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Word Recognition following Implantation of Conventional and 10-mm Hybrid Electrodes

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Key Words

Cochlear implant · Low-frequency hearing · Electroacoustic stimulation · Hybrid electrodes

Abstract

We compared the effectiveness of 2 surgical interventions for improving word recognition ability in a quiet environment among patients who presented with: (1) bilateral, precipitously sloping, high-frequency hearing loss; (2) relatively good auditory thresholds at and below 500 Hz, and (3) poor speech recognition. In 1 intervention (n = 25), a conventional electrode array was inserted into 1 cochlea. As a consequence, hearing was lost in the implanted ear. In the other intervention (n = 22), a Nucleus Hybrid short-electrode array was inserted 10 mm into 1 cochlea with the aim of preserving hearing in that ear. Both groups of patients had similar low-frequency hearing and speech understanding in the ear contralateral to the implant. Following surgery, both groups had significantly higher word recognition scores than before surgery. Between-group comparisons indicated that the conventional electrode array group had higher word recognition scores than the 10-mm group when stimulation was presented to the operated ear and when stimulation was presented to both ears.

Introduction

The benefits of combining information from low-frequency acoustic hearing and from a cochlear implant have been well documented [Ching et al., 2004; Dorman et al., 2008; Gantz et al., 2005; Gstoettner et al., 2004; Kiefer et al., 2005; Kong et al., 2005; von Ilberg et al., 1999; Wilson et al., 2002]. Both speech understanding in quiet and speech understanding in noise are significantly improved when patients have access to both acoustically and electrically stimulated information.

One surgical approach to produce combined acoustic and electric stimulation is to insert a conventional (long) electrode array into 1 cochlea of patients with bilateral, precipitously sloping hearing loss above 500 Hz. Hearing is usually lost in the implanted ear but patients can obtain low-frequency acoustic information from the contralateral ear. Dorman et al. [2008] report consonant-nucleus-consonant (CNC) scores averaging 74% correct when both electrically and acoustically stimulated information is available to patients [Gifford et al., 2007, 2008]. For results from patients with varying amounts of residual acoustic hearing, see Armstrong et al. [1997], Dunn et al. [2005], Ching et al. [2004], Hamzavi et al. [2004], Kong et al. [2005], Mok et al. [2006], Shallop et al. [1992] and Tyler et al. [2002].

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Another surgical approach to produce combined acoustic and electric stimulation is to insert an electrode array 10, 16 or 20 mm into the cochlea, with the aim of preserving hearing in the implanted ear [Gantz et al., 2005; Gantz and Turner, 2004; Gstoettner et al., 2004; Kiefer et al., 2005; Luetje et al., 2007; Skarzynski et al., 2004; von Ilberg et al., 1999]. When hearing is preserved, patients can use low-frequency acoustic stimulation from both ears and combine acoustic and electric hearing. For example, Gantz et al. [2005] studied 11 patients with 10-mm insertions and reported a mean CNC score of 69% correct in the combined electric and bilateral acoustic condition. Kiefer et al. [2005] studied 13 patients with 20-mm insertions and reported a mean monosyllabic word recognition score of 67% correct in the combined electric and bilateral acoustic condition.

In the research reported here, we compared the effectiveness of 2 of the surgical interventions described above for improving the word recognition ability in quiet of patients who presented with: (1) bilateral, precipitously sloping high-frequency hearing loss; (2) relatively good auditory thresholds at and below 500 Hz, and (3) poor speech recognition. In 1 intervention, a conventional electrode array was inserted into 1 cochlea. As a consequence, hearing was lost in the implanted ear. In the other intervention, a Nucleus Hybrid (Cochlear Corporation, Centennial, Colo., USA) electrode array was inserted 10 mm into 1 cochlea, with the aim of preserving hearing in that cochlea. Before surgery, both groups of patients had similar low-frequency hearing and speech understanding in the ears ipsilateral and contralateral to the implant.

Methods

Subjects

Forty-seven patients with bilateral, high-frequency hearing loss participated in this project. All patients met the audiometric and speech understanding criteria for entry into the Cochlear Corporation Nucleus Hybrid clinical trial, specifically: (1) thresholds at 500 Hz and below at ≤60 dB hearing level (HL); (2) thresholds at 2000 Hz and above at ≥80 dB HL, and (3) monosyllabic word recognition ≤60% in the ear to receive the implant and no greater than 80% in the nonimplanted ear.

One group was composed of 22 patients who received the Nucleus Hybrid implant. The hybrid electrode array is 10 mm in length. It has 6 electrode contacts spaced over the distal 4.3 mm of the array. The center frequency of the lowest input filter is variable and dependent on the degree of hearing preservation following surgery. Typically, the center frequency of the lowest input filter is 774 Hz and of the highest filter it is 6417 Hz. All electrode arrays were fully inserted, according to the surgeon's report. The patients were recruited from 3 implant centers in the USA. The patients ranged in age from 22 to 75 years, with a mean of 56 years. The patients' experience with electrical stimulation ranged from 3 to 18 months, with an average of 13 months.

The second group was composed of 25 patients who received a conventional cochlear implant. All electrode arrays were fully inserted, according to the surgeon's report. The patients were recruited from 4 implant centers in the USA. Twelve patients used Cochlear Corporation devices and 13 patients used Advanced Bionics Corporation (Sylmar, Calif., USA) devices. For the Cochlear Corporation devices the center frequency of the lowest input filter was 243 Hz and of the highest it was 7421 Hz. The center frequency values cited here are the geometric means of the upper and lower frequency cutoffs of the input filters for the most apical and basal channels, respectively. For the Advanced Bionics devices, the center frequency of the lowest input filter was 333 Hz and of the highest input filter it was 6665 Hz. Most of the patients had been identified as fitting the criteria for the clinical trial of the 20-mm Med El EAS device (Med El Corporation, Innsbruck, Austria), but opted for a full insertion when the clinical trial was postponed. Another group of patients was identified by chart review. For these patients, complete preimplant audiometric and speech data (e.g. audiometric thresholds at 125 Hz and bilateral, aided performance) were not always available. The patients ranged in age from 45 to 85 years, with a mean of 68 years. The patients' experience with electrical stimulation ranged from 5 to 98 months and averaged 20 months. This mean was influenced by 2 outliers – patients with 98 and 51 months' experience. For the remaining patients the mean was 15 months.

The prospectively identified patients were paid an hourly wage for participation. The research was approved by the institutional review boards at Arizona State University (encompassing the Arizona Ear Center), the Mayo Clinic in Rochester, the Midwest Ear Institute in Kansas City and the Carle Clinic in Urbana, Illinois, USA.

Preimplant Audiograms

The mean preimplant audiogram for the implanted ear of the 10-mm patients is shown in figure 1a (black symbols). The mean preimplant audiogram for the conventional electrode array patients is shown with gray symbols. The mean audiograms for the contralateral ears of the patients are shown in figure 1b using the same conventions.

Speech Material

Monosyllabic word recognition performance in quiet was assessed using the CNC word lists [Peterson and Lehiste, 1982]. In accordance with the research protocol defined in the Nucleus Hybrid clinical trial, the following conditions were tested: aided acoustic for the implanted ear (Ai); aided acoustic for the contralateral ear (Ac); binaural aided (Abin); electric only (E); electric plus ipsilateral acoustic (E + Ai or 'hybrid'); electric plus contralateral acoustic (E + Ac or 'bimodal'), and electric plus binaural acoustic (E + Aic or 'combined'). Two 50-item lists were administered for each of the conditions with the reported score representing the average performance across the 2 lists. The CNC lists were assigned randomly for each subject and condition. All testing was achieved using recorded stimuli presented via a single loudspeaker at a calibrated level of 70 dB SPL. The loudspeaker was placed at a 0-degree azimuth at a distance of 1 m from the subject. When acoustic input to an ear was not wanted (e.g. to the

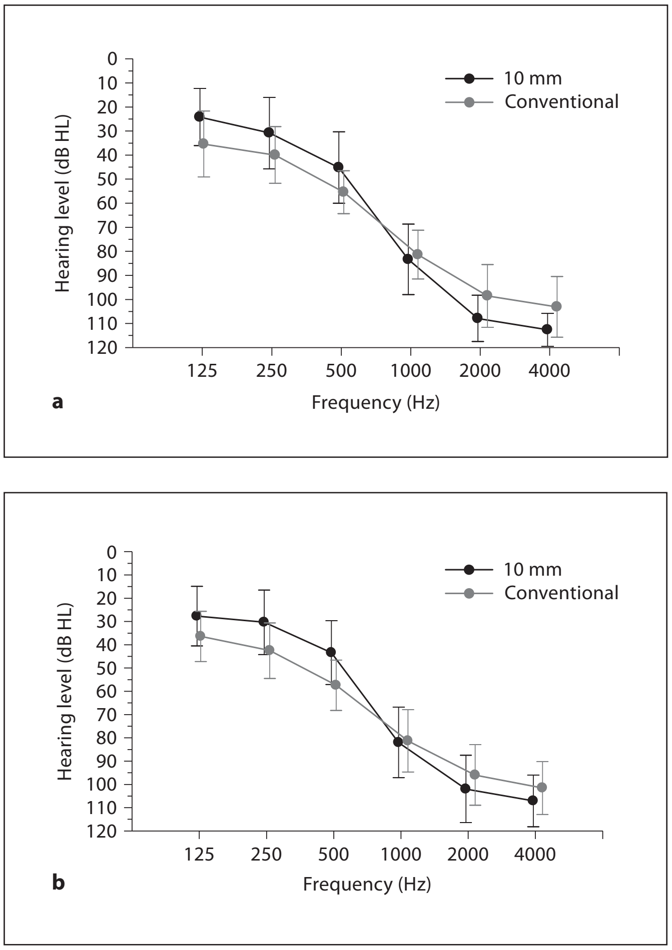

Fig. 1. Preimplant audiograms for patients in the 10-mm and conventional electrode array groups. **a** Implanted ear. **b** Contralateral ear. The symbols are slightly offset at each frequency to make the plots easier to examine. Error bars indicate ±1 standard deviation.

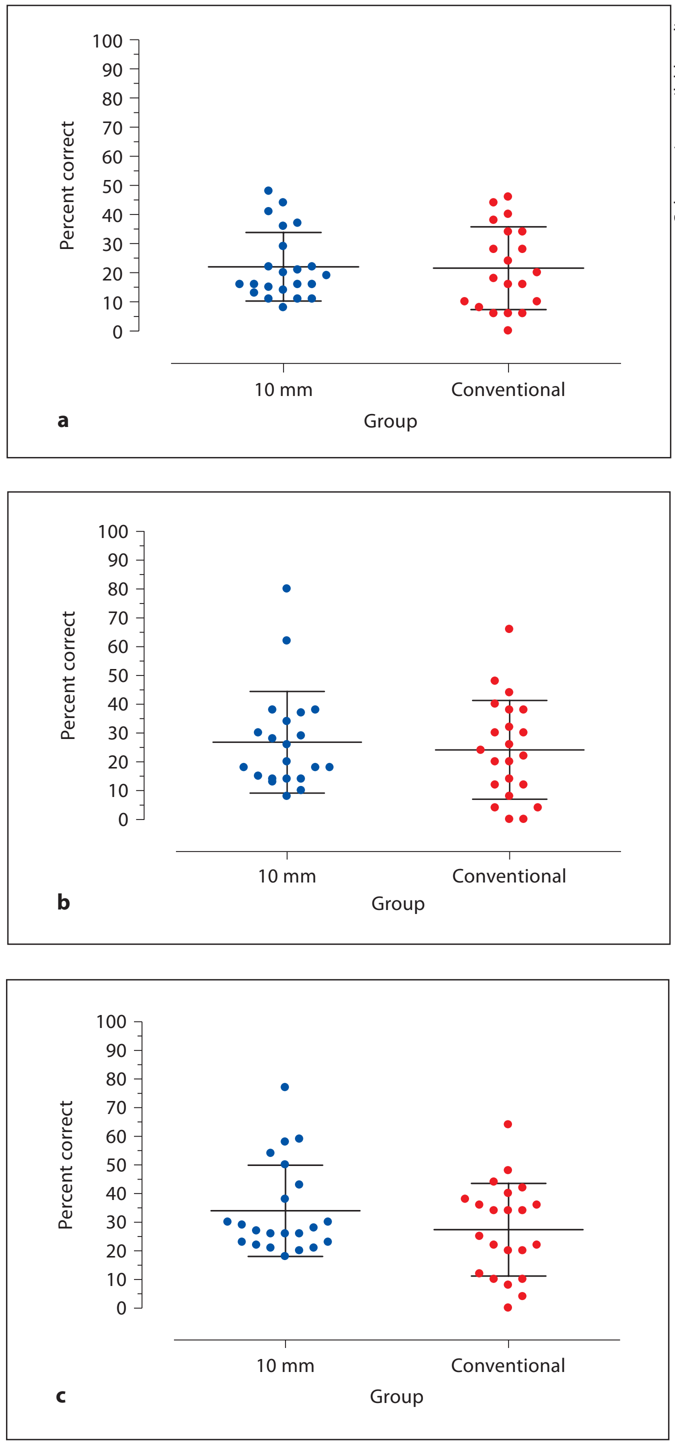

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Fig. 2. Preimplant, aided CNC scores for the 10-mm and conventional electrode-array groups. **a** Implanted ear. **b** Contralateral ear. **c** Binaural. The mean ± 1 standard deviation is indicated by horizontal lines.

ipsilateral ear in the E + Ac condition), that ear was occluded with a foam ear plug.

Preimplant Speech Understanding

Prior to testing, all hearing aid settings for the ipsilateral and contralateral ears were verified using the speechmap fitting system on the Audioscan Verifit real-ear mode to match the NAL-NL1 targets for 70-dB-SPL speech from the National Acoustic Laboratories (Sydney, N.S.W., Australia). The preimplant aided CNC scores for stimulation directed to the ear which was to receive the implant in the 10-mm patients and the conventional electrode array patients are shown in figure 2a. The mean score for both groups was 22% correct. The scores for stimulation directed to the contralateral ear are shown in figure 2b. The mean score for the 10-mm group was 27% correct. The mean score for the conventional electrode array group was 24% correct. The mean scores were not significantly different (t_{41} = 0.5045, p >

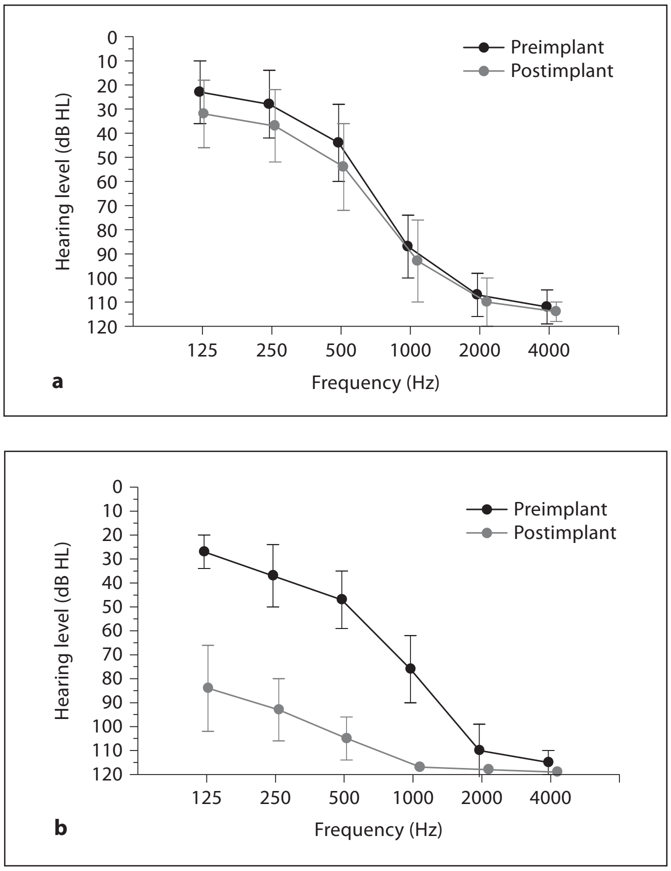

Fig. 3. a Audiograms for patients with preserved hearing (n = 15). **b** Audiograms for patients with major loss of hearing (n = 7). Error bars indicate ±1 standard deviation.

0.05). The scores for bilateral stimulation are shown in figure 2c. The mean score for the 10-mm group was 34% correct. The mean score for the conventional electrode array group was 27% correct. The mean scores were not significantly different ($t_{42} = 1.4$, $p > 0.05$). Overall, there were no significant differences in preimplant speech understanding between groups.

Results

The results are organized into 4 sections. In the first we describe hearing preservation for the patients who received a 10-mm electrode array. In the second we describe word recognition outcomes for those patients. In the third we describe word recognition outcomes for patients with a conventional electrode array. In the fourth we compare levels of performance for the 2 groups of patients. In each section we discuss separately performance with stimulation directed to the implanted ear and performance with stimulation directed to both ears. Because we conducted multiple t tests, we adjusted our α value using the Bonferroni correction. We report tests on 8 comparisons. The corrected α value is 0.05/8 or 0.0062.

Hearing Preservation in the Operated Ear

Hearing was well preserved in 15 of 22 patients. As shown in figure 3a, for those 15 patients the average, preoperative thresholds at 125, 250, 500, 1000, 2000 and 4000 Hz were 23, 28, 44, 87, 107 and 112 dB HL, respectively. Postoperative thresholds were 32, 37, 54, 93, 110 and 114 dB HL. Thus, the average hearing loss was approximately 10 dB over the low frequencies (i.e. 125–500 Hz). As shown in figure 3b, for the remaining 7 patients the average, preoperative hearing thresholds at 125, 250, 500, 1000, 2000 and 4000 Hz were 27, 37, 47, 76, 110 and 115 dB HL. Following surgery, the thresholds were 84, 93, 105, 117, 118 and 119 dB HL. There were several patterns of hearing loss. Three patients lost hearing within 1–3 months following surgery. One patient lost hearing in the implanted ear over a period of 6–12 months following surgery. One patient lost hearing in both ears over a period of 6–12 months following surgery. Two patients lost hearing due to accidents not related to surgery. Overall, 4 of the 7 losses appeared to be a consequence of surgery. Hearing loss and the subsequent loss of speech information delivered acoustically to the operated ear is one of the risks of hearing preservation surgery. All 22 patients were included in the statistical evaluations in all but 1 of the analyses reported below.

As noted above for preimplant speech testing, postimplant testing was also conducted following verification of hearing aid settings for both the ipsilateral and contralateral ears using the speechmap fitting system on the Audioscan Verifit real-ear mode to match NAL-NL1 targets for 70-dB-SPL speech.

10-mm Insertion with Stimulation Directed to the Implanted Ear

Figure 4 displays a within-group comparison of pre- and postimplant performance for stimulation directed to the implanted ear of the 10-mm patients. The preimplant Ai mean score was 22% correct. The postimplant E mean score was 28% correct. These mean scores were not statistically different ($t_{21} = 1.4$, $p = 0.18$). The postimplant E + Ai score was 39%. Four patients achieved slightly poorer scores in the E + Ai condition than in the Ai condition. Nonetheless, the group mean score in the E + Ai condition was significantly higher than the preimplant Ai score ($t_{21} = 4.01$, $p = 0.006$).

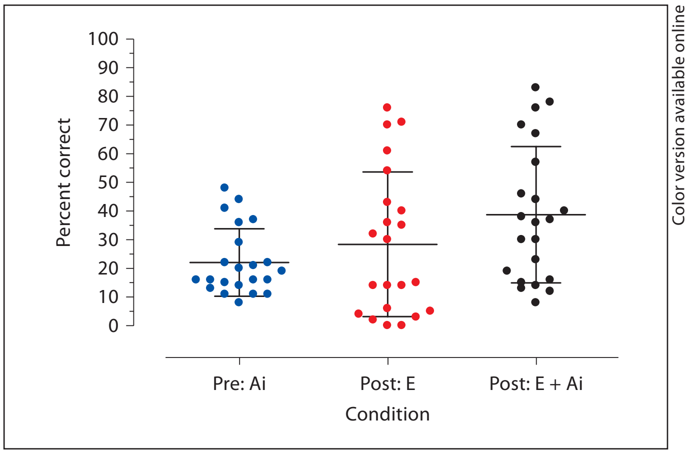

Fig. 4. Preimplant aided and postimplant, electric-only (E) and electric plus acoustic (E + Ai) recognition of CNC words. Data are for the implanted ears of 10-mm patients. The mean ± 1 standard deviation are indicated by horizontal lines.

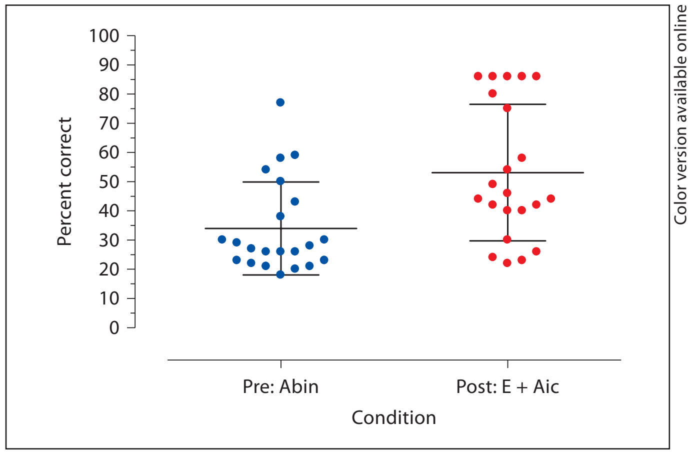

Fig. 5. Recognition of CNC words. The figure shows preimplant binaural aided (Abin) and postimplant electric plus binaural acoustic (E + Aic) recognition. Data are for both ears of 10-mm patients. The mean ± 1 standard deviation are indicated by horizontal lines.

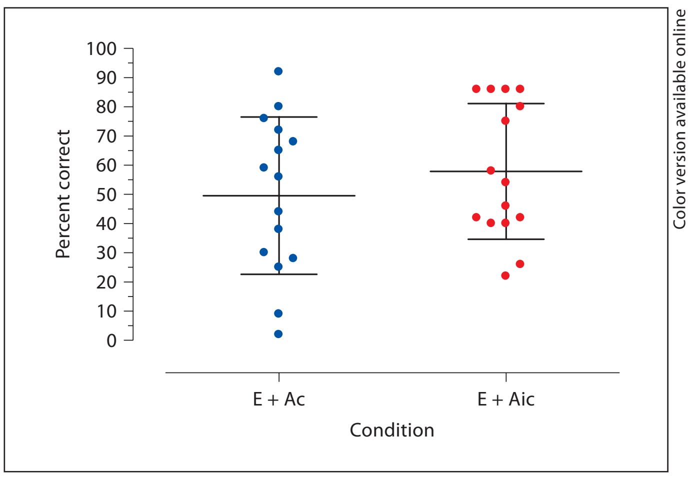

Fig. 6. Recognition of CNC words in the electric plus contralateral acoustic (E + Ac) and electric plus binaural acoustic (E + Aic) conditions among 10-mm patients with hearing preservation (n = 15). The mean ± 1 standard deviation are indicated by horizontal lines.

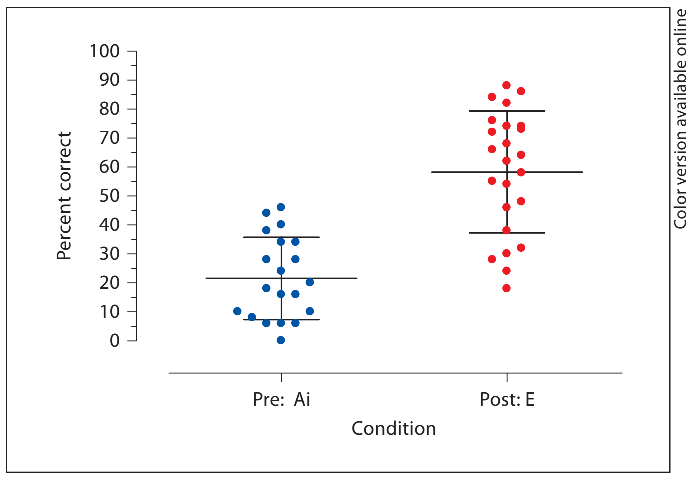

Fig. 7. Preimplant aided and postimplant electric-only (E) CNC word recognition. Data are for the implanted ears of conventional electrode-array patients. The mean ± 1 standard deviation are indicated by horizontal lines.

10-mm Insertion with Stimulation Directed to Both Ears

Figure 5 displays a within-group comparison of pre- and postimplant performance with binaural inputs. The preimplant Abin score was 34% correct. The postimplant E + Aic score was 53% correct. Two patients achieved poorer scores in the E + Aic condition than in the Abin condition. The mean scores for the Abin and E + Aic conditions were significantly different ($t_{21} = 5.5$, $p < 0.001$).

Figure 6 displays a within-group comparison for the 10-mm patients in the E + Ac and E + Aic conditions. This comparison speaks to the question of the benefit of preserving hearing in the implanted ear. In the E + Aic, or combined, condition in the Nucleus Hybrid clinical

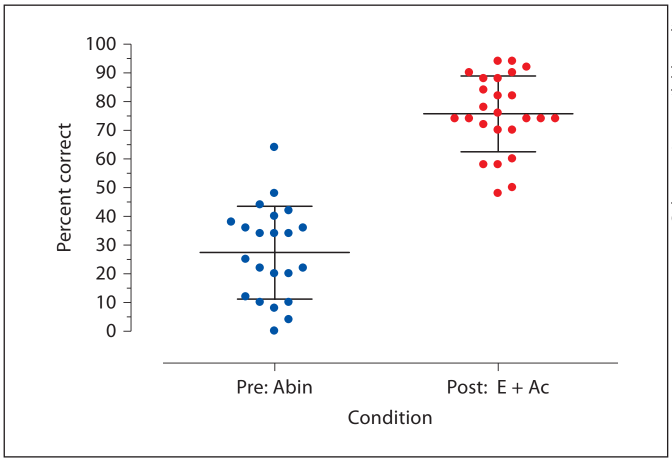

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Fig. 8. Preimplant, binaural aided (Abin) and postimplant electric plus contralateral acoustic (E + Ac) recognition of CNC words for conventional electrode-array patients. The mean ± 1 standard deviation are indicated by horizontal lines.

trial, stimulation was directed to the implant and to both ears. In the E + Ac, or bimodal, condition, stimulation was directed to the implant and to the ear contralateral to the implant (the ipsilateral ear was plugged). The difference between the conditions is the availability of low-frequency information from the implanted ear in the E + Aic condition. For this analysis only patients with preserved hearing (n = 15) were included.

As shown in figure 6, the mean score in the E + Ac condition was 50% correct. The mean score in the E + Aic condition was 58% correct. The mean scores were not statistically significant (t_{14} = 2.6, p = 0.023) using the Bonferroni corrected α value of 0.006. If this had been the only condition tested, or we had not used the correction, the mean scores would have been significantly different.

Full Insertion with Stimulation Directed to the Implanted Ear

Figure 7 displays a within-group comparison of pre- and postimplant performance for stimulation directed to the implanted ear of patients who received a conventional electrode array. The mean preimplant Ai score was 22% correct. The mean postimplant score for the E condition was 58% correct. Two patients had slightly poorer E scores than Ai scores. The mean scores for the E and Ai conditions were significantly different (t_{18} = 5.67, p < 0.001).

Full Insertion with Stimulation Directed to Both Ears

Figure 8 displays a within-group comparison of pre- and postimplant performance with binaural inputs. The preimplant Abin score was 27% correct. The postimplant E + Ac score was 76% correct. No patient had a poorer E + Ac score than Abin score. The mean scores for the Abin and E + Ac conditions were significantly different (t_{21} = 13.55, p < 0.0001).

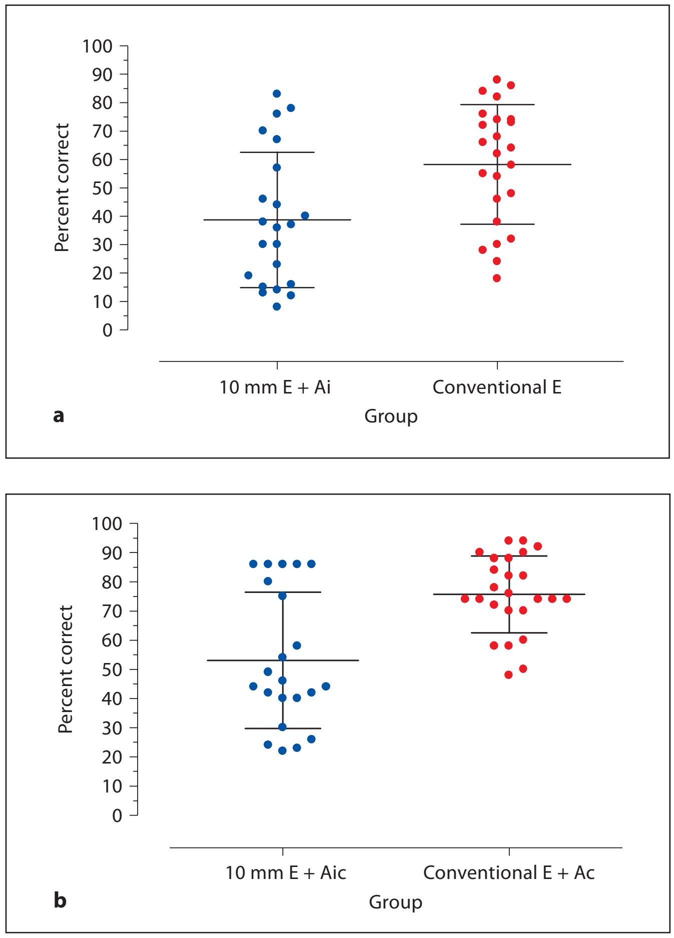

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Fig. 9. Between-group comparisons for CNC word recognition. **a** Stimulation directed to the implanted ear. **b** Stimulation directed to both ears. The mean ± 1 standard deviation are indicated by horizontal lines.

Comparing Results between Groups

Figure 9a displays a between-group comparison of performance with stimulation directed to the implanted ear. The mean score for the 10-mm patients in the E + Ai condition was 39% correct. The mean score for the conventional electrode array patients in the E condition was 58% correct. The mean scores were significantly different (t_{44} = 3.0, p = 0.0049).

Figure 9b displays a between-group comparison of performance with stimulation directed to both ears. The mean score for the 10-mm patients in the E + Aic condition was 53% correct. The mean score for the conventional electrode array patients in the E + Ac condition was 76% correct. The mean scores were significantly different ($t_{45} = 4.2$, $p < 0.0001$).

Discussion

The aim of the research reported here was to assess the efficacy of 2 surgical interventions for improving the word recognition abilities of patients who presented with: (1) bilateral, precipitously sloping high-frequency hearing loss; (2) relatively good auditory thresholds at and below 500 Hz, and (3) poor speech recognition. We have structured the discussion of outcomes around a set of questions.

Is Word Recognition Improved for Patients Who Receive a 10-mm Electrode Array with the Aim of Hearing Preservation?

The answer is 'yes' for both the operated ear alone and for all inputs combined. This outcome is consistent with previous reports of benefit from hearing preservation surgery with the Nucleus Hybrid 10-mm electrode array [Gantz et al., 2005; Luetje et al., 2007].

Is There Benefit from Preserving Hearing in the Implanted Ear?

Because the patients had low-frequency hearing in both ears, for the 10-mm patients, the critical case is performance in the E + Ac condition versus performance in the E + Aic condition. The E + Aic condition allows acoustic hearing in the operated ear to contribute to word recognition. When looking only at patients with preserved acoustic hearing, there was a mean increase of 8 percentage points in the E + Aic condition. While this was not significant when using a Bonferroni corrected α value, it was significant at the 0.02 level.

Why Would We Expect a Relatively Poor Ear to Add to the Speech Understanding Provided by a Relatively Good Ear (the Contralateral Ear)?

Consider first the preoperative condition of the patient. Both ears had relatively symmetrical high-frequency hearing loss and poor speech understanding. If there was a poorer ear, it was chosen for surgery. Following surgery, the hearing in the operated ear was reduced by a small amount – an average of 10 dB at 125, 250 and 500 Hz (for patients with preserved hearing).

Consider now the case of preoperative speech understanding when hearing in the operated ear had not yet been made a little poorer. For the patients who were to receive a 10-mm electrode array, there was a 7 percentage point improvement in performance in the bilateral aided condition versus the best single-ear, aided condition. For the patients who were to receive a conventional electrode array, there was a 3 percentage point improvement in performance in the bilateral versus best single-ear, aided condition. Thus, there was little reason to believe that following surgery the poorer ear would add greatly to the better ear when both were combined with electric stimulation. And that is the outcome we obtained: an average of an 8 percentage point improvement in the E + Aic condition relative to the E + Ac condition. The statistical significance of this small improvement is open to question. If the Bonferroni correction is not necessary [Perneger, 1998; Rothman, 1990], then the improvement is statistically significant.

From the standpoint of speech information, it is unclear why even an 8 percentage point improvement was obtained. There should have been no information from the operated ear that was not contained in the signal from the contralateral ear. Given that the speech signal was presented at a high level from a single speaker at a 0-degrees azimuth, binaural summation for loudness should not have played a role in performance. Perhaps it is useful to have 2 'looks' at the same information, even if the second 'look' (from the operated ear) is of lower fidelity than the 'look' from the better ear.

Is Word Recognition Better After than Before Implantation in Patients Who Receive a Conventional Electrode Array in 1 Ear?

The answer is 'yes', both for the case of inputs to the operated ear and for the case of inputs to both ears. This finding is consistent with our previous reports with smaller samples [Dorman et al., 2008; Gifford et al., 2007].

Do the Interventions Differ as an Aid to Word Recognition?

For stimulation directed to the operated ear and stimulation directed to both ears, patients with a conventional electrode array achieved higher scores than patients with a 10-mm array. For stimulation directed to the implanted ear the mean scores were 58% correct and 39% correct for the conventional electrode array and 10-mm groups, respectively. For stimulation directed to both ears, the mean scores were 76% correct and 53% correct, respectively. The significant differences in performance remained when patients who had large hearing losses in the ear ipsilateral to the implant were removed from the sample.

What Accounts for the Differences in Performance for the Conventional Electrode Array and 10-mm Patients?

Because both groups had access to similar acoustic information in the ear contralateral to the implant, and because preserved hearing in the implanted ear added little to intelligibility, we suggest that the difference in overall performance between groups was due largely to differences in the information made available by the 2 electrode arrays.

For the 10-mm patients, the signal was first high-pass filtered and then delivered to a 6-electrode array covering an extent of 4.3 mm. In contrast, the conventional electrode-array patients received a more broadband signal that was delivered to electrode arrays with 16 or 22 contacts that covered an extent of approximately 14–17 mm. From this point of view it is not surprising that the conventional electrode array patients achieved higher scores than the 10-mm patients.

On the other hand, it is surprising that three 10-mm patients achieved high scores (70, 71 and 76% correct) in the E condition. While not as high as the best E scores with a conventional electrode array (4 scores between 82 and 88% correct), the scores document that patients can 'remap' electrical stimulation at the base of the cochlea in the service of speech understanding. If there had been more patients in our sample who could remap, then our mean scores might have been closer to the mean scores reported by Gantz et al. [2005]. If remapping takes place over a long time period, then scores at >2 years after surgery might be higher than the scores we have recorded.

In our view, the most significant issue in hearing preservation surgery is not whether hearing is preserved in the operated ear. Instead, it is the ability of a basally positioned, shortened electrode array to convey speech information. It will be of interest to see whether deeper insertions – 16 and 20 mm – using longer electrode arrays (as used in ongoing clinical trials of hearing preservation surgery) will allow the same level of speech understanding as conventional electrode arrays. If they do, then there will be little 'risk' in hearing preservation surgery in terms of speech understanding because, even if hearing is lost, performance will be no worse than with a conventional electrode array.

How Can We Best Assess the Benefits of Hearing Preservation Surgery?

As noted above, there is little reason for a second, partially hearing ear (the implanted ear with preserved hearing) to be very useful for word recognition in quiet or in noise when (1) signals are presented from a single loudspeaker and (2) signals are presented at suprathreshold levels. For the case of signals at threshold, having 2 partially hearing ears could result in binaural summation that could be of benefit to a listener. However, the practical benefits of small changes in speech reception threshold are debatable. If large differences in speech understanding are to be found for patients with two partially hearing ears versus 1 partially hearing ear, then the differences will likely be found in complex sound environments – characterized by separate noise and signal sources – in which low-frequency, binaural cues could aid speech recognition.

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