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A Digital Processing Strategy to Optimize Hearing Aid Outputs Directly

Peter J. Blamey*†
Lois F.A. Martin*‡
Hayley J. Fiket*‡

Abstract

A new amplification strategy (ADRO™), based on 64 independently operating channels, was compared with a nine-channel wide dynamic range compression strategy (WDRC). Open-platform in-the-ear hearing instruments were configured either with ADRO or the manufacturer's WDRC strategy. Twenty-two subjects with mild to moderate hearing loss took home the ADRO or WDRC hearing aids. After three weeks' acclimatization, the aids were evaluated using monosyllables in quiet at 50 to 65 dB SPL and sentences in eight-talker babble. The acclimatization and evaluation were repeated in the second phase of the balanced reverse-block blind experimental design. The ADRO program showed a statistically significant mean advantage of 7.85% word score (95% confidence interval 3.19% to 12.51%; p = 0.002) and 6.41% phoneme score for the monosyllables in quiet (95% confidence interval 2.03% to 10.79%; p = 0.006). A statistically significant advantage of 7.25% was also found for the ADRO program in background noise (95% confidence interval 1.95% to 12.55%; p = 0.010). The results are consistent with earlier data for listeners with moderate to severe hearing loss.

Key Words: Amplification, compression, digital signal processing, hearing aids, multichannel

Abbreviations: BTE = behind-the-ear; CNC = consonant-nucleus-consonant; CUNY = City University of New York; DFT = discrete Fourier transform; DSL i/o = desired sensation level input/output; ITE = in-the-ear; NAL-NL1 = National Acoustics Laboratories—nonlinear 1; SNR = signal-to-noise ratio; WDRC = wide dynamic range compression.

Sumario

Se comparó una nueva estrategia de amplificación (ADRO™), basada en 64 canales operativos independientes, con la estrategia de compresión de rango dinámico amplio (WDRC). Se configuraron instrumento auditivos intra-auriculares de plataforma abierta, tanto con ADRO como con la estrategia WDRC del fabricante. Se adaptaron auxiliares auditivos con ADRO o con WDRC a veintidós sujetos con pérdidas auditivas leves a moderadas. Luego de un período de acostumbramiento de tres semanas, los audífonos fueron evaluados utilizando monosilábicos en silencio entre 50 y 65 dB SPL, y con frases en medio del balbuceo de ocho hablantes. El acostumbramiento y la

*Cooperative Research Centre for Cochlear Implant and Hearing Aid Innovation; †University of Melbourne; ‡Bionic Ear Institute

Prof. Peter Blamey, 2 Chapel Street, Richmond, Victoria, 3121, Australia; Phone: 61 3 8420 8500; Fax: 61 3 8420 8599; E-mail: pblamey@dynamichearing.com.au

evaluación se repitieron en la segunda fase de este diseño experimental de bloque-reverso, balanceado y ciego. El programa ADRO mostró una ventaja media estadísticamente significativa de 7.85% en el puntaje de palabras (intervalo de confianza del 95% de 3.19% a 12.51%; p = 0.002) y 6.41% en el puntaje de fonemas para los monosilábicos en silencio (intervalo de confianza del 95% de 2.03% a 10.79%; p = 0.006). Se encontró una ventaja estadísticamente significativa de 7.25% para el programa ADRO en medio de ruido ambiental de fondo (intervalo de confianza del 95% de 1.95% a 12.55%; p = 0.010). Los resultados son consistentes con datos previos en sujetos con hipoacusias moderadas a severas.

Palabras Clave: Amplificación, compresión, procesamiento digital de la señal, audífonos, multicanal

Abreviaturas: BTE = retro-auricular; CNC = consonante-núcleo-consonante; CUNY = Universidad de la Ciudad de New York; DFT = transformación discreta de Fourier; DSL i/o = nivel de sensación deseado (ingreso/salida); ITE = intra-auricular; NAL-NL1 = Laboratorios Nacionales de Acústica—No lineal 1; SNR = tasa de señal/ruido; WDRC = compresión de rango dinámico amplio

Hearing impairment leads to a number of difficulties that are not completely overcome by modern hearing aids. Recent surveys of hearing aid users show that their continuing needs include greater audibility for soft sounds, greater comfort for loud sounds, improved intelligibility for speech in background noise, and greater sound quality. For example, Kochkin (2002) reported that 83% of hearing aid users surveyed would like to hear more soft sounds; 81% wanted greater comfort for loud sounds; 95% would like improved speech intelligibility in background noise; and 88% wanted better sound quality. The amplification strategy most frequently used to address these problems is multichannel compression, which applies more gain to soft sounds and less gain to loud sounds to boost the audibility of the former and reduce the loudness discomfort of the latter. Compression was first suggested as an amplification strategy for hearing aids by Steinberg and Gardner (1937) to compensate for the loudness recruitment they discovered in their psychophysical studies. Compression was investigated in numerous research studies (e.g., Braida et al, 1979) and was released in a commercial hearing aid by Resound in 1987 (Allen, 2002). One of the reasons for the slow commercialization of compression in hearing aids was a doubt regarding the distortions that compression introduces into sounds (e.g., Bustamante and Braida, 1987). Did these distortions detract from the sound quality enough to limit the usefulness of compression compared with alternative linear amplification schemes? Another unknown was how to choose the appropriate compression parameters (Dillon, 1996; Kuk, 1996). Compression is now well accepted, and hearing aid manufacturers differentiate their products by implementing alternative forms of compression using parameters such as the number of frequency bands and channels, compression ratios, cross-over frequencies, compression thresholds, time constants, and supplementary processing algorithms such as noise suppression, feedback cancellation, and directional microphones (Kuk, 1996; Dillon, 2001).

The complex combination of features and compression parameters has led to sophisticated fitting methods and prescriptions that are necessary to achieve good outcomes for individual users of modern compression hearing aids. Typically, an "optimal" fitting will be prescribed using a formula based on audiometric thresholds, for example, the National Acoustics Laboratories—nonlinear 1 (NAL-NL1) (Dillon, 2001, pp. 255–256) or desired sensation level input/output (DSL i/o) formula (Cornelisse et al, 1995). Usually, the rationale for a fitting prescription is to restore the loudness of sounds to normal, or to maximize speech intelligibility (Keidser and Grant, 2001). Ideally, the "goodness of the fit" is verified using real-ear measurements of gain or output for specific input signals and input levels. If the real-ear measures match the prescribed gains and outputs, then the fit is a good one by definition. This type of approach has served the profession well and will continue to do so for many segments of the population of listeners with impaired hearing, despite a fundamental weakness. That is, each formula prescribes the same gain for everyone with the same audiogram (leaving aside differences in the prescription due to conductive hearing loss components, real ear to coupler differences, etc.). It is well known that there are large individual variations in suprathreshold hearing measures, whether they are loudness discomfort levels, maximum comfortable levels, preferred listening levels, or loudness scaling data. The variations can span a range of 30 dB even among individuals with the same audiogram (Kamm et al, 1978; Humes and Halling, 1994; Valente et al, 1994; Bentler and Nelson, 2001). For this reason alone, a prescribed compression scheme based on an individual's audiogram is unlikely to make optimal use of the listener's full dynamic range of hearing. Previous research has compared threshold-based and loudness-based fitting methods and concluded that the data do not support the use of additional clinical time to obtain individual loudness growth measures (Humes and Halling, 1994; Ricketts, 1996). In practice, a considerable degree of fine tuning and time is necessary to achieve the best possible use of the listener's hearing range, and this may result in a considerable departure from the "optimal" prescription based on the audiogram.

The ADRO™ (Dynamic Hearing Pty Ltd) approach began with a fresh look at the basic requirements of a hearing aid user: improved audibility of soft sounds and comfortable listening levels for loud sounds. The capabilities of the new generation of digital signal processors were used to formulate and implement stochastic rules that directly address the fundamental requirements of audibility and comfort. Systematic scientific inquiry followed, to discover the optimal listening ranges for people with impaired hearing, using cochlear implants, or hearing aids, or both. The ADRO rules were fine-tuned to directly place the output signals into the optimal listening range. The result was an innovative digital solution that could not have been implemented in analog devices (Blamey et al, 1999).

The ADRO processing is an amplification strategy, analogous to linear amplification and compression. The current study was designed to provide an objective comparison of ADRO processing with nine-channel wide dynamic range compression (WDRC) in an in-the-ear (ITE) hearing aid. Previous studies compared ADRO with three-channel WDRC in a behind-the-ear (BTE) hearing aid (Martin et al, submitted) and a linear hearing aid (Martin et al, 2001). The previous evaluations were conducted with listeners who had moderate to profound hearing losses. The current study provides new data for subjects with mild to moderate hearing loss using a different comparison device. The earlier studies showed improved intelligibility for speech presented at 50 to 65 dB SPL and for speech in multitalker babble with signal-to-noise ratios of 0 to 15 dB, when the ADRO processing was compared with the alternative amplification strategies. The hypotheses in the current study were that these two advantages of the ADRO strategy would also be observed when the listeners had mild to moderate hearing loss and the alternative amplification was a commercial nine-channel compression scheme.

METHOD

Experimental Design

The study was conducted by the Cooperative Research Centre (CRC) for Cochlear Implant and Hearing Aid Innovation in Melbourne, Australia, using a protocol that was designed with the help of independent international advisors. The schedule of sessions is summarized in Table 1. The study was conducted in two sequential phases because ADRO and the commercial WDRC embedded software could not be implemented simultaneously in the commercial ITE hearing aid. The study was conducted "blind" in that the participants did not know whether they were fitted with ADRO or WDRC hearing aid(s) in each phase of the study. The first session comprised a hearing evaluation, case history, and impression for a custom ITE shell. After the first session, each phase of the study involved five sessions over seven weeks. In the second session, the first hearing aid was fitted. Half the subjects started with the WDRC hearing

Table 1. Session Plan

Week	Activity
Phase 1	
1	Recruitment
2	Fitting
3	Fine-tuning and practice evaluation
4 and 5	Acclimatization
6 to 8	Evaluation
Phase 2	
9	Fitting
10	Fine-tuning and practice evaluation
11 and 12	Acclimatization
13 to 15	Evaluation

aid and half the subjects started with the ADRO hearing aid. The third session consisted of fine-tuning the fitting and practice with the speech materials for the later evaluation sessions. If no further fine-tuning was needed, the subjects took home the hearing aid for three weeks of acclimatization and experience. After acclimatization each subject returned for three sessions of speech perception evaluation. The second phase was a replication of the first phase with the second hearing aid.

Speech Perception Evaluations

Speech perception evaluations were used to assess the unaided condition in each phase of the study to check that there was no change in performance that could not be attributed to the difference between the hearing aids. A monosyllabic word test was used to assess the first hypothesis that speech intelligibility would be greater at low input levels in quiet with the ADRO evaluation strategy compared to the WDRC amplification strategy. Consonant-nucleus-consonant words (CNC; Peterson and Lehiste, 1962; Henry et al, 1998) were chosen in preference to an easier sentence test that may have resulted in ceiling effects for the participants with mild and moderate hearing losses. The CNC word lists consist of 50 monosyllabic words with the set format of consonant-nucleus-consonant. The initial and final phonemes are single consonants, and the nucleus is either a vowel or diphthong. Subjects were asked to repeat back the word. The lists were scored for whole words correct (word scores) and the individual speech sounds correct (phoneme score). The CNC words were presented using computer software that randomized the list of 50 words for each presentation. City University of New York (CUNY) sentences (Boothroyd et al, 1985) in eight-talker babble were used to test the second hypothesis that speech intelligibility in noise would be greater for the ADRO strategy compared to the WDRC amplification strategy. CUNY sentences consist of 102 words in 12 sentences per list. The subjects responded verbally, and each word in a list counted toward the score out of 102.

Prior to starting acclimatization and take-home experience with either the ADRO hearing aid or the WDRC aid, the subjects underwent a practice session with the speech materials to be used in the evaluation sessions. The purpose of the practice session was to:

- Set the volume control for each program so that 65 dB SPL of speech would be comfortable,
- Determine the presentation level for the CNC words for each listener to avoid floor and ceiling effects,
- Determine a noise level for each listener where the intelligibility of 65 dB of speech in eight-talker babble was reduced to approximately 50% for both programs.

At the first evaluation session, two lists of CNC words were presented in quiet without the subject wearing a hearing aid, as a control in the reverse block design, and two lists were presented with the hearing aid(s). Two lists of CUNY sentences were presented at 65 dB SPL with eight-talker babble at the predetermined signal-to-noise ratio. This procedure was repeated in two further evaluation sessions. Speech and noise were mixed at the required signal-to-noise ratio and presented from a single loudspeaker from directly in front of the listener. Word and sentence lists were randomly assigned to listeners, conditions, and order of testing to avoid potential bias from systematic list differences. Subjects were tested binaurally or monaurally depending on the hearing aid fitting. The non-test ear for subjects with monaural hearing aid fittings was not plugged or muffed for either aided or unaided testing. The individual response of each hearing aid was not tested with subjects who were fitted binaurally.

The test stimuli were presented in an Acoustic Design Ltd sound booth (4m x 4m x 2m). A Tannoy DC-1000 loudspeaker was placed three meters from the subject's sitting position at 0 degrees azimuth. The frequency response of this speech stimulus presentation system was -8, +2. 0, -5, -4, and -6 dB at 250, 500, 1000, 2000, 4000, and 8000 Hz with reference to the response at 1 kHz, respectively. Signals were generated with an IBM compatible computer (either from a Diamond MM200 audio card) or the internal Panasonic CD-ROM. The presentation levels for speech and noise were controlled via a Madsen 622 audiometer connected to a Rotel RA-931 MkII amplifier.

All materials were equalized in RMS (root mean square) level for individual test items using custom computer software. Soundfield calibration was made using a third-octave band of noise centered at 1 kHz with RMS equated to that of the speech stimuli. The dB SPL presentation levels reported are equivalent to a sound level meter reading on the linear dB fast (125 msec time window) setting. The equivalent RMS level is 5 dB below the quoted dB SPL level.

Participants

In view of the clinically and statistically significant results of the previous BTE trial with 19 subjects (Martin et al, submitted), a sample size of about 20 subjects was deemed to provide sufficient power to detect a difference between the treatment means in this experimental design. Twenty-four participants (12 females, 13 males) were recruited into the study. Their individual details are listed in Table 2. The average age of the group was 65 years, 6 months (standard deviation, 15 years, 10 months; range, 28 to 92 years). To facilitate interpretation of the results, the subjects were identified using a three-part label: The first part of the label is MILD/MOD, indicating whether their pure-tone-average hearing loss at 500, 1000, and 2000 Hz was less than or greater than 40 dB

Table 2. Profile of Hearing Aid Volunteers

Subject	PTA L (dB HL)	PTA R (dB HL)	Fitting	Phase 1	Phase 2
MILD1	17	32	right	WDRC	ADRO
MILD2S	30	25	binaural	WDRC	ADRO
MILD3	28	30	binaural	ADRO	WDRC
MILD4	33	32	binaural	ADRO	WDRC
MILD5S	32	58	right	ADRO	WDRC
MILD6	45	33	left	ADRO	WDRC
MILD7S	47	33	binaural	WDRC	ADRO
MILD8	37	35	right	ADRO	WDRC
MILD9	50	35	binaural	WDRC	ADRO
MILD10	37	48	right	WDRC	ADRO
MILD11	38	40	right	WDRC	ADRO
MILD12	42	38	binaural	WDRC	ADRO
MILD13	43	38	binaural	WDRC	ADRO
MOD14	42	47	right	WDRC	ADRO
MOD15S	42	48	binaural	ADRO	WDRC
MOD16	45	48	binaural	WDRC	ADRO
MOD17	48	47	binaural	WDRC	ADRO
MOD18	70	47	right	ADRO	WDRC
MOD19S	53	48	binaural	WDRC	ADRO
MOD20	55	53	binaural	ADRO	WDRC
MOD21	58	57	left	ADRO	WDRC
MOD22	58	57	binaural	ADRO	WDRC
MOD23	63	58	binaural	ADRO	WDRC
MOD24	120	58	right	WDRC	ADRO

in the ear with lower thresholds. The second part of the label is a number to identify the individual. The final optional part of the label is "S," indicating a sloping hearing loss. Because the study was investigating custom-made ITE hearing aids for mild to moderate hearing loss, a sensorineural pure-tone average hearing loss of between 30 to 60 dB was chosen as a selection criterion. Some subjects had hearing losses outside the criterion range for the contralateral ear. The most extreme examples were MOD24, who was profoundly deaf in the contralateral ear, and MILD1, who had near normal hearing in the other ear. All subjects, except for MILD4 and MOD14, were experienced hearing aid users. During the course of the study, subjects MILD1 and MOD14 withdrew for personal reasons unrelated to their hearing and the study. Their results were not included in the final results of the study.

Hearing Instruments and Fittings

The state-of-the-art comparison device was chosen from a set of eight commercial instruments on the basis of technical performance measures and the availability of an ITE model with the desired hardware and software features: a volume control, a program switch, a directional microphone, and a telecoil. It was an added convenience that the instrument chosen also used the open-platform Dspfactory Toccata hybrid that was suitable for implementation of the ADRO embedded software. The manufacturer's consent was obtained for the comparison study, and sufficient ITE hearing aids were purchased to provide the participants with binaural or monaural fittings as appropriate.

Ear impressions were sent to the manufacturer for fabrication of the shells for the in-the-ear hearing aids. All aids were full-concha hearing aids with a volume control. Two versions of the commercial compression hearing aid were available: high gain (maximum output of 125 dB, maximum gain of 60 dB) and low gain (maximum output of 115 dB, maximum gain of 50 dB). A directional microphone was available with the low-powered version, and a telecoil option was also available for those who requested it. The NAL-NL1 software (Dillon, 2001, pp. 255–256) was consulted to determine the recommended vent size for the degree of hearing loss. If this vent size proved unsatisfactory, the hearing aid was sent back to the manufacturer for recasing. Hearing aids were remodeled if the shell was uncomfortable for the subject.

The commercial multiprogram compression hearing aid had 15 frequency bands for frequency shaping and nine channels of compression, covering a frequency range of 200–6000 Hz. There were two compression thresholds for each channel. The lower compression threshold determined the onset for wide dynamic range compression that could be adjusted from 1:1 (linear) to 6:1. The higher compression threshold determined the point for output limiting fixed at 20:1. Two sets of time constants were specified for the hearing aid: fast—attack 10 msec, release 200 msec; slow—attack 200 msec, release 800 msec. The manufacturer indicated that the slow compression detectors were used in each of the nine compression channels and the fast compression detectors were used in each of the 15 frequency bands. The time constants were not under the direct control of the clinician fitting the hearing aid. Below the compression threshold, there was an option to have expansion to keep low level noise softer. The default expansion setting in each program was 0.75 to 1. The NAL-NL1 prescription was used to set the compression thresholds, gains, and compression ratios for each channel.

The clinician used the manufacturer's fitting procedure to program all WDRC parameters in the hearing aid and fine-tuning procedures to deal with any particular problems for an individual listener. The NAL-NL1 fitting prescription for nine channels was a standard feature of the manufacturer's software. In most cases, the volume range was set to the manufacturer's default range of 30 dB, but this could be altered to a 10 dB range if desired.

The ADRO processing has been described in more detail elsewhere (Blamey et al, 1999; Martin et al, 2001; Martin et al, submitted). The trademarked ADRO name is derived from the original name for the method of Adaptive Dynamic Range Optimization. Briefly, the digital signal processing uses a discrete Fourier transform (DFT) to split the signal into 64 frequency channels with fixed bandwidth of 125 Hz. The Dspfactory Toccata Plus processor is specifically optimized to perform DFT and inverse DFT operations efficiently (Brennan and Schneider, 1998).

For this configuration of the DSP processor, the group delay is 13 msec. Each of the 64 channels is controlled independently of every other channel using a set of four stochastic rules:

- If the 90th percentile of the output amplitude distribution for the channel is greater than the Comfort Target, the gain of the channel is reduced.
- If the 30th percentile of the output amplitude distribution for the channel is below the Audibility Target, the gain of the channel is increased.
- The gain for the channel may not exceed a specified Maximum Gain.
- The amplitude for the channel may not exceed a specified Maximum Output Level.

The ADRO hearing aid adapts the 64 gain values independently according to these four rules with very slow variations in the gain values. Gain variation rate was 3 dB per sec in the study. The first two rules directly address the main requirements of hearing aid users for comfortable listening to loud sounds, and audibility of soft sounds. In essence, the rules say that if the sound is too loud, then make it softer, and if the sound is too soft, then make it louder. If the sound is neither too soft nor too loud, the ADRO rules do nothing. ADRO does not attempt to remove background noise but allows the listener to hear as much as possible of the auditory environment at a comfortable level. After the ADRO rules have been applied, an inverse DFT is applied to produce the output signal.

The ADRO rules are designed to keep the signal dynamic range (from the 30th to the 90th percentile) within the listener's dynamic hearing range (from the Audibility Target to the Comfort Target). For this study, the ADRO targets were based on in-situ measurements with 1/6-octave noise bands made directly through the hearing aid. Although a prescriptive method could have been used, direct measurement is more consistent with the basic principles of the ADRO processing: The audiologist asked the listener to determine levels that were "audible," "comfortable," or "loud but OK," and the ADRO targets were set accordingly. The in-situ measurement approach avoided the need for probe-tube microphone measures to convert from audiometric thresholds and loudness measures under headphones to in-situ target levels. The suprathreshold measurement approach also took into account the preferences of the individual listener instead of using average values derived from a large population.

For this study, in-situ thresholds ("audible"), comfortable levels ("comfortable"), and loudness discomfort levels ("loud but OK") were determined at 11 frequencies with half-octave spacing from 125 Hz to 6 kHz. Thresholds were measured using an up/down procedure with step sizes of 2 dB and 4 dB for up and down respectively. The subject was instructed to indicate when a sound was audible, as in a standard test with an audiometer. The audiologist could select any point on the graph using the mouse and then output a 1/6-octave band of noise at the frequency and level selected. Initially, the ADRO comfort targets were set at the measured comfortable levels; the audibility targets were set 20 dB below the comfort targets or at threshold, whichever was greater; and the maximum output levels were set below the "loud but OK" levels. The targets and maximum output levels were set conservatively at first because loudness summation effects were expected across the 64 frequency channels. The maximum gain parameters were set at or above the gain values at the low compression threshold for the NAL-NL1 prescription. A volume control was used to adjust all parameters up or down by the same number of dB to achieve a comfortable listening level for speech at normal input levels and to allow for loudness summation in broadband signals. Further fine-tuning adjustments were made to deal with any issues that remained, such as feedback and occlusion effects.

RESULTS

During the first practice session a presentation level was selected for each individual subject that enabled them to score about 10% correct for unaided presentation of the CNC words. This level was varied between subjects to avoid floor effects in the CNC word scores. Seven subjects were tested at 50 dB SPL, nine subjects at 55 dB SPL, four subjects at 60 dB SPL, and two subjects needed a presentation level at 65 dB SPL to achieve an acceptable score for the protocol. Note that the same presentation level was used for both WDRC and ADRO phases of the study. For sentence testing in noise, most subjects used a signal-to-noise ratio between 0 and +6 dB. Four subjects required a signal-to-noise ratio of +10 dB. These signal-to-noise ratios were chosen individually to obtain scores in the region of 50% to avoid both floor and ceiling effects for each individual. The same signal-to-noise ratio was used for both ADRO and WDRC phases of the study.

Table 3 shows the presentation levels and mean scores for each participant in the ADRO and WDRC phases of the study. Group data are shown in Table 4. The data were analyzed using single factor repeated measures ANOVA to assess each hypothesis for the test and control conditions. The hypothesis that word recognition scores would be greater for ADRO than for WDRC at moderate input levels was supported by the data. The mean ADRO score for CNC words was 7.85% higher than the corresponding WDRC score (F = 12.3; df = 1,21; p = 0.002; 95% confidence interval 3.19% to 12.51%). The mean ADRO score for CNC phonemes was 6.41% higher than the corresponding WDRC scores (F = 9.2; df = 1,21; p = 0.006; 95% confidence interval 2.03% to 10.79%). The scores for the two phases were not significantly different in the control unaided condition (Difference = 0.2%; F = 0.05; df = 1,21; p = 0.821 for CNC words; Difference = 1.1%; F = 0.98; df = 1,21; p = 0.334 for CNC phonemes). The second hypothesis that speech would be more intelligible in noise for the ADRO processor than for the WDRC processor was also supported by the data. For the CUNY sentences presented in multitalker babble, there was a mean difference of 7.25% in favor of the ADRO hearing aid (F = 8.11, df = 1,21, p = 0.010; 95% confidence interval 1.95% to 12.55%) and the difference between the two phases in the unaided condition was not significant (Difference = 0.7 %; F = 0.09; df = 1,21, p = 0.767).

Table 3. Mean Speech Intelligibility Scores for Individual Participants

	CNC words			CNC phonemes		CUNY sentences in babble		
Subject	Level (dB SPL)	ADRO (%)	WDRC (%)	ADRO (%)	WDRC (%)	SNR (dB)	ADRO (%)	WDRC (%)
MILD2S	55	46.0	37.0	67.6	67.4	5	69.4	75.7
MILD3	50	48.3	24.3	66.3	48.2	3	69.6	41.5
MILD4	50	29.0	24.0	54.0	46.4	3	64.7	63.7
MILD5S	55	24.0	14.7	47.9	37.0	5	49.5	32.7
MILD6	60	8.7	8.0	29.8	29.2	10	14.9	3.4
MILD7S	50	46.3	42.7	70.0	68.1	2	51.6	46.7
MILD8	55	76.7	47.3	89.0	72.9	4	65.8	73.4
MILD9	50	60.3	60.3	76.2	76.4	0	78.8	85.6
MILD10	55	19.7	20.0	43.0	41.4	5	60.8	66.7
MILD11	50	17.0	21.3	39.1	48.4	3	49.2	40.6
MILD12	55	37.7	33.7	63.6	59.9	6	53.1	62.1
MILD13	55	58.3	46.3	75.8	68.6	3	65.5	67.0
MOD15S	55	33.3	42.0	50.6	61.6	4	22.1	31.7
MOD16	55	26.0	18.7	50.2	45.8	6	44.1	32.8
MOD17	50	14.7	18.0	34.6	41.6	6	73.5	66.8
MOD18	60	65.0	63.3	82.0	80.2	5	68.3	63.8
MOD19S	65	25.0	15.0	50.1	39.1	10	81.4	63.6
MOD20	60	22.3	20.0	49.4	41.9	6	25.3	3.9
MOD21	55	45.3	26.3	65.7	43.0	4	52.1	27.6
MOD22	50	46.0	40.3	70.9	63.4	5	54.2	41.3
MOD23	60	29.7	14.7	54.4	36.1	10	66.0	40.5
MOD24	65	53.7	22.3	73.9	46.4	10	65.8	55.1

Table 4. Summary of Group Mean Scores for Speech Evaluation for Each Phase of the Study

	ADRO Phase		WDRC Phase	
	Unaided (%)	Aided (%)	Unaided (%)	Aided (%)
CNC word scores				
mean	13.9	37.9	13.7	30.0
standard deviation	12.5	18.1	12.0	15.3
CNC phoneme scores				
mean	31.8	59.3	30.7	52.9
standard deviation	18.0	15.9	17.7	14.7
CUNY sentences in babble				
mean	27.1	56.6	26.4	49.4
standard deviation	17.2	17.6	19.6	21.9

Discussion

The ADRO amplification strategy is an alternative technology to compression in hearing aids. The evaluations found statistically significant benefits of the ADRO strategy compared to WDRC in the speech perception scores of listeners with mild and moderate hearing losses. Anecdotal reports and questionnaire responses from the subjects indicated that the differences between the strategies were clinically as well as statistically significant. The differences in speech intelligibility are equivalent to about one extra word correct in every one or two sentences in conversational speech. This makes a clearly noticeable difference to the speed, ease, and accuracy of communication.

There are five key technological differences between the two amplification strategies. Most of these differences stem from ADRO's direct approach to the fundamental problems of hearing loss and the use of the inherently digital properties of the new open-platform technology.

1. The use of the discrete Fourier transform with 64 narrow-frequency channels is computationally direct and efficient for a digital processor. The same narrow-frequency channels are used for the statistical analysis of the signal (the calculation of the 90th and 30th percentiles) and the response of the hearing aid to signals. The fine frequency resolution of the DFT coefficients allows the ADRO processor to respond accurately to spectral shape and dynamic range changes. Fine frequency resolution also produces an accurate fit to the frequency response requirements of individual users. Narrow bands have substantial advantages over broader bands for signal analysis also. The larger number of narrow channels provides more information to control the operation of the hearing aid. Narrow channels contain a maximal concentration of signal energy and a minimum of noise energy, thus maximizing the signal-to-noise ratio within each channel. The ADRO processor has access to more information and has a greater capacity to respond to that information than the nine-channel WDRC processor. The combination of a large number of narrow-frequency channels and compression with fast time constants can lead to reduction in spectral contrast. The WDRC processor avoided this problem by using a relatively small number of compression channels (nine). The ADRO processor avoided this problem by having extremely slow time constants.
2. The use of stochastic rules is a second inherently digital feature of ADRO. The rules directly address the requirements of the listener. If any frequency channel is too soft, the strategy makes it louder. If any component of the sound is too loud, the strategy makes it softer. If the sound is comfortable and acceptable, the amplitude is not adjusted. By contrast, compression schemes continually adjust the gain of the hearing aid every time the input level changes, even if the sound is neither too soft nor too loud. The continual adjustments of the compression gain prescription reduce the temporal

dynamics of the signal and reduce sound quality. The potentially detrimental effects of compression with fast time constants and many channels are sometimes described as "spectral and/or temporal smearing." These effects can be avoided by a careful trade-off between the number of channels and the speed of adaptation for the channels.

3. The ADRO time constants are several seconds, compared to fractions of seconds for most hearing aids. This results in a computational advantage in that percentile estimates and gains do not have to be recalculated in every DFT window. Less frequent calculation prolongs battery life and also provides a more valid representation of the statistical properties of the signals because the percentiles are not based on correlated data from overlapping windows. Slow time constants also guarantee that the loudness changes perceived by the listener are real, and not artifacts introduced by the processing itself. In essence, an ADRO processor is a linear hearing aid that adapts slowly to keep the frequency response and dynamic range in the optimal configuration.
4. The ADRO audibility, comfort, and maximum output level targets are intuitively clear to the audiologist and the hearing aid user, making it easy to tune the hearing aid. The separate adjustment of audibility targets and maximum gains for softer sounds, and comfort targets and maximum output levels for louder sounds, is more straightforward for the audiologist than manipulation of cross-over frequencies, compression thresholds, and compression ratios that interact in complex ways. Target levels are typically set and checked with the hearing aid in place, so that fitting is based on individual preferences rather than population averages, prescriptive calculations, and detailed calibrations. The use of output targets rather than gain prescriptions allows the ADRO processor to adapt to the type of input device used with the hearing aid, as well as adapting to a wide range of environments and sounds without refitting or adjustment.
5. The highly adaptive ADRO processes are similar in some respects to the nonlinear adaptive processes of the normal ear. The processing adapts in the same way to any sound. There is no fundamental reason why the ADRO processing could not be tuned differently for different situations–there has just not been a need to do so.

As indicated above, the two processors were controlled by different parameters: targets for ADRO and gain prescriptions for WDRC. Thus, the fitting task for the audiologist was inherently different for the two processors. If one scheme had been fitted more accurately or more effectively than the other, this would clearly influence the outcome of the study. Compression had a potential advantage over ADRO in that the fitting of compression schemes has been optimized in many research and clinical studies over many years. This accumulated know-how has been encapsulated in compression gain prescriptions such as DSL i/o and NAL-NL1. The NAL-NL1 prescription was chosen for the present study because it was derived by optimizing values for speech intelligibility for a wide range and degree of hearing losses. The NAL-NL1 prescription represents one of the current state-of-the-art approaches to hearing aid fitting, where average values are prescribed for an assumed set of circumstances. The ADRO fitting approach had been tested in an earlier study (Martin et al, 2001) but was at an early stage of sophistication compared with NAL-NL1. On the other hand, the ADRO in-situ approach to fitting is potentially more intuitive and more directed towards the listener's individual preferences than the NAL-NL1 software. This should be viewed as an inherent advantage of using the ADRO processor rather than a potentially confusing variable in the study.

An equal amount of time was devoted to fitting the ADRO and WDRC instruments. The individual subject's requirements for each program were essentially the same: there should be no feedback, the listener's own voice should sound comfortable and natural, other voices should sound audible and intelligible, and environmental sounds should be comfortable and not unpleasantly loud. Only if these requirements were fulfilled could the hearing aid user be expected to wear the hearing aid for any length of time to meet their daily communication needs. Note that satisfying these conditions meant that the WDRC fitting was not necessarily an exact implementation of NAL-NL1. Because of the difference in rationale and fitting approaches and fitting software, the audiologist had a different repertoire of actions available to satisfy these requirements.

Compression fine-tuning:

1. To make loud sounds more acceptable the audiologist changed the maximum power output.
2. To avoid feedback and the occlusion effect, the audiologist adjusted the gain.
3. The volume range was set so that the listener had some control over the amount of gain needed for particular listening situations.

ADRO fine-tuning:

1. If sound levels were unacceptable, the in-situ measurements could be revisited to check the reliability of the threshold, comfort and uncomfortable levels.
2. The targets were adjusted to take into account problem areas in the dynamic range. For example, in frequency ranges with severe or profound sensorineural hearing loss, the dynamic range was typically very small. The audiologist could control the amount of information presented to this region by adjustment of the targets. This was particularly useful when some acclimatization was needed for subjects who had not heard sounds in these frequency regions, possibly for years beforehand.
3. To optimize the acceptability of sounds such as the listener's own voice, the low-frequency maximum gain was adjusted, while at the same time boosting the high-frequency gain to maximize speech intelligibility.

It is important to note that the maximum gain in the ADRO strategy can be adjusted independently of the target levels without affecting the required output for the target provided the minimum required gain is available to reach the targets. Thus, in most circumstances, increasing the maximum gain will not make loud sounds louder, but it will make low-level sounds more audible. This contrasts with WDRC strategies in which an increase in the gain will increase the loudness of all inputs, unless the compression ratio is increased to maintain comfort at high levels. If the compression ratios are changed, then the audiologist is no longer following the NAL-NL1 prescription. This contrast demonstrates the intuitive flexibility that is provided for the audiologist using the ADRO strategy.

In summary, it is noted that both strategies were optimized so that conversational speech and everyday sounds were acceptable to the listener. The audiologist did not know whether she had fitted one strategy more optimally than the other until the subject returned from the acclimatization period and started formal evaluation, and the subject knew only that there were two different hearing aids. Thus, the methodology was considered suitable for assessing the differences between the two rationales, independent of the potential fitting differences.

Both hypotheses in this study were supported by the data, in accord with the previous comparisons of ADRO processing with linear amplification (Martin et al, 2001) and three-channel WDRC (Martin et al, submitted). The observed advantage of 7.9% for perception of CNC words at moderately low input levels was smaller than the previously observed advantages of 36.4% (Martin et al, 2001) and 14.2% (Martin et al, submitted). The smaller advantage in the current study may be because the materials were different (CNC words compared to CUNY sentences), the comparison processor was more effective (nine-channel WDRC compared to linear or three-channel WDRC), or because the participants in the present study had more residual hearing than in the other studies (mild and moderate losses compared with moderate and severe hearing losses).

The mean size of the ADRO advantage in background noise was consistent across all studies. Identical evaluation methods were used in the ITE and BTE studies to evaluate perception of CUNY sentences in multitalker babble. The results from Table 3 in the present study were combined with the corresponding results from the BTE study (table 5, Martin et al, submitted) and a correlation analysis performed to detect any trends across listeners with hearing losses from mild to severe. The result showed no significant trend (r^2 = 0.07; df = 1,39;

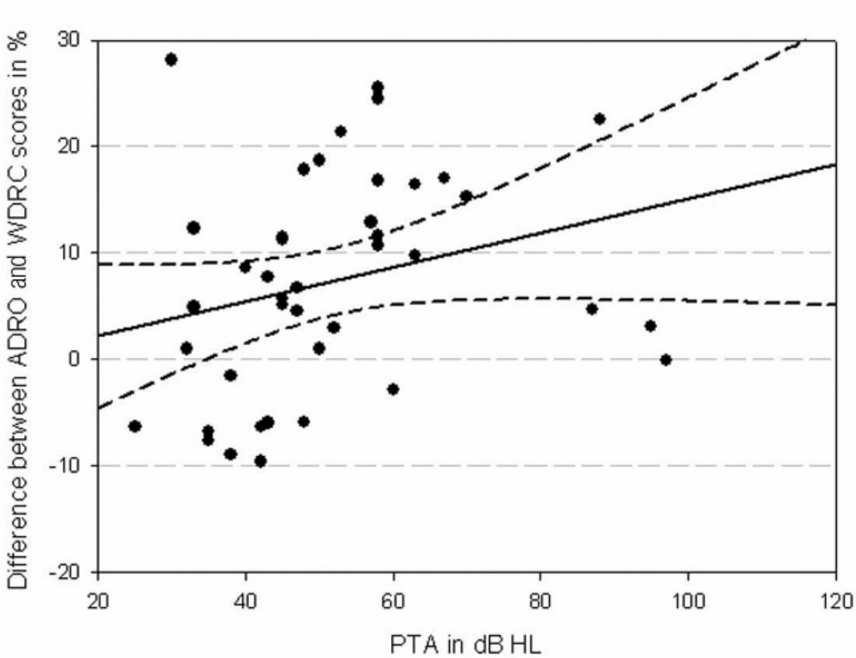

Figure 1. The difference between the scores for CUNY sentences in babble for the ADRO and WDRC amplification strategies are plotted against PTA for 41 individual subjects. The regression line and 95% confidence interval show no significant trend, indicating that the advantage observed with ADRO was not strongly dependent on the degree of hearing loss.

p = 0.094.), indicating that the ADRO processing is equally effective in background noise for all degrees of hearing loss from mild to severe (see Figure 1). Very few hearing aid evaluations have been able to show a consistent advantage of one processing scheme over another in background noise. The results of the two studies together show that the advantages of the ADRO processing over WDRC in quiet and in noise are robust across a wide range of hearing loss degrees and configurations.

CONCLUSIONS

ADRO addresses the major problems that hearing aid users report, as described in the Marke Trak VI survey (Kochkin, 2002). The results of the ITE study support the hypotheses that the ADRO amplification strategy produces improved intelligibility for speech at moderately low input levels and in background noise, compared to the alternative WDRC amplification strategy. These data extend these conclusions to listeners with mild to moderate hearing loss. A combined analysis of the present data with data from a previous BTE study of people with moderate to severe hearing loss demonstrated no significant trend for the size of the advantage in background noise, which averaged 7.3% for CUNY sentences in multitalker babble. The ADRO amplification strategy provides an alternative to WDRC in hearing aids. It is a flexible option, which is fitted in the same manner for all clients, whatever the extent and configuration of their hearing loss, and without complicated fitting rules. The study results show significant listening benefits in comparison with WDRC and additional benefit in simplicity of fitting.

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