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Effects of Converting Bilateral Cochlear Implant Subjects to a Strategy With Increased Rate and Number of Channels

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Objectives: Three different Advanced Bionics processing strategies were evaluated: 1) 8-channel, 813 pulses per second (pps), Continuous Interleaved Sampling (CIS); 2) 16-channel, 5,100 pps, HiResolution Paired (HiRes P); and 3) 16-channel, 2,900 pps, HiResolution Sequential (HiRes S).

Methods: Seven adult bilateral Clarion CII cochlear implant recipients who had been using a CIS processing strategy for at least 18 months participated in this study. Sentence recognition in multitalker babble from the front was collected on subjects using their CIS strategy and after subjects were programmed for the first time with HiRes P and HiRes S strategies. An ABAB design was implemented for 1 month whereby subjects used each HiResolution strategy every other day. Sentence recognition testing was repeated at the 1- and 3-month post-HiResolution test intervals.

Results: Comparisons between the CIS and HiResolution strategies showed immediate improvements for 5 subjects in favor of the HiResolution strategies. After 1 month of alternating between the HiRes P and HiRes S strategies, remarkably, 2 subjects showed improvements of 60%, 2 subjects showed improvements of 40%, and 2 subjects showed improvements of 30% over the CIS strategy that they had previously used for at least 18 months. The results after 3 months of use were consistent with those obtained at 1 month.

Conclusions: The HiRes S and HiRes P strategies resulted in dramatic improvements in speech perception in noise for a subset of subjects who had been using the CIS strategy bilaterally. This finding demonstrates that these subjects were able to tolerate a more difficult signal-to-noise ratio. Further work is needed to determine the independent effects of rate versus number of channels.

Key Words: bilateral cochlear implants, HiResolution strategy, sound processing, speech perception in noise.

Over the past couple of years, cochlear implant clinicians have been converting cochlear implant patients wearing the Clarion CII behind-the-ear (BTE) and Platinum Sound Processor (PSP) from conventional Simultaneous Analog Stimulation (SAS), Continuous Interleaved Sampling (CIS), or Multiple Pulsatile Stimulation (MPS) processing strategies to HiResolution (Advanced Bionics Corporation, Sylmar, California) sound processing. In order to evaluate speech perception performance with a strategy that provides a faster rate and uses an increased number of channels (HiResolution), the University of Iowa conducted a field trial study on 7 patients with bilateral cochlear implants who had previously used a conventional CIS strategy and were converted to HiResolution sound processing. It is hypothesized that the greater representation of temporal fluctuations produced by the higher-rate HiResolution strategies (up to 2,800 Hz), in comparison to the conventional CIS strategy, which produces temporal information up to 400 Hz, would provide increased fine timing cues enabling better speech perception.

The Clarion CIS strategy delivers trains of biphasic pulses to 8 electrodes in sequence (one after the other) at a maximum stimulation rate of 813 pulses per second (pps) with a pulse width of 75 μs. By stimulating in a sequential pattern rather than in a simultaneous pattern, electrical field interactions (channel interactions) may be minimized.

HiResolution sound processing is a processing strategy that provides high-rate pulsatile stimulation by means of biphasic pulses and monopolar coupling.[1] Two different pulsatile stimulation patterns can be produced with the Advanced Bionics

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TABLE 1. DETAILS OF STRATEGIES

	No. of Active Channels	*Rate (pps)*	*Pulse Width (μs)*	*Rectification*	*Center Frequency Range (Hz)*
Continuous Interleaved Sampling	8	813	75	Full-wave	422-5,514
HiResolution Paired	16	5,156	11	Half-wave	333-6,665 (extended lows)
HiResolution Sequential	16	2,900	11	Half-wave	333-6,665 (extended lows)

pps — pulses per second.

SoundWave Software. One stimulation pattern, HiResolution Paired (HiRes P), pairs the pulsatile stimulation with nonadjacent electrodes. For example, when 16 electrodes are used, electrodes 1 and 9 will stimulate together or 2 and 10 will stimulate together, and so on. When a paired stimulation mode with a narrow pulse width (11 μs) is used, the maximum rate obtained is 5,156 pps. In a second stimulation pattern, HiResolution Sequential (HiRes S), electrodes stimulate sequentially, starting with electrode 1 and proceeding through the 16-electrode array. When a sequential stimulation mode with a narrow pulse width (11 μs) is used, the maximum rate obtained is 2,900 pps. This faster rate of stimulation allows HiResolution to follow temporal fluctuations up to 2,800 Hz. Table 1 defines the differences between the conventional CIS strategy and HiResolution strategies.

Research studying the conversion of subjects from conventional Clarion strategies to HiResolution strategies has found that most subjects perform better when using a faster rate of processing and an increased number of channels. Filipo et al[2] studied 14 postlingually deafened adults implanted with a unilateral Clarion CII device. Six subjects utilized the CIS strategy, and 8 utilized the SAS strategy for an average of 9 months after implantation and were then converted to HiResolution. Results on Italian bisyllabic phonetically balanced word and sentence lists showed that on average, scores for words and sentences in quiet improved from 66% and 73% with CIS and SAS strategies to 91% and 83%, respectively, with HiResolution. Words and sentence scores in a +10 signal-to-noise ratio (S/N) showed improvements from 32% and 16% with CIS and SAS to 77% and 62%, respectively, with HiResolution. Furthermore, Koch et al[3] studied 51 patients from 19 different implant centers who were postlingually deafened and implanted with a unilateral HiResolution Bionic Ear. After cochlear implant connection, the subjects used a conventional strategy (16 used CIS, 21 used SAS, and 14 used MPS) for 3 months. The subjects were evaluated on speech perception at 1 and 3 months after connection. The subjects were then fitted with HiResolution and evaluated on speech perception at 1 and 3 months after HiResolution conversion. Three-month Iowa Consonant Identification[4] scores with conventional strategies compared to 1- to 3-month HiResolution scores showed that 10 of 30 subjects showed significant improvement with HiResolution. One subject showed an immediate decrement. Average word and sentence testing in noise at 3 months with the conventional strategy versus average 3-month post-HiResolution results showed that 8 and 14 listeners of the 51 showed a statistically significant improvement on CNC words and HINT sentences in noise with HiResolution. Bosco et al[5] studied speech perception skills in 17 children implanted with Clarion 1.2 and 23 children implanted with Clarion CII. The children implanted with the Clarion 1.2 utilized either the CIS or SAS strategy, and the children implanted with the Clarion CII utilized the HiResolution strategy. The results showed that at 12 months, children using the HiResolution strategy developed better speech perception skills than did children using the CIS or SAS strategy.

In the University of Iowa field trial, subjects who had used the conventional CIS strategy for at least 18 months were asked to alternate between HiRes P and HiRes S strategies for a 1-month time period. The goals of this study were to 1) document the effects of converting to HiResolution sound processing after using CIS for at least 18 months, 2) evaluate differences in the effects of HiRes S and HiRes P sound processing, and 3) evaluate the effects of HiResolution sound processing after 1 month of alternation between HiRes S and HiRes P sound processing.

METHODS

Participants. The subjects for this study consisted of 7 individuals (2 men and 5 women) who received bilateral Advanced Bionics CII High Focus cochlear implants during a single operation. At the time of the study, all subjects had at least 18 months of cochlear implant experience. Table 2 displays individual demographic information. The subjects ranged in age from 28 to 69 years. All subjects had postlingually acquired profound bilateral sensorineural hearing loss, received minimal benefit from hearing aids before implantation, and met the standard cochlear

TABLE 2. DEMOGRAPHIC DATA

Subject	Age at Time of HiRes Conversion (y)	Sex	Duration of Deafness (y) Left	Right	Cause of Deafness	Cochlear Implant Experience at Time of HiRes Conversion (mo)
H16B	56	M	3	3	Enlarged vestibular aqueduct	24
H22B	68	F	55	55	Otosclerosis	24
H18B	69	M	24	24	Noise exposure	24
H27B	63	F	18	18	Unknown	30
H40B	42	F	22	22	Unknown	25
H17B	28	F	9	9	Genetic	34
H48B	44	F	10	10	Genetic	18

implant criteria, at that time, in each ear. That is, before operation the subjects scored less than 40% correct on the Hearing in Noise Test (HINT) everyday sentences, audition-only.[6] All subjects wore the CII BTE processor. Two subjects (H16B and H18B) used a standard microphone that sits above the pinna, and the other 5 subjects used the T-microphone that sits within the concha.

Preconversion Programming. Before crossing over to HiResolution sound processing, all subjects used an 8-channel CIS sound processing strategy. (Subject H22B used SAS for 18 months after implantation and then switched to CIS before crossing over to HiResolution at 24 months.) All subjects' CIS strategies processed sound at a rate of 813 pps with a pulse width of 75 µs. The center frequency bands of the 8 channels ranged from 422 to 5,514 Hz.

Postconversion Programming. After the HiResolution conversion, all patients were asked to use a 16-channel HiRes P strategy and a 16-channel HiRes S strategy. The HiRes P strategy was placed in program 1 of their CII BTE processors, and the HiRes S strategy was placed in program 2 of their processors. The subjects were blind to which strategy was placed in each of the programs. The HiRes P strategy processed sound at a rate of 5,156 pps with a pulse width of 11 µs. The HiRes S strategy processed sound at a rate of 2,900 pps with a pulse width of 11 µs. The center frequency bands of the 16 channels ranged from 333 to 6,665 Hz (extended lows) for both HiRes P and HiRes S.

Materials. All speech perception tests were presented in the sound field, in a sound-treated booth in the bilateral condition. Speech perception was measured in multitalker speech babble noise with recorded City University of New York (CUNY) sentences.[7] The sentences were presented in the most difficult listening situation with the noise from the front at 0° azimuth. When identical signals are presented to both ears, the brain uses binaural redundancy and binaural loudness to produce binaural listening advantages. Signal-to-noise ratios (S/N) were individually set in an attempt to avoid possible ceiling and floor effects. For example, the sentence was presented at a level of 70 dB(C) sound pressure level, and the level of the noise was adjusted in order to produce sentence recognition for each subject between 35% and 70%. Because each subject had different listening capabilities in noise, the S/N was individually set for each subject. Once the S/N was determined for the preconversion testing with the CIS strategy, the S/N was held constant for the postconversion HiResolution testing in order to make a direct comparison between the conventional CIS and HiResolution strategies. Speech materials were presented at 70 dB(C) sound pressure level. The CUNY sentences were scored by dividing the total number of key words correctly identified by the total number of key words possible. A total of 72 lists of 12 CUNY sentences were available for presentation to the subject. Four randomized lists were administered to each subject, with a total of 102 key words per list. No lists were presented to any subject twice.

Procedures. Speech perception was assessed with the subject's conventional CIS strategy. Immediately afterward, the patient was converted to HiResolution and was tested with both the HiRes P and HiRes S strategies. The testing with HiRes P and HiRes S strategies was counterbalanced.

One of the goals of this study was to determine differences in effects seen by two different higher-rate processing strategies. Therefore, an ABABAB field design was implemented by asking the subjects to alternate the HiRes P and HiRes S strategies every day for a 1-month time period. This particular method was implemented so that all subjects would have equivalent amounts of experience with each of the strategies and to eliminate order effects. The subjects were given calendars to remind them which program they were supposed to use and were given a daily journal to write comments in. The order in which programs were worn was counterbalanced among subjects. Specifically, some subjects started

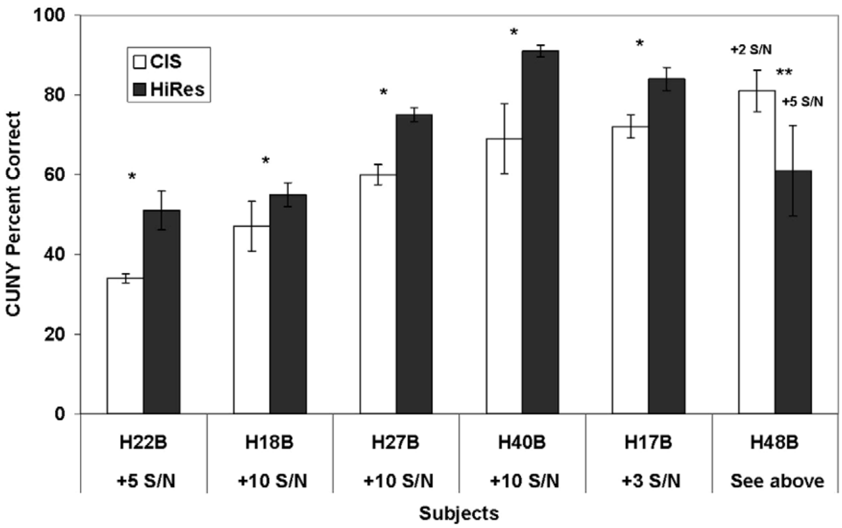

Fig 1. Individual performance on City University of New York (CUNY) sentences in noise with speech and noise presented from front. Individually set signal-to-noise (S/N) ratios are shown. Continuous Interleaved Sampling (CIS) and immediate best HiResolution performance scores (percent correct) are shown with ±1 SE bars. Asterisks highlight significant improvement ($p < .05$) with HiResolution program over CIS program, whereas double asterisks show significant decrement. One subject (H16B) did not have immediate HiResolution conversion speech perception testing.

out using program 1 (HiRes P), and other subjects started out using program 2 (HiRes S).

At the 1-month follow-up, speech perception was assessed by the same testing methods that were used the day of HiResolution conversion. The order of testing with the HiResolution strategy was counterbalanced between subjects. The subjects were then given the choice of continuing to use both HiResolution strategies or picking one HiResolution strategy to use over the other. The subjects were again reevaluated on speech perception abilities between 3 and 6 months after the HiResolution conversion.

RESULTS

Immediate Crossover Results. The speech perception results obtained with CUNY sentences before conversion with conventional CIS and the highest-scoring HiResolution strategy (Paired or Sequential) immediately after conversion are shown in Fig 1. All statistical results were analyzed with the binomial model. Significant results were at the .05 level. Results for subject H16B are not shown because of time constraints with the postconversion HiResolution testing. No immediate crossover data were collected at this time. When we compared the CIS score to the HiResolution score, 5 subjects showed a 10% to 20% immediate significant improvement after conversion. One subject (H48B) showed a significant decrement in speech perception performance with HiResolution, even with an easier S/N (+2 with CIS and +5 with HiResolution). A paired *t*-test showed no significant difference ($p > .05$) between CIS results (mean, 60.5%; SD, 17.3%) and the immediate HiResolution results (mean, 69.5%; SD, 16.2%).

One-Month HiResolution P Versus HiResolution S. The CUNY sentence results obtained with the HiRes P and HiRes S strategies after 1 month of HiResolution use are shown in Fig 2. Only 2 of 7 subjects (H16B and H22B) showed a difference

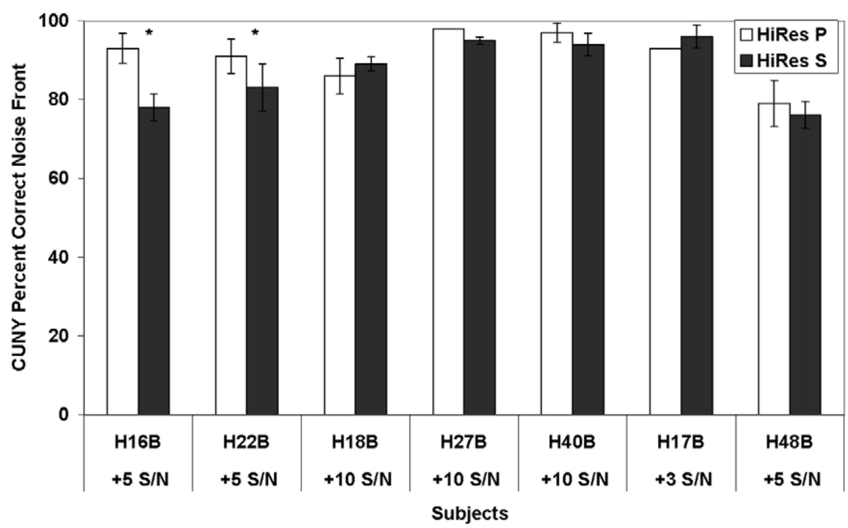

Fig 2. Individual performance on CUNY sentences in noise with speech and noise presented from front. Individually set S/N ratios are shown. One-month HiResolution Paired (HiRes P) and HiResolution Sequential (HiRes S) performance scores (percent correct) are shown with ±1 SE bars. Asterisks highlight significant difference ($p < .05$) between strategies.

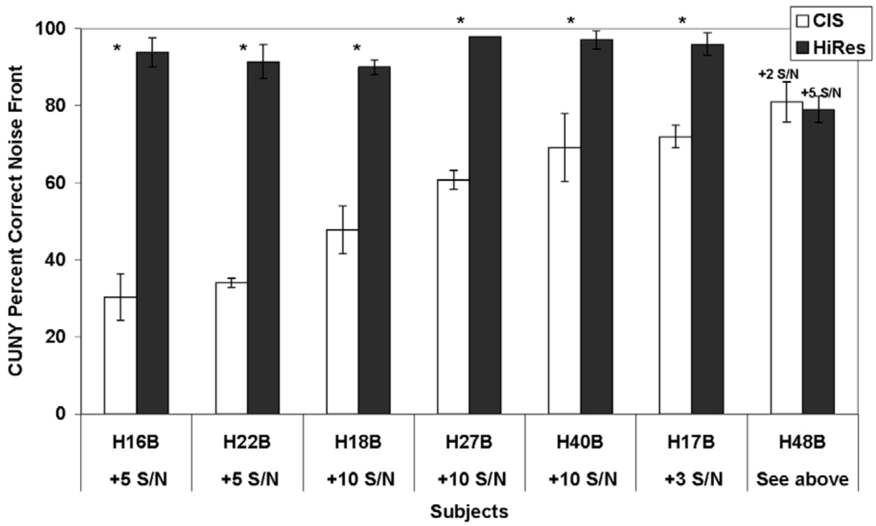

Fig 3. Individual performance on CUNY sentences in noise with speech and noise presented from front. Individually set S/N ratios are shown. CIS and 1-month best HiResolution performance scores (percent correct) are shown with ±1 SE bars. Asterisks highlight significant improvement ($p < .05$) with HiResolution program over CIS program.

in performance between the HiRes P and HiRes S strategies. (The HiRes S results were worse than the HiRes P results.) A paired *t*-test showed no significant difference ($p > .05$) in performance between the HiRes P (mean, 91.0%; SD, 6.6%) and HiRes S (mean, 87.2%; SD, 8.3%) strategies.

CIS Versus One-Month HiResolution. The CUNY sentence results obtained with the conventional CIS strategy versus the highest-scoring 1-month HiResolution (Paired or Sequential) strategy are shown in Fig 3. The scores improved approximately 30% to 60% from CIS to HiResolution for 6 subjects. Specifically, 2 subjects (H16B and H22B) showed a significant improvement of 60%, 2 subjects (H18B and H27B) improved significantly by 40%, and 2 subjects (H17B and H40B) significantly improved by 30%. One subject's (H48B) results were similar with CIS and HiResolution (although the S/N was at +2 for CIS and +5 for HiResolution). A paired *t*-test showed a statistically significant improvement ($p < .001$) in performance with HiResolution (mean, 92.1%; SD, 6.5%) at 1 month in comparison to CIS (mean, 56.4%; SD, 19.4%).

One-Month HiResolution Versus 3- to 6-Month HiResolution. The CUNY sentence results obtained with the highest-scoring HiResolution strategy (Paired or Sequential) at 3 to 6 months compared to the highest-scoring HiResolution strategy (Paired or Sequential) at 1 month are shown in Fig 4. After 1 month of alternating between the HiRes P and HiRes S strategies every other day, the subjects were given the choice to wear their preferred strategy. Five subjects showed no difference in speech perception performance between their best HiResolution strategy at 1 month and their best HiResolution strategy at 3 months. Two subjects (H18B and H27B) showed a decrement in scores between 1 and 3 months of HiResolution use. A paired *t*-test showed no significant difference ($p > .05$) in performance between the 1-month HiResolution (mean, 92.1%; SD, 6.5%) and

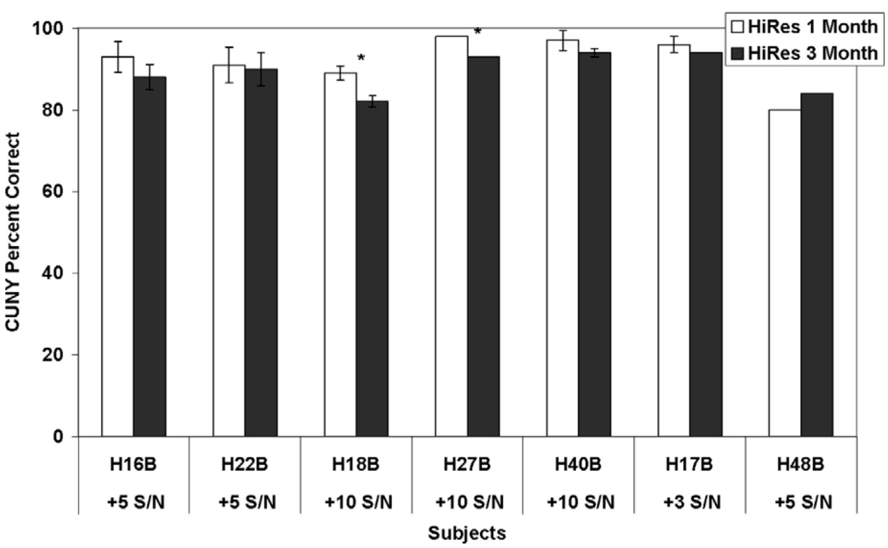

Fig 4. Individual performance on CUNY sentences in noise with speech and noise presented from front. Individually set S/N ratios are shown. Best 1-month HiResolution and best 3-month HiResolution performance scores (percent correct) are shown with ±1 SE bars. Asterisks highlight significant difference ($p < .05$) between performance at two different times.

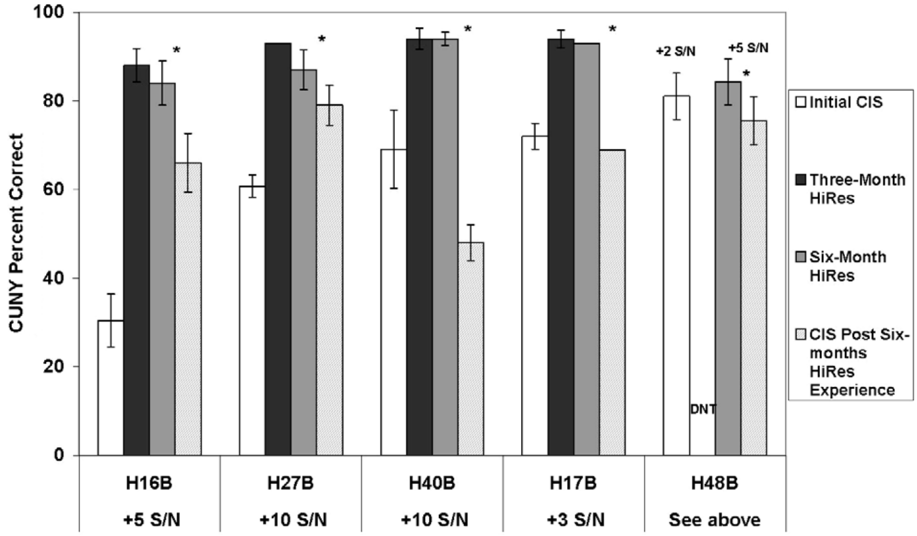

Fig 5. Individual performance on CUNY sentences in noise with speech and noise presented from front. Performance scores (percent correct) are shown with ±1 SE bars for initial CIS, 3-month HiResolution, 6-month HiResolution, and CIS at 6 months after HiResolution conversion. Asterisks highlight significant difference ($p < .05$) between 6-month HiResolution results and 6-month CIS results.

the 3-month HiResolution (mean, 89.2%; SD, 4.8%) results.

Testing With CIS After Use of HiResolution. Five subjects were retested with their original CIS program and HiResolution program at least 6 months (range, 6 to 18 months) after HiResolution conversion. This CIS strategy was programmed with SoundWave programming software. Each subject was allowed 12 hours to listen to their CIS strategy before testing. Figure 5 shows that 4 of the 5 (H16B, H27B, H40B, and H17B) subjects continued to do significantly better (on the binomial model) with their HiResolution programs at 6 months than with the initial conventional CIS program. Two subjects (H22B and H18B) were not using HiResolution at the time of the 6-month post-HiResolution conversion data collection, so their data were not included. All 5 subjects showed statistically better performance (with the binomial model) with their 6-month HiResolution program than with their CIS program after using HiResolution. Interestingly, 2 subjects (H16B and H27B) performed better with their CIS program after using HiResolution than with CIS prior to HiResolution conversion. In contrast, 2 subjects (H40B and H48B) performed worse with a CIS program after using HiResolution than with CIS prior to HiResolution conversion. A repeated-measurement analysis of variance (with Bonferroni adjustment used for the multiple comparison) showed that there was no statistically significant difference ($p > .05$) between performance with the initial CIS strategy (mean, 62.7%; SD, 19.4%) the 6-month HiResolution strategy (mean, 88.5%; SD, 4.8%), and the 6-month CIS strategy (mean, 67.5%; SD, 12.1%) because of the small sample size.

DISCUSSION

The main goals of this field trial were threefold. Our first goal was to document the effects of converting to a sound processing strategy with a faster rate and an increased number of channels (HiResolution). The second goal was to evaluate differences in performance between a strategy that stimulates sequentially through 16 adjacent electrodes (HiRes S) and a strategy that stimulates in a paired, nonadjacent electrode fashion (HiRes P). The third goal was to evaluate speech perception performance after the subject alternated between two different HiResolution sound processing strategies for a 1-month time period.

The results of our first goal showed that most subjects were able to immediately take advantage of faster sound processing utilizing more electrode contacts. This finding is impressive, as these subjects did not need time to acclimate to the processing strategy before receiving benefit. Although some subjects expressed preferences between the HiRes P and HiRes S strategies, no subject reported not liking the quality of the sound produced by either HiResolution strategy.

After the subjects were converted to HiResolution from their conventional CIS strategy, they were asked to alternate between HiRes P and HiRes S strategies for 1 month. The purpose was to evaluate differences in performance with a strategy that stimulates sequentially versus a strategy that stimulates in a paired configuration. The HiRes S strategy stimulates at a slower rate than does the HiRes P strategy (2,900 pps versus 5,156 pps) and stimulates tonotopically, whereas the HiRes P strategy does not. By the subject's alternating strategies daily, the brain of the subject would have equal representation from each strategy, but the subject would not use either strategy long enough to acclimate to one or the other. Although some subjects had a preference for one strategy over the other, all subjects were willing to alternate use of the strategies daily. Our research team is relatively confident that all subjects abided by this demanding regimen. The subjects were all briefed on the importance of this research approach. In addition, each subject consistently wrote, on a daily basis, in a journal documenting what he or she liked and disliked about each strategy. The fact that there were no differences between the results obtained with the strategies after 1 month of use leads us to believe that the tonotopic stimulation mode and rate did not have an overwhelming effect for most subjects.

Performance with HiResolution after 1 month of alternating between the HiRes P and HiRes S strategies showed a dramatic improvement in speech perception compared to sentence perception with conventional CIS. We are unable to determine whether the improvements in speech perception were due to the increase in channels, the increase in rate, or both, because the rate and number of channels changed simultaneously during conversion to HiResolution. All but 1 subject's scores with HiResolution improved between 30% and 60% and ranged from 80% to 95% on sentences in noise, demonstrating that these subjects were able to tolerate a more difficult S/N. To compare these results to those of unilateral listeners, we looked at a study by Koch et al,[3] which showed improvements on average of 14% on HINT sentences in noise with HiResolution. The conventional CIS strategy is only capable of representing temporal information up to 400 Hz; therefore, it may be possible that the greater representation of temporal fluctuations produced by the higher-rate HiResolution strategies (up to 2,800 Hz) produces binaural cues that monaural listeners cannot obtain.

After at least 6 months of experience with the subjects' preferred HiResolution strategies, 5 subjects were tested with their preferred HiResolution strategy and retested with a CIS strategy. Eighty percent of the subjects (as subject H48B did not have 3-month HiResolution results) continued to have stable results with their HiResolution strategy and performed better on speech perception tasks with their HiResolution program versus their initial CIS program. (Subject H48B showed better performance with her initial CIS.) This outcome shows that for these 4 subjects, HiResolution is superior to the CIS strategy. When retested with a CIS strategy after having the HiResolution experience, 2 subjects (H16B and H27B) showed an improvement in performance with their CIS program after using HiResolution, as compared to their performance with their initial CIS strategy prior to using HiResolution. One explanation for the improvement in CIS scores is that the subjects have learned the test material. However, these subjects showed no difference in performance between their 3- and 6-month HiResolution scores. A second explanation is that the listeners have adopted a different listening strategy with the higher rate and increased number of channels with HiResolution. The subjects may be able to utilize temporal cues in the higher-rate strategy that they are now able to recognize in the slower-rate strategy. Two subjects (H40B and H48B) showed a decline in performance with their CIS program after using HiResolution, as compared to their performance with their initial CIS strategy. It is possible that this decrement is due to the acute nature of testing these subjects with a strategy that they had not worn for more than 6 months.

CONCLUSIONS

The Advanced Bionics HiRes S and HiRes P strategies resulted in dramatic improvements in speech perception in noise after 1 month of use in subjects who had been using conventional CIS bilaterally. This finding indicates that subjects were able to tolerate a more difficult S/N with HiResolution than with conventional CIS. In addition, in comparison to conversion results of subjects with unilateral cochlear implants,[3] the improvements for bilateral listeners were much larger, possibly indicating central integration. After 3 months of HiResolution use, all speech perception improvements stayed consistent. After at least 6 months of HiResolution experience, 80% of the subjects continued to perform better with the HiResolution strategy than with the CIS strategy. Further work is needed to determine the independent effects of rate versus number of channels of stimulation.

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