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Optimizing Dynamic Range in Children Using the Nucleus Cochlear Implant

P. W. Dawson, J. A. Decker, and C. E. Psarros

Objective: The aim of this study was to investigate the benefits of the preprocessing scheme “Adaptive Dynamic Range Optimization” (ADRO) in children using Nucleus cochlear implants. Previous research with adults indicates improved speech perception in quiet and improved sound quality in everyday listening environments with the ADRO scheme.

Design: Children were given 4 wk of take-home experience with ADRO, with a minimum of 2 wk in which ADRO was “locked-in.” After 1 wk of ADRO use and again after 4 wk of ADRO use, Bench-Kowal-Bamford (BKB) sentence perception in quiet at a low input level of 50 dB SPL (unweighted root mean square) and sentence perception in noise were compared with the child’s everyday (Standard) program and the ADRO program. Children also rated the loudness of a variety of environmental sounds and indicated which program provided the best hearing in a variety of everyday listening situations.

Results: On average, BKB sentence perception in quiet at 50 dB SPL was significantly better with the ADRO program compared with the Standard program. The group mean improvement was 8.60%. Similarly, group mean scores for BKB sentences presented at 65 dB SPL in multitaler babble were significantly higher with the ADRO program (an improvement of 6.87%). The ADRO program was the preferred program in 46% of the listening situations, whereas the Standard program was preferred in 26% of situations. Everyday sounds were not unacceptably loud with ADRO.

Conclusions: There was an ADRO benefit for this group of children in quiet and in noise. These findings suggest that young children would benefit from the ADRO programming option being locked in along with other processor settings in the SPrint processor once their MAP levels have stabilized. Some older children and teenagers may choose to use ADRO selectively for specific listening situations.

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Adaptive dynamic range optimization (ADRO) is

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currently implemented in the SPrint speech processor (Cochlear Ltd.). It is a multichannel, preprocessing digital strategy, which continually adjusts the gain of the input signal with the aim of placing the signal optimally in the dynamic range of the cochlear implant user’s hearing (the range between the thresholds [T-levels] and maximum comfort levels [C-levels]). This processing adjusts the gain in individual frequency channels before the selection of the spectral peaks or maxima. It is not a new strategy in itself but is used in conjunction with the SPEAK (McKay & McDermott, 1993; Skinner et al., 1994) or the ACE (Vandali, Whitford, Plant & Clark, 2000) speech processing strategies. Continuously interleaved stimulation (CIS) strategies (Wilson, Lawson, Finley & Wolford, 1995) may be emulated using ACE; for example, an 8-channel CIS strategy may be achieved by selecting 8 active electrodes and 8 maxima in the programming software. ADRO aims to make low-level sounds more audible and high-level sounds more comfortable than with the standard linear system of amplification.

The channel gain adjustments in ADRO are made according to specific rules. In general, these rules aim to maintain the signal in the audible-to-comfortable range. There are three rules: the comfort rule, the audibility rule, and the background noise rule. These gain rules use percentile estimates of the long-term output level in a frequency band. Approximately every 2 msec, these estimates are calculated by using a percentile level estimator. The time constants for the percentile estimates are approximately 20 dB per second. The comfort rule specifies that the gain will be reduced in a frequency band or channel if the 98th percentile of the long-term output level in that band is greater than the channel amplitude value that produces C-level stimulation (i.e., the value corresponding to the automatic gain control (AGC) knee-point). Table 1 shows that the target for the comfort rule is 0. This is because it is expressed in dB relative to the value that produces C-level stimulation. The comfort rule only allows 2% of peaks to stimulate at C levels in the child’s MAP. The audibility rule specifies that the gain in each band will be increased if the 70th percentile of the signal output is lower than the channel amplitude target of –15 dB relative to the value that produces C-level stimulation. The background noise rule spec-

TABLE 1. Target levels for the ADRO gain rules for the 30 dB default instantaneous input range of the SPEAK and ACE processing strategies

Rule	Percentile rank (%)	Target (dB)
Comfort	98%	0 dB
Audibility	70%	-15 dB
Background noise	10%	-5 dB

0 dB corresponds to C level and -30 dB corresponds to the T level.
ADRO = Adaptive Dynamic Range Optimization program.

ifies that the gain will be decreased if the 10th percentile of the signal output is greater than the AGC knee-point minus 5 dB (see Table 1). Finally, a maximum gain rule aims to limit the amplification of low-level background noise and is set at approximately 5 dB greater than the fixed-channel gain in a program without ADRO.

A preliminary study with 9 adult cochlear implant users indicated significant speech perception improvements in quiet at a variety of presentation levels with the ADRO program compared with the Standard program (James et al., 2002). For example, at 50 dB SPL (unweighted RMS), there was an improvement of 16% ($p < 0.001$) in mean open-set City University of New York (CUNY) sentence scores. Furthermore, an average improvement of 20% was reported for spondees presented at 40 dB SPL (RMS) and an average improvement of 9.5% was found for CNC monosyllabic words presented at 60 dB SPL (RMS). James et al. (2002) found no significant difference in sentence perception between the ADRO and Standard programs for CUNY sentences presented in 8-talker babble. Subjects were given 1 to 2 wks' take-home experience with the ADRO program and asked to rate the loudness of a variety of environmental sounds and to state whether they preferred one program over the other another in a number of everyday listening situations. ADRO was judged as the preferred program in 59% of listening situations, whereas the Standard program was preferred in 10% of the situations.

The findings of the preliminary study by James et al. (2002) were further validated by a multicenter trial involving 16 postlinguistically deafened adults (James et al., Reference Note 1). The multicenter trial indicated a significant ADRO benefit for speech in quiet presented at a range of presentation levels. At the low input level of 50 dB SPL (unweighted RMS), there was an improvement for CUNY sentences of 11.54%. Sentence perception in noise with speech presented at 70 dB SPL (unweighted RMS) was equivalent with the ADRO and Standard programs. As in the preliminary study, ADRO was judged to be the preferred program in 59% of the listening situations surveyed. The Standard pro-

gram was preferred in 17% of situations. Furthermore, 11 of the 16 subjects preferred the ADRO program in the majority of listening situations. Two subjects judged that there was no difference between the two programs in the majority of listening situations, and 3 subjects preferred the Standard program in the majority of situations. Some environmental sounds were judged to be louder with the ADRO program, but the number of uncomfortably loud sounds was almost equivalent for both programs.

The present study hypothesized that children using cochlear implants programmed with ADRO would have benefits similar to the adult groups. It is not a foregone conclusion that children will benefit from new sound processing strategies or schemes in the same way as adults, especially given that they are typically congenitally or prelinguistically deafened. Past research, however, has shown significant improvements in speech perception with use of the SPEAK strategy compared with the MPEAK strategy for both adults and children (Cowan et al., 1995; Skinner et al., 1994). Processor settings are often "locked in" by using the button lock on the SPrint processor to prevent children from tampering with the controls. It is important to ensure that the child will have no adverse effects if the ADRO program is locked in along with other processor settings such as the sensitivity and volume settings. It is possible that some environmental sounds could be uncomfortably loud with the ADRO program compared with the Standard program, given that the program can provide up to 5 dB more gain. Furthermore, it is unknown whether this added gain with ADRO might be unacceptable for children using an aid on the contralateral ear with summation of the inputs from the cochlear implant and the hearing aid. The ADRO software is offered as an option in the advanced parameters in the WIN 124 software for the SPrint processor. An objective of this study was to suggest some fitting guidelines for use of ADRO in children.

More specifically, this study investigated the following questions:

- (1) Does ADRO benefit speech perception in quiet at the low input level of 50 dB SPL (unweighted RMS)?
- (2) Is the perception of sentences presented in multitalker babble equivalent with the ADRO and Standard programs?
- (3) Does speech perception performance with ADRO improve with increased experience with the program?
- (4) Are environmental sounds acceptably loud for children using ADRO?

(5) Do children prefer ADRO in everyday listening situations?

METHODS

Patients

Fifteen children using the SPrint body-worn processor of the Nucleus 24 cochlear implant system participated in the study. Children were selected who had a stable MAP and at least 6 months' implant experience and language skills appropriate for sentence testing. Hence, preschool children were not included in this study. Table 2 provides a summary of case history details for these children. The ages of the children ranged from 6 to 15 yr. All were using oral/aural communication in the educational setting at the time of the study. Eleven of the children were using the ACE strategy, with a range of rates, and 4 children were using the SPEAK strategy. Implant experience ranged from 2 to 13 yr. The age at onset of bilateral profound deafness ranged from birth to 6 yr, 9 mo, with a mean age of onset of 1 yr, 5 mo. Duration of profound bilateral deafness ranged from 5 mo to 11 yr, 7 mo, with a mean of 4 yr, 5 mo. Subjects 5, 9, and 14 had meningitis as the underlying cause. The underlying cause of the remaining subjects was unknown, with the exception of subjects 12 and 13, whose origin of disease was genetic. Six of the 15 children wore a hearing aid on the contralateral ear. Table 2 provides details on the number of active channels in the subjects' MAPs and the mean dynamic ranges across these channels and standard deviations. Most subjects had MAPs with 20 or 22 active channels, with the exception of subject 5, whose MAP had 11 active channels.

The majority of children used a microphone sen-

sitivity setting of 12 and all children used a volume setting of 9. The sensitivity setting adjusts the knee-point of the AGC so that signals at or above this level will be presented at the maximum comfortable levels or C levels in the child's MAP. With a setting of 12, the AGC operates at approximately 64 dB SPL (for a speech-weighted noise). This means that inputs at or higher than 64 dB SPL are presented at C-level, and inputs 30 dB below this level are presented at threshold or T-level in the map. With a microphone sensitivity setting of 8 the AGC knee-point is set at approximately 70 dB SPL and input levels of 40 dB SPL are presented at threshold.

All of the children in the study used the same amplitude mapping functions with a Q value of 20 and a base level of 4. The Q value determines the steepness of the loudness growth function from the T-levels to the C-levels and the base level determines the level at which initial stimulation occurs. The base level of 4 provides an instantaneous input dynamic range of approximately 30 dB.

Speech Processor Programs

In the initial assessment, the child's T-levels and C-levels in his or her MAP were checked and adjusted where necessary. Both the Standard and ADRO programs consisted of the child's MAP and the child's processing strategy (ACE or SPEAK). The only difference between the two programs was the inclusion of the ADRO preprocessing scheme in the ADRO program. The adaptive dynamic range optimization processing scheme was created by selecting the ADRO option in the prototype software. The ADRO program was placed into one of the program locations on the SPrint processor. It could be selected or deselected by a push of a button on the processor. When ADRO was

TABLE 2. Subject details

Subject	Age at testing (yrs)	Onset of loss (yrs)	Duration of deafness (yrs)	Implant use (yrs)	Hearing aid	Strategy	Rate per channel (Hz)	Sensitivity setting	Number of channels	Dynamic range (C levels minus T levels) Mean (SD)
1	6.72	0	2.87	3.81	yes	SPEAK	250	8	20	32.2 (1.9)
2	12.47	6.74	2.95	2.75	no	ACE	900	12	20	74.9 (8.2)
3	9.71	4.0	2.25	3.47	no	ACE	900	12	22	48.9 (7.6)
4	6.14	0	1.44	4.67	no	SPEAK	250	12	20	47.4 (12.3)
5	16.04	2.75	.42	12.71	no	ACE	1800	12	11	54.8 (12.8)
6	13.44	0	11.58	1.80	no	ACE	1200	9	22	54.1 (11.1)
7	8.94	1.4	3.15	4.36	no	SPEAK	250	12	20	21.3 (4.5)
8	14.76	0	11.08	3.57	yes	ACE	900	8	22	61.8 (7.0)
9	6.62	4.0	.41	2.17	no	ACE	900	12	20	51.7 (8.0)
10	12.68	0	8.08	4.57	yes	SPEAK	250	12	20	43.4 (1.5)
11	11.12	0	8.57	2.52	yes	ACE	900	12	22	70.9 (10.3)
12	7.35	0	3.19	4.10	yes	ACE	900	12	22	26.8 (9.3)
13	9.17	0	4.63	4.51	no	ACE	900	12	22	10.9 (6.9)
14	15.47	2.67	.58	12.20	no	ACE	900	12	20	49.6 (9.2)
15	8.50	0	5.33	3.12	yes	ACE	900	12	22	48.2 (8.1)

selected, an A appeared in the processor window. When ADRO was deselected, the program reverted to the Standard program and the letter A did not appear in the window. The child and the parent/caretaker were informed about how ADRO works and asked to compare the Standard and ADRO programs at home and in different environments. All of the children in the study used the same microphone sensitivity setting for both the ADRO and Standard programs. This was the same setting that the child had been using predominantly in everyday life.

Design

The study used a repeated-measures, single-subject design in which each subject served as his or her own control. Performance with the ADRO and Standard programs were compared for each subject. Each child received 4 wk of take-home experience with the new ADRO program. Speech perception testing was conducted during session 2 after 1 wk of ADRO use and again in session 3 after 4 wk of ADRO use. It was recommended that the child use the ADRO program for at least 4 hours a day during the first week. Some parents/caretakers preferred to lock in ADRO along with other processor settings. In these cases, the child was shown how to unlock the processor and deselect ADRO if he/she could not tolerate the loudness of sounds with ADRO. Toward the end of the first week, the children were asked to fill in the Environmental Sounds questionnaire. During the second and third weeks of the study, subjects were asked to lock in the ADRO program. The purpose of this was to ensure that all subjects had a reasonable amount of experience with the new program. In the fourth week, subjects were asked to toggle between the two programs, comparing the ADRO and Standard programs in 12 different everyday listening situations.

Speech Test Materials and Procedures

The children were assessed with the BKB sentence test (Bench, Kowal and Bamford, 1979) adapted for Australian conditions (Bench, Doyle, and Greenwood, 1987). The lists consist of 16 sentences, including 50 key words. To minimize testing time, the BKB/A sentences in quiet were only evaluated at one presentation level, 50 dB SPL (unweighted RMS) (see the Appendix for comparison to other methods). In the adult study by James et al. (2002), this was the input level at which the greatest improvement was seen between the Standard and ADRO programs. Sentences were also presented at 65 dB SPL (unweighted RMS) in the presence of 8-talker babble. The signal-to-noise ratio (SNR) was individually selected to avoid ceiling or floor effects.

The SNRs selected ranged from 0 to +15 and are listed in Table 3. The sentences, spoken by a male speaker, were presented from compact disk recordings. The 8-talker babble was mixed with the sentences through the same loudspeaker. The sound field was calibrated using a one-third octave noise centered at 1 kHz with an RMS sound pressure level equivalent to that of the speech.

In the second test session after 1 wk of take-home experience with ADRO, two BKB sentence lists were administered in both quiet and in noise for each program. Two further lists were administered in quiet and in noise for the Standard and the ADRO programs after 4 wk of ADRO use. The order of testing was counterbalanced across the two test sessions. For each child, no BKB list was repeated during the evaluations. The lists available were assigned in random order to the children.

During the sentence perception evaluations, the children used the same sensitivity setting and volume controls worn most often in everyday life. For each child, these settings were identical for the Standard and the ADRO programs. Children wearing a hearing aid on the contralateral ear did not wear their hearing aid during the laboratory testing.

Questionnaires

In the initial test session, the child was given a personalized booklet with procedural instructions and two questionnaires. Toward the end of the first week, the child (under adult supervision when necessary) was asked to fill out the Environmental Sounds questionnaire. This involved rating the loudness of eight environmental sounds with both the Standard and ADRO programs. The sounds were (1) traveling in the car on a busy street; (2) traffic noise when standing on the footpath; (3) running water such as a toilet or shower; (4) a vacuum cleaner about 1 meter away; (5) a school bell or music at the start of school (a) close by to the loudspeaker and (b) far away from the loudspeaker; (6) classroom noise when a lot of children are talking; (7) the principal/teacher talking at assembly; and (8) noise in the playground at playtime or lunchtime. Subjects rated each sound according to a 5-point pictorial scale: (1) very soft; (2) soft; (3) medium; (4) loud; and (5) too loud. The child was asked to select a "not applicable" category if he or she did not hear the environmental sounds in question. The child and parents were instructed that the child should listen for approximately 1 to 2 minutes with one of the programs and rate the loudness of the sound and then immediately rate the loudness of the same sound with the other program. It was emphasized that the listening conditions should be as similar as possible when these ratings are made.

TABLE 3. Results for BKB sentences in quiet at 50 dB SPL (RMS) and for BKB sentences presented at 65 dB SPL (RMS) in babble

Program	Session number	Subject															
		S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12	S13	S14	S15	
Sentences in Quiet																	
Standard	1	48	84	51	58	76	75	69	52	76	73	84	80	71	97	74	
	2	41	65	57	75	82	82	74	79	95	87	91	92	74	95	83	
	Mean	44.5	74.5	54.0	66.5	79.0	78.5	71.5	65.5	86.5	80.0	87.5	86.0	72.5	96.0	78.5	
ADRO	1	66	90	60	76	88	89	75	56	96	82	94	83	73	91	64	
	2	58	94	80	86	94	91	89	90	92	92	91	95	76	100	89	
	Mean	62.0	92.0	70.0	81.0	91.0	90.0	82.0	73.0	94.0	87.0	92.5	89.0	74.5	95.5	76.5	
ADRO > Standard		**	**	**	**	**	**	*		*							
Sentences in Babble																	
SNR dB		+15	+10	+15	+10	+10	+5	+10	+5	+10	+5	+8	+10	+15	0	+5	
Standard	1	74	79	66	56	66	75	58	54	67	57	81	67	50	33	33	
	2	65	67	69	69	90	82	76	73	68	75	70	74	77	56	79	
	Mean	69.5	73.0	67.5	62.5	78.0	78.5	67.0	63.5	67.5	66.0	75.5	70.5	63.5	44.5	56.0	
ADRO	1	72.0	71	73	83	70	61	81	44	69	53	76	78	67	29	77	
	2	67	86	75	89	90	85	78	78	79	77	84	73	78	80	87	
	Mean	69.5	78.5	74.0	86.0	80.0	73.0	79.5	61.0	74.0	65.0	80.0	75.5	72.5	54.5	82.0	
ADRO > Standard					**			**						*	**		
Program Preference																	
Preference		ADRO	ADRO	ADRO	ADRO	ADRO	ADRO	ADRO	ADRO	ADRO	ADRO	Std	ADRO	ADRO	ADRO	Std	tied

Mean percent correct scores in each session and across sessions for each program are shown for individual subjects. Also shown are the signal-to-noise ratios used in the speech-in-noise testing. Asterisks refer to significantly greater performance in the Adaptive Dynamic Range Optimization (ADRO) condition compared with the Standard condition (ADRO > Std), using the binomial statistic.

* $p < 0.05$, ** $p < 0.01$. Program preference refers to the program that received more preferences (ADRO or Standard [Std]). Subject 15 gave equal preferences to the two programs.

The Environmental Sounds questionnaire also asked two open-ended questions of the parent/care-taker and the child's main teacher; (1) "Has child X reacted or shown awareness of any new sounds since using the ADRO program?" and (2) "Has child X complained of any sounds being too loud with the new ADRO program?"

Subjects were also required to fill out a Program Preference questionnaire after 4 wk of ADRO use (and under adult supervision when necessary). For 12 different listening situations they were asked, "Which program helps you to hear the best?" For each listening situation, the child was instructed to try out each program, one after the other, for approximately 1 to 2 minutes under very similar listening conditions. For example, in the situation "talking with one friend outside in the playground," it was emphasized that the programs should be compared with a similar level of background noise.

The listening situations were (1) at home when someone close by is speaking (about 1 meter away), (2) at home when someone is speaking from across the room, (3) at home when someone is speaking from another room, (4) many people talking around the dinner table, (5) talking with one friend outside in the playground; (6) talking with a small group of friends outside in the playground, (7) listening to the principal or teacher speaking at assembly, (8) listening in a classroom when there is a lot of noise, (9) listening to the teacher or a child in a quiet classroom, (10) conversation in a car, (11) using the telephone,

and (12) listening to the TV. The questionnaire included a "No difference" category, which was to be ticked if the child felt that there was no difference between the two programs. The child was also able to select a "not applicable" category, if a particular listening situation was not experienced. For example, it was envisaged that not all children would necessarily use the telephone. The program preference questionnaire also included an open-ended question for the child's parent/caretaker "Has child X shown any change in understanding speech in any listening situations at home or elsewhere with the new program?" and a similar open-ended question for the child's teacher, "Has child X shown any change in understanding speech in any listening situations in the classroom or in the school ground with the new program?"

Children wearing a hearing aid on the contralateral ear were asked to fill out the questionnaires while using the combined input of the cochlear implant and the hearing aid. They were asked to use their typical hearing aid volume settings. If they were unable to tolerate sounds with the ADRO program, they were instructed to inform the audiologist conducting the study.

RESULTS

Speech Perception Testing

A 2-way repeated-measures analysis of variance (ANOVA) (15 subjects \times 2 programs \times 2 sessions) was computed to assess the effect of the factors

“program” and “session” on BKB sentence scores in quiet. Scores in each condition in each session were an average of two lists. Averages were computed rather than using the multiple list scores because treating the multiple list scores as separate experimental units violates the assumption of independent error effects and results in an overinflated number of degrees of freedom for the error term (Kerlinger, 1986; Kirk, 1995; Max & Onghena, 1999).

There was a significant program effect for BKB sentences presented in quiet at 50 dB SPL ($F(1,14) = 28.25, p = 0.000$). Figure 1 shows that on average, mean performance was significantly higher with the ADRO program compared with the Standard program (an improvement of 8.60%). There was also a significant session effect with performance in session 2 being significantly greater than performance in session 1 ($F(1,14) = 10.53, p = 0.006$). This is shown in Figure 2. The interaction between session effect and program effect was not significant ($F(1,14) = 0.44, p = 0.516$). Holm-Sidak post hoc analyses indicated that there were significant mean increases in performance from session 1 to session 2 for both the ADRO and Standard programs (8.9% and 6.9%, respectively, $p < 0.05$). Figure 2 shows these increases across sessions for the two programs. Individual data are shown in Table 3, which includes the mean performance for individual subjects in each session and across sessions for each program condition. A 2-tailed binomial test was used to determine whether or not there was a significant difference between the cumulative score (combination of four list scores) for the ADRO pro-

gram and the cumulative score for the Standard program. It can be seen in Table 3 that performance with the ADRO program was significantly greater than performance with the Standard program for 8 subjects (subjects 1 through 7 and subject 9).

A 2-way repeated measures ANOVA with the independent factors “program” and “session” was computed for BKB sentences presented at 65 dB SPL in 8-talker babble. There was a significant program effect ($F(1,14) = 9.43, p = 0.008$). Figure 1 shows an improvement in mean group scores of 6.87% with the ADRO program. There was also a significant session effect ($F(1,14) = 15.01, p = 0.002$), with performance in session 2 being significantly greater than performance in session 1 (shown in Figure 2). The interaction between session effect and program effect was not significant ($F(1,14) = 0.065, p = 0.803$). Holm-Sidak post hoc comparisons indicated significant mean increases in performance from session 1 to session 2 for both the ADRO and Standard programs (13.47% and 12.27%, respectively, $p < 0.05$). These increases can be seen in Figure 2. In Table 3, it can be seen that performance with the ADRO program in noise was significantly greater than performance with the Standard program in noise for 4 subjects (subjects 4, 7, 14, and 15).

Relation Between Sentence Scores and Demographic Factors

A forward stepwise regression analysis indicated that the variables of onset of profound hearing loss,

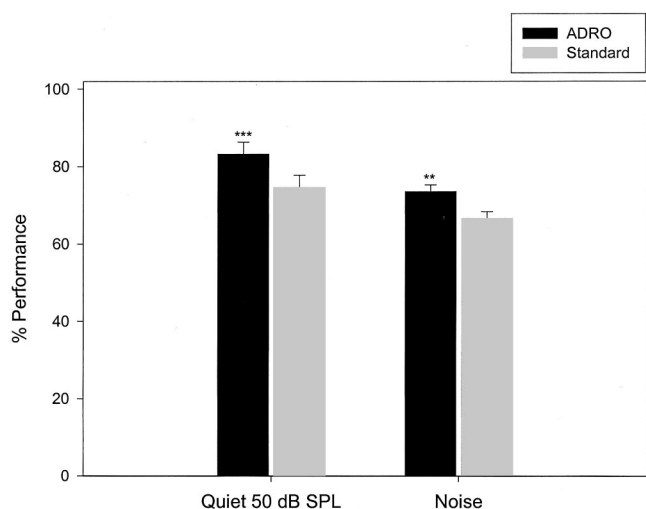


Fig. 1. Mean group Bench-Kowal-Bamford (BKB) sentence perception scores in quiet and in noise for the Standard and Adaptive Dynamic Range Optimization (ADRO) programs. Error bars show standard errors of the means. Significance levels refer to the ANOVAs comparing the programs, ** $p < 0.01$, *** $p < 0.001$.

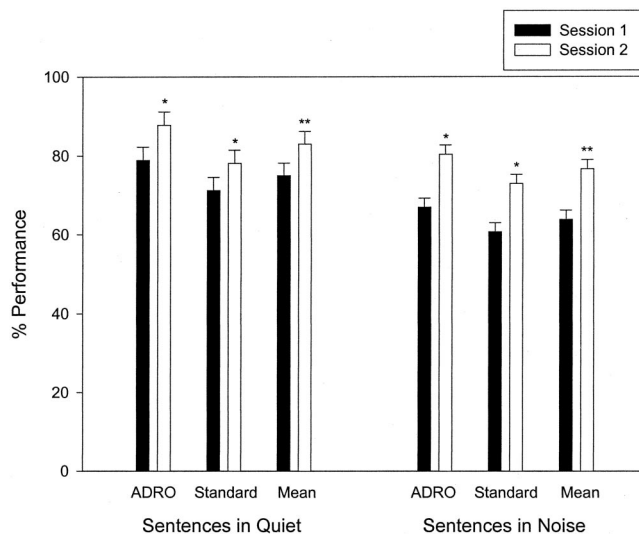


Fig. 2. Mean group BKB sentence perception scores in sessions 1 and 2 in quiet and in noise for the Adaptive Dynamic Range Optimization (ADRO) and Standard programs. Overall mean scores for sessions 1 and 2 are labeled on the x-axis as “Mean.” Error bars show standard errors of means. * $p < 0.05$, ** $p < 0.01$.

duration of profound deafness, implant experience, stimulation rate, microphone sensitivity, number of active channels, and average dynamic range (average of the C-levels minus T-levels across electrodes) did not significantly account for any of the variance in the average difference sentence scores in quiet (ADRO minus Standard). The microphone sensitivity setting was a significant predictor of average difference sentence scores in noise (ADRO minus Standard) ($r = 0.53$, $p = 0.041$). The variables of onset of profound loss, duration of profound deafness, implant experience, rate of stimulation, number of active channels, average dynamic range, and the SNR used in sentence testing did not account for any additional variance in the difference scores in noise.

Questionnaires

All of the six children wearing a hearing aid on the contralateral ear filled out the questionnaires using their usual volume settings on the hearing aid and usual sensitivity settings on the cochlear implant. There were no complaints of the ADRO program being intolerable with the bimodal input.

There were 12 different listening situations in which subjects could indicate if they preferred one program to the other (see Table 4). Although children were encouraged to respond to all situations, four children (S1, S5, S7, and S9) did not provide responses for all listening situations because of personal time constraints. There were seven responses in which the listening situation was deemed "not applicable" (S2 and S8 did not use the telephone during the study; S1, S9, and S15 did not attend

assembly during the course of the study; and S6 and S13 used captions on the TV). As a consequence, the total number of judgments made were 160 instead of a possible 180. Table 4 indicates that of these 160 judgments made, ADRO was the preferred program in 46% of the listening situations. The Standard program was preferred in 26% of situations, and in 28% of situations it was judged that there was no difference between the two programs.

Table 4 also shows individual program preference results. Eight subjects (S1, S2, S4, S6, S7, S11, S12, and S13) judged ADRO as their preferred program in the majority of listening situations reported, whereas two subjects (S10, S14) expressed a clear preference for the Standard program. Of the remaining five subjects, four preferred the ADRO program more often than the Standard program (S3, S5, S8, and S9) and S15 gave equal preferences to the two programs.

Fisher Exact tests of significance for 2×2 contingency tables ($p < 0.05$) were conducted to determine whether a child's distribution of preferences for the ADRO versus Standard programs was significantly different. The Fisher Exact test calculates exact probabilities rather than estimating the probabilities from the continuous Chi-square curve and is used when there are small expected cell frequencies. The 2×2 contingency tables tested the null hypothesis that preference is independent of program type for an individual, the columns being represented by the ADRO, and Standard programs and the rows by the number of situations "preferred" and number of situations "not preferred" (the latter being the number of responses not assigned to

TABLE 4. Summary of results for the Program Preference questionnaire

Subject	ADRO	Standard	No difference	Total	<i>p</i> value
1	4	0	3	7	0.070
2	6	2	3	11	0.183
3	3	0	9	12	0.217
4	8	3	1	12	0.040
5	4	3	2	9	1.000
6	6	0	5	11	0.012
7	5	1	1	7	0.103
8	3	0	8	11	0.214
9	4	3	3	10	1.000
10	2	10	0	12	0.001
11	7	1	4	12	0.027
12	8	0	4	12	0.001
13	8	2	1	11	0.010
14	1	11	0	12	0.001
15	5	5	1	11	1.000
Total responses	74	41	45	160	0.000
Percentage responses	46%	26%	28%	100%	

Subjects were asked to select their preferred program. Note that some subjects did not experience all of the 12 listening situations. The *p* values associated with the Fisher exact tests of significance are provided.

ADRO = Adaptive Dynamic Range Optimization program.

ADRO). The p values for the Fisher Exact tests are provided in Table 4. For subjects 4, 6, 7, 11, 12, and 13, there were significantly more preferences for the ADRO program than for the Standard program. For subjects 10 and 14, there were significantly more preferences for the Standard program than for the ADRO program. A Chi-square analysis was conducted to determine whether there was a significant relation between program type and the total number of preferences (across individuals and across situations). Table 4 indicates that the total number of ADRO preferences were significantly greater than the total number of preferences for the Standard program (Chi-square = 14.782, $p < 0.001$).

It can be seen in Table 5 that the ADRO program was preferred most in specific listening situations: when talking with one friend in the playground, when talking with a small group of friends in the playground, when listening in a noisy classroom, and when having a conversation in the car (in traffic). For each of these listening situations, ADRO was judged as the preferred program for more than half of the responses. Fisher Exact tests of significance ($p < 0.05$) showed that the ADRO program was preferred significantly more than the Standard program in each of these situations.

The Program Preference questionnaire also allowed the child's parents/caretakers and teacher to provide comments on any change in understanding speech in any listening situations. In some cases, no comments were offered. The mother of S1 commented "TV seemed to be much better with ADRO than with the Standard program." She wrote "You could see it in his eyes." The mother explained that her child could understand the TV much better with the ADRO program. The parent of S2 wrote, "when other noises are present ADRO seems beneficial."

The teacher of S3 said that "he can hear softer, quieter sounds like a whisper" with ADRO. Furthermore, the mother of this subject wrote, "his voice sounds louder" with ADRO and clarified that without ADRO, her son's voice was sometimes inappropriately soft. The parent of S13 commented that her child "listens better and understands more" and has "improved voice quality" with ADRO. The teacher of this subject reported, "ADRO is a good improvement." Not all comments about ADRO were positive. One parent (S10) wrote "I think the sounds are soft as I notice he doesn't hear as well." The parents of S3, S6, S11, S14, and S15 reported no change with ADRO. The teachers of S11 and S15 also reported no real change with the ADRO program.

Relation Between Preferences and Demographic Factors

A forward stepwise linear regression analysis was conducted to determine whether or not any demographic factors accounted for variance in the questionnaire preference differences (ADRO minus Standard). The questionnaire preference differences were calculated for each subject by obtaining the quotient of the difference in the number of preferences (ADRO minus Standard) divided by the total number of responses made by an individual (remembering that not all subjects experienced all of the 12 listening situations, see Table 4). Degree of implant experience was a significant predictor of preference differences (ADRO minus Standard) ($r = 0.53$, $p = 0.044$), accounting for 28% of the total variance. A greater proportion of preferences for ADRO were associated with less implant use. However, when the data of subject 14 were removed, the factor of implant experience was no longer significantly associated with preference differ-

TABLE 5. Subject preferences for each of the 12 listening situations

Listening situation	ADRO program	Standard program	No difference	Total	p value
At home, someone speaking close by	2	6	7	15	0.215
At home, someone speaking from across the room	5	5	5	15	1.000
At home, someone speaking from another room	5	5	5	15	1.000
Many people talking around dinner table	7	4	3	14	0.246
Talking with one friend in playground	8	2	3	13	0.016
Talking with small group of friends in playground	8	1	3	12	0.009
Listening to principal or teacher at assembly	5	4	2	11	1.000
Listening in the classroom when there is a lot of noise	8	2	2	12	0.013
Listening to teacher or child in a quiet classroom	4	4	5	13	1.000
Conversation in a car	11	2	2	15	0.000
Using the telephone	7	4	2	13	0.234
Listening to the TV	4	2	6	12	0.640
Total responses	74	41	45	160	

Note that some subjects did not provide responses to all of the listening situations, hence $N < 15$ in the Total column for many listening situations. The p values associated with the Fisher exact tests of significance are shown.

ADRO = Adaptive Dynamic Range Optimization program.

ences ($r = -0.18, p = 0.529$). The other demographic variables, onset of loss, duration of profound deafness, rate of stimulation, microphone sensitivity setting, use of a hearing aid on the contralateral ear, number of active channels, and dynamic range, did not account for any of the variance in the questionnaire data.

The loudness ratings of everyday environmental sounds were collated across subjects. Of the 120 possible responses to this questionnaire, there were 90 responses. Subject 8 did not return the questionnaire, and many subjects did not provide responses for all listening situations. The situations "listening to the school bell or music close by the loud speaker," "listening to the school bell far away from the loudspeaker," and "listening to the principal/teacher talking at assembly" were not experienced by many of the subjects. Table 6 shows the median loudness ratings and range of ratings for each of the programs (Standard and ADRO) for each of the eight environmental sounds. It can be seen that the medians are generally in the "medium loudness" to "loud, but OK" categories for the Standard program and are in the "soft" to "medium" categories for the ADRO program. The median ratings for six of the eight environmental sounds surveyed were louder with the Standard program. The ADRO program was rated louder than the Standard program in seven instances only. One subject rated the ADRO program louder for car travel in traffic, four subjects rated the ADRO program louder when listening to the school bell or music far away from the loudspeaker, and two subjects rated ADRO louder when listening to the principal or a teacher talking at assembly. For the Standard program, 11 sounds were rated as "too loud." Subject 9 rated six sounds as too loud, S3 rated four sounds as too loud, and S12 judged one sound as too loud. No sounds were rated as too loud for the ADRO program. Furthermore, no child using a hearing aid on the contralateral ear complained of intolerance to loud sounds

when using his or her typical hearing aid setting and cochlear implant sensitivity setting.

The Loudness Questionnaire also asked specific questions of the parents/caretakers and the child's teacher. There were no reports of children complaining of any sounds being too loud with the ADRO program. Subject 12's parent commented that when using ADRO her child was able to hear "whisper in class and unvoiced sentences at home." There were no other reports of children showing awareness of new sounds since using the ADRO program.

Relation Between Strategy Preferences and Speech Perception Scores

It is difficult to quantify the degree of association between subjects' preferences on the questionnaire for the Standard versus ADRO programs and the speech test scores for these two programs. Table 3 indicates for each subject which program (ADRO or Standard) received more preferences. There were 12 subjects for whom ADRO was preferred more often than the Standard program. All of these 12 subjects had a higher mean score for sentences in quiet for the ADRO program. Subject 10 clearly preferred the Standard program (see Table 4) but had a slightly higher mean score for sentences in quiet for the ADRO program. Subjects 14 and 15 did not prefer ADRO to the Standard program and showed slightly lower mean scores for sentences in quiet with the ADRO program. With the exception of subjects 1, 6, 8, and 10, all subjects showed higher mean scores for sentences in noise with the ADRO program. Of these subjects, most gave more preferences to the ADRO program with the exception of subjects 14 and 15. The shortfall of this analysis is that it does not consider the degree of difference in the speech scores or in the preferences. For some subjects, speech scores for the two programs only differed by a few percent.

Another means of assessing the degree of association between subjects' preferences on the questionnaire and the speech test scores for these two programs is a correlational analysis. Preference differences were defined as the difference in the number of preferences for the ADRO versus Standard programs divided by the total number of responses made by the subject. The Pearson Product Moment correlations between preference differences and sentence score differences in quiet and in noise were not significant ($r = 0.38, p = 0.168$ and $r = -0.04, p = 0.88$, respectively).

DISCUSSION

The aim of the present study was to determine whether children using the Nucleus multichannel

TABLE 6. Median loudness ratings and range of ratings (minimum to maximum) for environmental sounds

	Standard		ADRO	
	Median	Range	Median	Range
Car travel	4	2-5	2	1-4
Traffic noise	4	3-5	2	2-4
Water running	3	2-5	2	1-4
Vacuum cleaner	4	3-5	3	2-4
School bell/music close by	4	3-5	2	2-4
School bell/music far away	2	2-3	2	1-4
Classroom noise	4	3-5	3	2-3
Principal assembly	3	3-5	3	1-4
Playground noise	4	3-5	2	2-4

1 = very soft; 2 = soft; 3 = medium; 4 = loud; and 5 = too loud.

cochlear implant benefit from the ADRO preprocessing program and whether they find it acceptable. Given the reported benefits and acceptability of this program for adults using the SPrint speech processor, it was expected that children would experience improvement. As in the multicenter adult study (James et al., Reference Note 1), it was found that BKB sentence perception in quiet at 50 dB SPL (RMS) was on average significantly higher with the ADRO program than with the Standard program. However, the mean improvement of 8.6% in this study was less than the 11.54% mean increase reported by James et al. (Reference Note 1) for 16 postlinguistically deafened adults for CUNY sentences in quiet at 50 dB SPL.

The smaller mean group improvement for sentences in quiet at 50 dB SPL for the children in this study compared with the adults in the study by James et al. (Reference Note 1) could be attributable to a number of factors. First, differences can obviously be expected since the study with the adults (James et al., Reference Note 1) and the present study with children were not identical with respect to testing conditions and test materials. Second, it is worth noting that the majority of the adults in the study by James et al. (Reference Note 1) used a microphone sensitivity setting of 8, whereas the children in the present study predominantly used a sensitivity setting of 12. The ADRO audibility rule would increase the gain of a 50 dB SPL (RMS) speech signal to a greater extent for the lower sensitivity setting of 8 than for the higher setting of 12, given that the audibility target would be higher for the lower sensitivity setting. The audibility target is -15 dB down from the AGC threshold in the 30 dB instantaneous input range typical of the SPEAK and ACE processing strategies. If the sensitivity is set to 8, the target will be 6 dB higher than the target for a sensitivity setting of 12, because the AGC threshold is set 6 dB higher for the sensitivity setting of 8 (see Introduction). Burdo, Razza and Moalli (Reference Note 2) investigated the effect of sensitivity setting on ADRO benefit for speech tracking in quiet and in cafeteria noise with normal voice (60 dBA) and whispered voice (45 dBA) in a group of nine patients between the ages of 18 and 45 yr. They found that there were significant group benefits to speech tracking at both sensitivity settings but that the mean group benefit for the lower sensitivity setting of 8 was higher than for the sensitivity setting of 12 in all conditions tested.

It is important that changes in processing that aim to improve audibility of soft speech do not compromise speech perception in noise. Sentence perception in noise was similar for the Standard and ADRO programs in the adult studies reported by

James and colleagues (James et al., 2002; James et al., Reference Note 1). Improvements in audition-alone speech tracking in noise with ADRO were reported by Burdo et al. (Reference Note 2). For example, there was an average group improvement of 16% with the ACE+ADRO MAP versus the standard ACE map for speech tracking with whispered voice in cafeteria noise (SNR +5 dB). In the present study, there was a significant increase in mean scores for sentence perception in noise for the children when using ADRO as compared with the Standard program.

It may seem somewhat surprising that the present study reported a significant group improvement in noise with ADRO for sentences presented at 65 dB SPL in 8-talker babble, given that the studies with adults by James and colleagues did not find a significant improvement with ADRO for sentences presented under similar conditions (although the presentation level of the speech in the adult study was 70 dB SPL [RMS]). It is important to explain that the ADRO preprocessing scheme does have the potential to enable improved sentence perception in noise. Speech perception in noise, using peak-picking schemes such as SPEAK and ACE, depends on the electrical current level differences between the speech peaks and the noise peaks. The current level difference will depend on the slope of the amplitude-to-current mapping function. Given the Q-values used in the mapping function, this slope is smaller for amplitudes close to the top of the input dynamic range than for amplitudes lower in the dynamic range. ADRO aims to use the top end of the dynamic range for a smaller proportion of time than the Standard program and will therefore be operating on a lower (steeper) part of the mapping function. One would expect this effect to be greater for children than for adults because children tend to have wider dynamic ranges (C-levels minus T-levels) than adults and therefore steeper mapping functions (Hughes, Brown, Abbas, Wolaver & Gervais, 2000).

However, dynamic range was not found to be associated with an ADRO benefit in noise for the group of children in this study. There are obviously other factors that contribute to whether the cochlear implant recipient can use this potential benefit of ADRO processing in noise. Further research would be required to systematically investigate the effect of dynamic range on an ADRO speech perception benefit in noise while holding other factors constant. In the present study, factors such as the SNR used in the speech perception in noise testing and the sensitivity setting were not constant across subjects. For this group of children, the microphone sensitivity setting was positively associated with the ADRO benefit in noise, with the lower settings of 8 and 9 associated with less ADRO benefit in noise. Al-

though this finding is based on only a small number of children using the lower microphone settings, it is not a surprising finding. Given that the presentation level of the speech was 65 dB SPL in the speech in noise testing, the higher sensitivity setting of 12 would have activated the comfort rule more frequently than the setting of 8. As a consequence the ADRO program on a setting of 12 would be using the top end of the dynamic range for a smaller proportion of time than the Standard program.

In keeping with the adult studies on ADRO (James et al., 2002; James et al., Reference Note 1), this study found that significant improvements in speech perception with ADRO were not related to the particular rate of stimulation. In addition, the present study found that speech perception benefit with ADRO was not related to onset of loss, duration of profound deafness, implant experience, number of active channels, or dynamic range.

Although there were significant ADRO improvements in quiet and in noise for the group of children in this study, it should be noted that these gains were modest (single-digit percentage differences between the ADRO and Standard programs). Furthermore, there were many children who did not show a significant individual improvement with the ADRO program.

In keeping with the previous adult studies (James et al., 2002; James et al., Reference Note 1) the ADRO program was preferred more than the Standard program in everyday listening situations by the children in this study. However, the reported preference level for the ADRO program was higher for the adult groups than for this group of children; it was judged to be the preferred program in 59% of situations for the adult groups compared with 46% of situations for the children.

One of the subjects in the present study, who expressed a clear preference for the standard program, complained that the ADRO program was too soft. Furthermore, a 7-yr-old child who began the study but withdrew before formal data collection also complained that the program was too soft. As a consequence she rejected the program and withdrew from the study. Future work will explore this issue and determine whether any mapping changes can resolve the problem. It is possible, for example, that the behavioral C-levels in the subjects' MAPs were not set high enough and that the ADRO program was attempting to optimize the signal within a less than optimal dynamic range.

Of interest in the present study is the finding that ADRO was preferred most in specific listening situations (see Table 5). In four of the situations, the ADRO program received significantly more preferences than the Standard program. These situations

share something in common; it is likely that there is a reasonable degree of background noise in each that causes the ADRO program to turn down the gain in at least some channels. For example, the gain in predominantly low frequency channels will be turned down in the presence of low frequency traffic noise, allowing more opportunity for higher frequency information to be selected. The comfort rule also aims to make the signal more comfortable for the listener. It is interesting to note that the ADRO program was not preferred compared with the Standard program in two situations in which speech would be presumably at lower input levels. In the situation "at home, listening to someone speaking from across the room," and in the situation "at home, listening to someone speaking from another room," the votes were distributed equally across the categories, "ADRO," "Standard," and "no difference." This rather unexpected finding could be, in part, attributable to the earlier mentioned hypothesis that the ADRO benefit in quiet is weakened for higher sensitivity settings. Most of the children in this study were using the higher sensitivity setting of 12.

A regression analysis indicated that there were no significant relations between a number of demographic variables such as duration of profound deafness and program preference. There was a significant relation between implant experience and program preference, but this was no longer present when the data for an outlying subject (subject 14) were omitted in the analysis.

Consistent with the findings from the adult studies by James and colleagues, the Environmental Sounds questionnaire indicated that everyday sounds were not unacceptably loud with the ADRO program for this group of children, nor were they unacceptably loud when a hearing aid was worn on the contralateral ear. There were, however, differences between the results of the adult studies and the present study. In the studies by James et al. (2002) and James et al. (Reference Note 1), some environmental sounds were louder with ADRO than the Standard program. In contrast, in the present study, many sounds were judged to be softer with ADRO than with the Standard program. This difference is probably due to the differences in the sensitivity settings used by the two groups. The AGC was operating at a lower input level for a sensitivity of 12 (the sensitivity used by most of the children) than for a sensitivity setting of 8 (the sensitivity setting used by most of the adults). This would result in the ADRO comfort rule being activated more frequently in everyday situations with medium to loud sounds. Hence, medium-to-loud sounds would be turned down with ADRO. In the adult studies, several medium-level everyday sounds (e.g., water running) could have activated the audibility rule for adults using lower sensitivity settings.

The findings from this investigation suggest some preliminary fitting guidelines for the pediatric population. It is recommended that school-aged children, who have the appropriate language skills to express their preferences, be fitted with ADRO. Many children are expected to prefer ADRO to the Standard program, although some will prefer the Standard program and may only choose to use the ADRO program selectively for specific listening situations.

Fitting of ADRO in preschoolers will be less straightforward. Young children often have the speech processor controls "locked in" to avoid tampering with the controls. This study's results suggest that young children are unlikely to experience everyday sounds as uncomfortably loud with ADRO locked in but that it is possible that they may find speech too soft, as was reported by a few subjects in this study. It is recommended that ADRO should not be locked in during the first few months after implantation, when the C-levels in the MAP are more likely to be conservatively set and unrepresentative of the child's true comfort levels. Once the MAP levels are considered stable, ADRO could then be locked in.

APPENDIX

Unweighted RMS speech levels were used as a calibration reference by the Melbourne and Sydney test centers participating in the study. However, in other centers, A-weighted levels and/or peak levels may be used, so the example below provides conversions from the unweighted RMS levels quoted in this study to other levels obtained by different methods of calibration. Measurements were conducted with the use of a Brüel and Kjaer 2260 sound analyzer: 70 dB SPL (RMS unweighted) or 70 dB_{Leq} ≈ 75 dB SPL (fast); ≈ 70 dBA (fast); ≈ 65 dBA_{Leq}; ≈ 67 dBA (slow).

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