test was administered at 3 signal levels in quiet (designated as 52Q, 62Q, 74Q) and elicited ratings of loudness, noise interference, and overall liking. It was also administered at the same signal levels with an absolute S/B ratio of 10 dB (designated as 52N, 62N, and 74N), which means that the level of the speech was 10 dB greater than the level of the multitalker babble.

TABLE 1 shows no differences in the loudness ratings between the unaided means for each condition. Significant differences were observed, however, for the aided condition across the 3 circuits for both the quiet and background noise conditions for the lowest (52-dB SPL) and for the highest signal levels (74-dB SPL) ($P<.001$). The WDRC circuit was rated as being more comfortably loud (ie, a rating closer to 5) than the other 2 circuits for the 52-dB SPL conditions ($P=.003$) and 74-dB SPL conditions ($P=.003$). The CL circuit was more comfortably loud compared with the PC circuit for the 74-dB SPL condition.

A summary of data for the noise interference task is shown in TABLE 2. Analysis of the mean unaided data revealed no differences. For the aided data, the analysis also showed no significant differences among circuit types, except for the 62N condition ($P=.01$). Pairwise comparison revealed that the PC circuit scored higher (less noise interference) than the WDRC circuit.

A summary of data for the overall liking task is shown in TABLE 3. There were no significant differences between the unaided means at each condition. The analyses of the data among circuit types for the aided condition showed significance for the 74Q condition ($P = .001$). Pairwise comparisons across circuits showed that the PC was less liked than both the CL and the WDRC.

Finally, for each circuit, significant improvement in overall liking was observed for soft and conversational speech levels ($P \leq .05$). For the loud conditions (74Q, 74N), however, negative average benefit ratings were observed ($P \leq .01$) except for the 74N condition for the WDRC ($P = .39$), suggesting that the aided experience was rated as being less liked than the unaided experience for loud sounds.

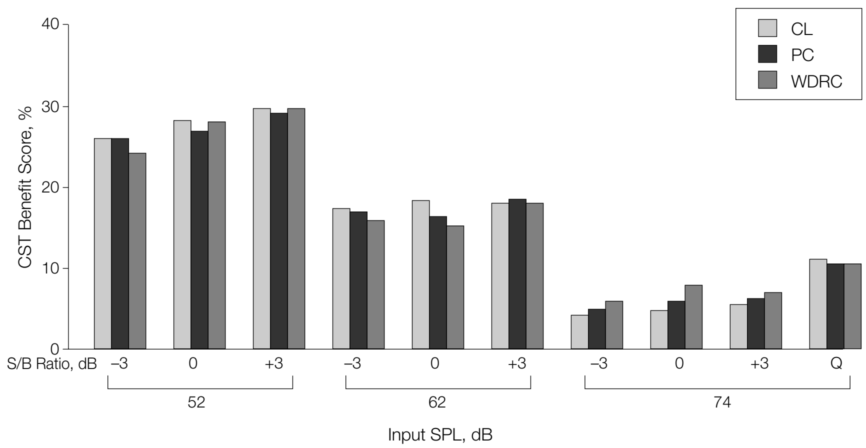
Subjective Assessment

No differences were observed among the unaided means for the PHAP. For the aided means, the analysis showed statistical significance ($P < .001$) for 2 of the 7 scales: distortion of sounds and aversiveness of environmental sounds. Pairwise comparisons showed that the scores for the PC were significantly different (ie, higher frequency of problems) than both the CL and WDRC circuits on the aversion and distortion scales ($P \leq .02$). The mean values for the PC circuit were 4% to 5% higher (ie, higher frequency of problems) for aversion and were 2% to 3% higher for distortion.

The PHAB scores also showed that each circuit significantly reduced the frequency of problems reported on 6 of the 7 scales ($P < .001$). For aversion, however, all circuits produced a significantly higher frequency of problems ($P < .001$) than in the unaided condition. In the analysis comparing circuit types, significant differences were observed for aversion ($P < .001$) and distortion ($P = .02$). Pairwise comparisons for aversion showed that the PC circuit was more aversive than both of the other circuits ($P = .003$) with the mean frequency of problems being 4% to 5% higher. The PHAB scores also showed that the PC score was significantly higher than the WDRC for distortion ($P = .02$) with the mean difference between PC and WDRC being 3%.

Finally, on completion of the study, the patients provided, from memory, a ranking of the 3 hearing aid circuits. The CL circuit received the highest percentage of first rankings (41.6%), followed by the WDRC (29.8%), and the PC (28.6%). In addition, the CL circuit was ranked third by the lowest percentage of patients (25.4% for the CL vs 36.2% for the PC and 38.4% for the WDRC).

Figure 5. Mean Benefit Scores on the CST of Different Ratios of Signal to Ambient Noise



Abbreviations are expanded in the legend of Figure 4. The abscissa labels the conditions as signal/babble level (dB) for 9 conditions (52/–3 through 74/+3). S/B indicates signal-to-babble; Q that the test was performed in quiet. Sample sizes across conditions varied from 277 to 321.

Table 1. Loudness Ratings Obtained in the Aided and Unaided Conditions*

Condition, dB	Type of Circuit	Aided No. of Subjects	Aided Mean (SD)	Aided P Value	Unaided No. of Subjects	Unaided Mean (SD)	Unaided P Value
52Q	CL	335	4.14 (0.94)	<.001†	318	2.77 (1.24)	.97
	PC	333	4.15 (1.00)		314	2.77 (1.31)	
	WDRC	330	4.43 (0.99)		312	2.78 (1.26)	
52N	CL	335	3.92 (1.06)	<.001†	318	2.46 (1.23)	.92
	PC	333	3.81 (1.08)		316	2.45 (1.24)	
	WDRC	328	4.21 (1.07)		312	2.43 (1.22)	
62Q	CL	335	5.33 (0.90)	.26	325	4.36 (1.21)	.48
	PC	333	5.34 (0.90)		325	4.31 (1.22)	
	WDRC	330	5.41 (1.00)		320	4.29 (1.16)	
62N	CL	334	5.31 (1.19)	.35	326	3.85 (1.27)	.73
	PC	333	5.20 (1.09)		325	3.86 (1.33)	
	WDRC	330	5.25 (1.31)		320	3.90 (1.37)	
74Q	CL	335	7.96 (1.55)	<.001‡	335	6.30 (1.63)	.84
	PC	333	8.31 (1.49)		332	6.28 (1.64)	
	WDRC	330	7.73 (1.59)		330	6.30 (1.67)	
74N	CL	335	7.57 (1.89)	<.001‡	335	5.88 (1.72)	.72
	PC	333	8.11 (1.69)		334	5.81 (1.74)	
	WDRC	330	7.26 (1.94)		330	5.87 (1.84)	

*CL indicates compression limiter; PC, linear peak clipper; and WDRC, wide dynamic range compressor.
†Pairwise comparison reveals PC and WDRC, and CL and WDRC are statistically significant.
‡Pairwise comparison reveals all 3 circuits are statistically significantly different.

Statistical analysis using the Friedman test showed a significant overall difference among the rankings ($P=.002$). Subsequent analyses using the Wilcoxon test showed that, overall, the CL was preferred more frequently than the PC ($P=.001$) and the WDRC ($P=.001$) and that there were no significant differences between the rankings for the PC and the WDRC ($P=.86$).

Table 2. Noise Interference Ratings Obtained in the Aided and Unaided Conditions*

		Aided			Unaided		
Condition, dB	Type of Circuit	No. of Subjects	Mean (SD)	*P* Value	No. of Subjects	Mean (SD)	*P* Value
52Q	CL	335	9.74 (0.93)		317	9.53 (1.33)	
	PC	332	9.80 (0.79)	.42	314	9.57 (1.15)	.16
	WDRC	329	9.74 (0.86)		309	9.45 (1.46)	
52N	CL	336	7.10 (2.24)		316	6.96 (2.43)	
	PC	332	7.18 (2.24)	.56	315	6.93 (2.41)	.99
	WDRC	330	7.07 (2.19)		309	6.95 (2.47)	
62Q	CL	336	9.83 (0.66)		323	9.66 (1.25)	
	PC	332	9.85 (0.53)	.86	324	9.74 (0.95)	.22
	WDRC	328	9.83 (0.57)		318	9.66 (1.15)	
62N	CL	336	6.41 (2.28)		320	6.36 (2.28)	
	PC	333	6.55 (2.34)	.01†	322	6.37 (2.29)	.62
	WDRC	329	6.17 (2.38)		317	6.47 (2.23)	
74Q	CL	336	9.74 (0.73)		332	9.67 (1.22)	
	PC	331	9.73 (0.85)	.92	330	9.74 (1.07)	.22
	WDRC	329	9.72 (0.77)		327	9.66 (1.20)	
74N	CL	336	5.13 (2.47)		334	5.48 (2.31)	
	PC	333	5.18 (2.48)	.69	333	5.37 (2.36)	.80
	WDRC	329	5.25 (2.65)		329	5.43 (2.34)	

*CL indicates compression limiter; PC, linear peak clipper; and WDRC, wide dynamic range compressor.
†Comparison of PC circuit with WDRC circuit, which is statistically significantly different in pairwise comparison tests.

Table 3. Overall Liking Ratings Obtained in the Aided and Unaided Conditions*

		Aided			Unaided		
Condition, dB	Type of Circuit	No. of Subjects	Mean (SD)	*P* Value	No. of Subjects	Mean (SD)	*P* Value
52Q	CL	335	7.70 (2.36)		316	5.63 (2.93)	
	PC	333	7.78 (2.39)	.14	314	5.56 (2.80)	.88
	WDRC	330	7.96 (2.21)		308	5.57 (2.81)	
52N	CL	335	6.77 (2.38)		316	4.86 (2.77)	
	PC	332	6.66 (2.45)	.64	314	4.87 (2.74)	.72
	WDRC	330	6.76 (2.33)		309	4.75 (2.76)	
62Q	CL	336	8.44 (1.85)		322	7.28 (2.53)	
	PC	331	8.43 (1.84)	.97	323	7.31 (2.55)	.28
	WDRC	330	8.45 (1.78)		318	7.14 (2.51)	
62N	CL	335	6.85 (2.27)		321	5.86 (2.55)	
	PC	330	6.97 (2.30)	.07	323	5.82 (2.51)	.90
	WDRC	330	6.70 (2.30)		318	5.79 (2.60)	
74Q	CL	336	7.43 (2.60)		331	7.73 (2.31)	
	PC	332	6.91 (2.76)	.001†	330	7.94 (2.23)	.08
	WDRC	329	7.49 (2.54)		325	7.72 (2.24)	
74N	CL	336	5.80 (2.57)		334	6.04 (2.39)	
	PC	331	5.59 (2.77)	.12	333	6.05 (2.55)	.70
	WDRC	330	5.92 (2.64)		329	5.97 (2.47)	

*CL indicates compression limiter; PC, linear peak clipper; and WDRC, wide dynamic range compression.
†Comparison of CL circuit with PC circuit and comparison of PC circuit with WDRC circuit are statistically different in pairwise comparison tests.

COMMENT

Each of the 3 hearing aid circuits provides substantial benefit over unaided listening. Benefit was observed for measures of speech recognition and ratings of speech quality in a variety of noisy and quiet conditions as well as for subjective measures. Each circuit improved monosyllabic word recognition scores in a quiet background at conversational levels by an average of 29% (absolute score improvement). Speech recognition ability, as shown by the CST, in noise was improved by each circuit by amounts ranging from 10% to 30% (absolute score improvement), with greater improvement observed for speech at soft and conversational levels. Loudness rating data suggested that all 3 circuits amplified soft and conversationally loud speech to comfortable levels. The noise interference ratings showed that none of the circuits had a deleterious effect. For soft and conversational speech levels, each circuit improved the overall quality of the listening experience. For loud speech, the overall quality of listening was not significantly degraded. The results of 6 of the 7 subscales of the subjective measure of hearing aid benefit (PHAB) showed a significant reduction in the frequency of problems associated with communication in everyday environments.

Statistically significant differences (small in comparison with the benefits seen with each of the circuits) were noted among the circuits on several components of the outcome measures. The results of the loudness rating suggest that the WDRC circuit was more comfortably loud than the other 2 circuits for soft and for loud speech input conditions. Because of its operating characteristics, the WDRC was expected to produce a more comfortable listening experience for the soft and loud input levels. Differences in scores on the PHAP/PHAB for 2 subscales were statistically significant among circuits, with the PC rated as 4.5% more aversive than the other 2 circuits and producing an average of 3% more problems for distortion of sounds compared with the WDRC circuit. The preference rankings provided at the end of the trial favored the CL circuit. Because the differences between the hearing aid circuits were small in most cases, dispensing decisions should take into account cost vs benefit considerations for individual patients. In this regard, many programmable hearing aids (such as the one used in this trial) may be configured to function as a PC, CL, or WDRC and, as such, there are no cost differences between circuit options; however, for conventional, nonprogrammable devices, compression circuitry (either CL or WDRC) adds significantly to the single-unit price of the device.

Because concerted efforts were made to recruit patients into the study from both sexes and all racial groups, the study sample was a good representation of US adults who are candidates for hearing aids. We believe, therefore, that the study results are generalizable to the US population with sensorineural hearing loss. One limitation of the trial is that it did not measure other domains, such as affect and cognition, which are influenced by hearing loss.

Author Affiliations: Department of Veterans Affairs Medical Center, Washington, DC (Drs Larson, Beck, and Boysen); Hines VA Cooperative Studies Program Coordinating Center, Hines, Ill (Mr Williams and Dr Henderson); National Institute on Deafness and Other Communication Disorders, Bethesda, Md (Drs Luethke and Donahue); Greater Los Angeles VA Health Care System, Los Angeles, Calif (Dr Noffsinger); Department of Veterans Affairs Medical Center, Mountain Home, Tenn (Dr Wilson); University of Texas Health Sciences Center, San Antonio (Dr Dobie); Department of Veterans Affairs Medical Center, Iowa City, Iowa (Dr Haskell); Department of Veterans Affairs Medical Center, Nashville, Tenn (Dr Bratt); Department of Veterans Affairs Medical Center, Long Beach, Calif (Dr Shanks); Boys Town National Research Hospital, Omaha, Neb (Dr Stelmachowicz); University of Memphis, Memphis, Tenn (Dr Studebaker); Harbor-view/University of California, Los Angeles, Medical Center, Torrance (Dr Canalis); Department of Veterans Affairs Medical Center, Portland, Ore (Dr Fausti); and Department of Veterans Affairs Medical Center, Albuquerque, NM (Dr Rappaport).

NIDCD/VA Hearing Aid Clinical Trial Group: Vernon D. Larson, PhD,* chairman and principal investigator; Jillyn Roxberg, MA, clinical coordinator, and Rose Lee Jacob, program assistant, Veterans Affairs Medical Center, Mountain Home, Tenn; Joyce S. Kang, MS, clinical coordinator, and Megan M. Wilkinson, BA, program assistant, Veterans Affairs Medical Center, Washington, DC.

Participating Veterans Affairs Medical Centers, Participating Investigators and Audiologists: Albuquerque, NM: Bruce Z. Rappaport, PhD, Karen K. Stewart, MA, Sheree Smith, MA, and Jonni K. Dressendorfer, MS; Iowa City, Iowa: George B. Haskell, PhD, Kathy Vander Werff, MA, Adriana Rodriguez, MA, and Janette L. Rogers, MA; Long Beach, Calif: Janet E. Shanks, PhD, Charlene M. Mikami, MA, and Donna J. Gelnett, MA; Mountain Home, Tenn: Richard H. Wilson, PhD, Anne L. Oyler, MA, Kristen L. Bauer, MA, Colleen Noe, PhD, and Jennifer Crocket, MA; Nashville, Tenn: Gene W. Bratt, PhD,* Mia A. L. Rosenfeld, MS, Kjersten Branscome, MS, Mary Beth Trine, MS, and Barbara Peek, PhD; Portland, Ore: Stephen A. Fausti, PhD, James Henry, PhD, Wendy Helt, MA, Craig Larson, MA, and Alison Gilbert, MS; Washington, DC: Lucille B. Beck, PhD,* Gerald Schuchman, PhD, and Holly A. Sandvik, MS; and West Los Angeles, Calif: Douglas Noffsinger, PhD,* Donald D. Dirks, PhD, Diane Kenworthy, MA, Sheril A. Plunkett, MS, and Eleanor L. Wilson, MS.

Hines VA Cooperative Studies Program Coordinating Center, Hines, Ill: William G. Henderson, PhD,* director, Domenic Reda, MS, associate director, David Semlow, BS, assistant director, David W. Williams, MS,* study biostatistician, Mary Biondic, BA, programmer, and Barbara J. Christine, statistical assistant.

National Institute on Deafness and Other Communication Disorders, Bethesda, Md: James B. Snow, Jr, MD, retired director; Lynn E. Luethke, PhD,* health scientist administrator, and Amy Donahue, PhD,* chief, Hearing and Balance/Vestibular Sciences Branch.

Department of Veterans Affairs Headquarters, Washington, DC: John R. Feussner, MD, chief research and development officer, Joseph Gough, MA, program manager, and Ping C. Huang, PhD, staff assistant, Cooperative Studies Program; Lucille B. Beck, PhD,* director, and Allen E. Boysen, PhD,* retired director, Audiology and Speech Pathology Service.

Executive Committee: Rinaldo Canalis, MD, Torrance, Calif; Robert A. Dobie, MD, San Antonio, Tex; Patricia Stelmachowicz, PhD, Omaha, Neb; and Gerald A. Studebaker, PhD, Memphis, Tenn.

An asterisk indicates that a person is an Executive Committee member in the other sections above.

Data and Safety Monitoring Board: Noel Cohen, MD, chairman, New York, NY; Marilyn Demorest, PhD, Baltimore, Md; G. Pamela Burch-Sims, PhD, Nashville, Tenn; Wayne O. Olsen, PhD, Rochester, Minn; Richard A. Chole, MD, PhD, St Louis, Mo; Julianna Gulya, MD, Washington, DC; Debra L. Tucci, MD, Durham, NC; and Marie Diener-West, PhD, Baltimore, Md.

Funding/Support: Financial support was provided by the National Institute on Deafness and Other Communication Disorders and the Cooperative Studies Program of the Department of VA Research and Development Service.

REFERENCES

1. Collins JG. Prevalence of selected chronic conditions. *Vital Health Stat 10.* 1997;194:1-89.
2. Ries PW. Prevalence and characteristics of persons with hearing trouble: United States, 1990-1991. *Vital Health Stat 10.* 1994;188:1-75.
3. Kochkin S. MarkeTrak III. *Hear J.* 1992;45:47-54.
4. Goldstein DP. Hearing impairment, hearing aids and audiology. *ASHA.* 1984;26:24-35,38.
5. Leske MC. Prevalence estimates of communicative disorders in the US. *ASHA.* 1981;23:229-237.
6. Havlik RJ. Aging in the eighties, impaired senses for sound and light in persons age 65 and over. *Vital Health Stat 125.* 1986;125:1-8.
7. Mulrow CD, Aguilar C, Endicott JE, et al. Quality-of-life changes and hearing impairment: a randomized trial. *Ann Intern Med.* 1990;113:188-194.
8. Mulrow CD, Aguilar C, Endicott JE, et al. Association between hearing impairment and the quality of life of elderly individuals. *J Am Geriatr Soc.* 1990;38:45-50.
9. Uhlmann RF, Larson EB, Koepsell TD. Hearing impairment and cognitive decline in senile dementia of the Alzheimer's type. *J Am Geriatr Soc.* 1986;34:207-210.
10. Palmer CV, Adams SW, Bourgeois M, Durrant J, Rossi M. Reduction in caregiver-identified problem behaviors in patients with Alzheimer disease post-hearing-aid fitting. *J Speech Lang Hear Res.* 1999;42:312-328.
11. Russell JN, Hendershot GE, LeClere F, et al. Trends and differential use of assistive technology devices. *Vital Health Stat 292.* 1997;292:1-9.
12. Kochkin S. MarkeTrak III identifies key factors in determining consumer satisfaction. *Hear J.* 1992;45:39-44.
13. Kochkin S. Customer satisfaction and subjective benefit with high performance hearing aids. *Hear J.* 1996;49:16-26.
14. Cox RM, Alexander GC. The abbreviated Profile of Hearing Aid Benefit. *Ear Hear.* 1995;16:176-186.
15. Humes LE, Christensen LA, Bess FH, Hedley-Williams A. A comparison of the benefit provided by well-fit linear hearing aids and instruments with automatic reductions of low-frequency gain. *J Speech Lang Hear Res.* 1997;40:666-685.
16. Humes LE, Christensen L, Thomas T, Bess FH, Hedley-Williams A, Bentler R. A comparison of the aided performance and benefit provided by a linear and a two-channel wide dynamic range compression hearing aid. *J Speech Lang Hear Res.* 1999;42:65-79.
17. Dillon H, Birtles G, Lovegrove R. Measuring the outcomes of a national rehabilitation program. *J Am Acad Audiol.* 1999;10:67-79.
18. Hickson L. Compression amplification in hearing aids. *Am J Audiol.* 1994;3:51-65.
19. Dillon H. Compression? *Ear Hear.* 1996;17:4, 287-307.
20. Anderson BA, Hagen LT, Peterson TS, et al. Hearing instrument distortion. *Hear Rev.* 1996;69:18-26.
21. Hawkins DB, Naidoo SV. Comparison of sound quality and clarity with asymmetrical peak clipping and output limiting compression. *J Am Acad Audiol.* 1993;4:221-228.
22. Krebs D. Distortion and methods of output limiting. *Scand Audiol.* 1972;1:167-175.
23. Braida LD, Durlach NI, Lippmann RP, et al. Hearing aids—a review of past research on linear amplification, amplitude compression, and frequency lowering. *ASHA Monogr.* 1979;19:1-114.
24. Moore BCJ. Signal processing to compensate for reduced dynamic range. In: Beilin J, Jensen GR, eds. *Recent Developments in Hearing Instrument Technology, 15th Danavox Symposium, Kolding, Denmark, Mar 30-Apr 2, 1993.* Scanticon, Denmark: Danavox Jubilee Foundation; 1993:147-165.
25. Teder H. Compression in the time domain. *Am J Audiol.* 1993;2:41-46.
26. Plomp R. The negative effect of amplitude compression in multichannel hearing aids in the light of the modulation-transfer function. *J Acoust Soc Am.* 1988;83:2322-2327.
27. Wilson RH. Development and use of auditory compact discs in auditory evaluation. *J Rehabil Res Dev.* 1993;30:342-351.
28. American National Standards Institute. *Specification of Hearing Aid Characteristics.* New York, NY: Acoustical Society of America; 1996. ANSI S3.22-1987.
29. Byrne D, Dillon H. The National Acoustic Laboratories' (NAL) new procedure for selecting the gain and frequency response of a hearing aid. *Ear Hear.* 1986;7:257-265.
30. Hawkins DB, Walden BE, Montgomery A, et al. Description and validation of an LDL procedure designed to select SSPL90. *Ear Hear.* 1987;8:162-169.
31. Cox RM, Alexander GC, Gilmore C. Development of the Connected Speech Test (CST). *Ear Hear.* 1987;8(5 suppl):119S-126S.
32. Cox RM, Alexander GC, Gilmore C, Pusakulich KM. Use of the Connected Speech Test (CST) with hearing-impaired listeners. *Ear Hear.* 1988;9:198-207.
33. Cox RM, Gilmore C. Development of the Profile of Hearing Aid Performance (PHAP). *J Speech Lang Hear Res.* 1990;33:343-357.
34. Studebaker GA. A "rationalized" arcsine transform. *J Speech Lang Hear Res.* 1985;28:455-462.