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Acoustic Plus Electric Speech Processing: Longitudinal Results

Bruce J Gantz, MD¹, Camille C Dunn, PhD¹, Jacob Oleson, PhD², and Marlan R Hansen, MD¹

¹Department of Otolaryngology – Head and Neck Surgery, University of Iowa, Iowa City, IA, USA

²Department of Biostatistics, University of Iowa, Iowa City, IA, USA

Abstract

Objective—Few studies have investigated the longitudinal stability of residual hearing and speech perception outcomes in individuals who were implanted with a shorter electrode device.

Study Design—Longitudinal, single-subject design.

Methods—Fifty subjects who received a Nucleus® Hybrid™ short electrode cochlear implant and had a minimum of 2 years (and up to 15 years) of post-operative longitudinal experience were included in this study. Twenty-three subjects received a Hybrid S8; 14 subjects received a Hybrid L24; and 13 received a Hybrid S12. Audiometric thresholds and Consonant-Nucleus-Consonant (CNC) words were collected pre and postoperatively for up to 15 years for the S8 subjects and 7 years for the S12 and L24 subjects. AzBio Sentences in multi-talker babble was collected for up to 7 years on the S12 and L24 subjects.

Results—Longitudinally, 83% of the S8 subjects, 92% of the S12 subjects, and 86% of the L24 subjects maintained a functional hearing pure-tone average (PTA; 125–500 Hz). Predicted change using a piecewise linear mixed model in PTA over time showed a postoperative linear decrease in hearing for each group until 0.5 years after which the PTA stabilizes and is maintained. The averaged individual data for CNC and AzBio sentences show a significant improvement in scores by 0.25 to 0.5 years post implantation after which scores start to reach their maximum.

Conclusion—This longitudinal study demonstrates that A+E hearing and improvement in speech understanding in quiet and in noise can be accomplished and sustained for many years with a short electrode cochlear implant.

Keywords

Hybrid; Residual Hearing; Cochlear Implant; Longitudinal studies

Corresponding author: Bruce J Gantz MD, Professor and Head, University of Iowa, Dept of Otolaryngology–Head and Neck Surgery, 200 Hawkins Drive (21201 PFP), Iowa City, Iowa 52242-1078, 319-356-2173 Tel, 319-356-3967 Fax, bruce-gantz@uiowa.edu.

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Level of Evidence: 2C

Introduction

Cochlear implantation has provided remarkable speech perception improvements for many patients over the past 30 years who have profound hearing loss pre-operatively. In early studies, while these cochlear implant devices provided benefits to speech perception, it was commonly found that these devices did not conserve acoustic hearing in patients who had any level of residual hearing. In studies comparing pre and post-operative hearing conservation, most showed substantial shifts in audiometric thresholds^{1,2} while others demonstrated preservation in approximately half of the subjects reviewed^{3,4}. Of those that had some hearing conservation, most did not have preservation of hearing that was considered functional or useable³. It was remarkable that hearing could be preserved by placing the long and somewhat space occupying electrode into the scala tympani. In fact, it was thought that opening the round window or a cochleostomy would most likely eliminate any acoustic hearing.

Over the past 15 years, we and others have been investigating the use of combined acoustic-electric processing (A+E) to address the needs of individuals who have functional residual low-frequency hearing and severe to profound high-frequency sensorineural hearing losses⁵⁻¹⁹. Electrode-arrays of different lengths and diameters have been designed to preserve residual hearing. In 2014, the Nucleus® Hybrid™ L24 cochlear implant was approved by the Food and Drug Administration (FDA) for implantation in those with significant residual hearing²⁰ and the results from that clinical trial have been published²¹.

Research studying A+E shows that listeners are able to successfully integrate low-frequency acoustic hearing with high-frequency electrical stimulation for improved speech perception abilities^{5,15,18,19}. Preservation of residual low frequency acoustic hearing has demonstrated significant benefit for fine-timing information^{16,22} which aids the listener in understanding speech in noise^{12,15,18,19,21,23}, maintenance of sound localization²⁴⁻²⁷, and music appreciation^{14,28} while access to the electrically coded high-frequency information provides important spectral information. There continues to be some risk to residual hearing with surgical implantation and also after activation of the device. It appears that shorter arrays preserve more hearing than longer ones^{8,29-31}. It also appears that the inner ear might be more robust than once thought³². Strategies have been designed to reduce insertion trauma during implantation of the device, but there appears to be progressive acoustic hearing loss that occurs typically between 1 and 6 months following activation of the device⁵.

Few studies have investigated the longitudinal stability of residual hearing and speech perception in individuals implanted with a hybrid cochlear implant. Gantz et al.,⁵ reported multicenter clinical trial data on 87 subjects implanted with a Nucleus Hybrid S8. At 1 year post-implantation, 80% of subjects maintained functional hearing and 87.5% of the subjects had improvements on word scores in the combined hearing condition (CI and bilateral hearing aids). Another study evaluated patterns of hearing loss longitudinally on 17 patients following implantation with a hearing preservation device³³. Average follow-up was 2.3 years. Most patients experienced a gradual decline (n=7) in hearing or fluctuating hearing (n=6). Only one subject experienced a sudden loss of hearing. In a further study, residual hearing at 1500 Hz and below was analyzed on N=97 Nucleus Hybrid L24 and N=51

Nucleus Freedom CI 422 subjects 2 years after initial fitting³⁴. Results indicated that residual hearing was preserved for the majority of implanted patients with the Hybrid L24 and the CI422 implant with greater stability and less median hearing loss over time for those with the Hybrid L24 implant.

While all of these studies demonstrated short-term benefit of A+E hearing, they do not answer the continued concern of whether preservation of residual hearing is sustainable over several years. All of the previously mentioned reports were limited to data through 1 – 2 years following activation. Moreover, it is also unknown if the speech perception benefits that A+E listeners obtain shortly after implantation are maintained over time. Examining hearing preservation and performance over time is important to determine if implantation with a short-electrode device is a long-term solution for patients with good low-frequency hearing loss. The University of Iowa Cochlear Implant Program has up to 15 years of hearing and speech perception data on individuals implanted with a variety of hearing preservation electrodes. The goal of this study, therefore, is to examine longitudinal trends in low-frequency hearing and speech perception performance over a 15 year observation period.

Materials and Methods

The first shortened hearing preservation electrode placed at our institution was completed in 1999 following FDA approval for a feasibility clinical trial. Since that time, we have implanted 87 adults with various lengths of short electrode devices. Of those, 49 subjects received a Nucleus® Hybrid™ L24 (L24), 14 subjects received a Nucleus® Hybrid™ S12 (S12), and 24 received a Nucleus® Hybrid™ S8 (S8). Table 1 provides further description of the devices used in this study. In this study, we only included Hybrid subjects who had a minimum 2 years or more post-operative longitudinal data. As a result, we will be showing data from 14 with a L24, 13 subjects with a S12, and 23 subjects with a S8. Twenty-one of these subjects were male and 29 were female. Average age at implantation was 58 years (SE: 2.4; range 29 to 80 years) for the S8 subjects; 55 years (SE: 2.6; range 33 to 65 years) for the S12 subjects; and 46 (SE: 3.7; range 23 to 62 years) for the L24 subjects. Using an ANOVA model, the mean age for the SE group was significantly different from the mean age for the L24 group ($p=0.01$), while the mean age for the S12 group was not significantly different from either the S8 ($p=0.26$) or the L24 group ($p=0.23$).

All subjects in this study fit the inclusion criteria for a Hybrid cochlear implant²⁰. That is, the subject was a post-lingually deafened adult with severe to profound (a threshold average of 2000, 3000, & 4000 Hz 75dB HL) sensorineural hearing loss for frequencies > 1500 Hz and low-frequency thresholds up to and including 500 Hz no poorer than 60 dB. Consonant-Nucleus-Consonant (CNC) monosyllabic word³⁵ scores were between 10–60% in the ear to be implanted and up to 80% understanding in the contralateral ear in the best-aided condition. Device choice was based upon the Food and Drug Administration Investigational Device Exemption availability at the time that the subject was evaluated for a cochlear implant. Subjects implanted with the S12 and L24 devices were 65 year of age or younger at the time of implantation and had a duration of profound high-frequency hearing loss less than 30 years.

Surgery was performed using soft surgery techniques, as described in Gantz, Turner, Gfeller, Lowder¹⁶. A standard facial recess mastoidectomy with a cochleostomy (0.6–0.7 mm) anterior and inferior to the anterior round window annulus was accomplished for all of the S8 and S12 subjects and N=8 of the L24 devices (N=8 cochleostomy and 6 round window). Importantly, a suture secured the electrode at the bony overhang at the tegmen mastoideum. This suture stabilized the springy lead of the implant and prevented translational movement in the scala tympani as the electrode was advanced slowly over 1 to 2 minutes. A fascia washer or a strip of fascia was used to seal the cochleostomy or round window opening. Dexamethasone (10 mg) was systemically administered intraoperatively.

Subjects were tested pre- and postoperatively at 0.25 and 0.5 years, 1 year and annually using a battery of speech perception measures tested in the combined (bilateral hearing aids and the CI) listening condition. If a subject did not maintain functional hearing on the implanted ear following surgery, they were followed and tested as bimodal listeners (CI and a HA on the opposite ear). These listening conditions were considered by the subject to be their preferred listening mode.

Following FDA guidelines, all of our patients returned within ± 30 days of the target return date. The CNC³⁵ word recognition test in quiet and the AzBio Sentence Test³⁶ played in a multi-talker babble at a +5 Signal-to-Noise Ratio (SNR) at 0°-azimuth were the primary speech perception measures. Unaided air in dB HL for the frequencies of 125, 250, 500, 1000, 2000, 3000, 4000, 6000, and 8000 Hz were obtained for each ear using the standard audiometric technique for pure-tone air conduction testing. S8 subjects have speech perception and residual hearing data extending out to 15 years with averaged longitudinal data of 9 years (Range: 2 years to 15 years; SE: 9.4). The S12 subjects data out to 7 years with averaged longitudinal data of 4.5 years (Range: 2 years to 7 years; SE: 7.4). The L24 subjects have data that extends out to 7 years with averaged longitudinal data of 3.8 years (Range: 2 years to 7 years; SE: 6.9).

A piecewise linear mixed model was used to evaluate the longitudinal change in outcome measures of pure-tone-average (PTA; 125–500 Hz) and CNC words. It is understood that performance for implant recipients will change dramatically at initial activation, and then at about 0.5 years, the individual has reached a threshold and then achieves a level of maintenance in the outcome measure. This phenomenon results in a nonlinear trend across time. The piecewise linear mixed model allows us to model these two separate trends within the framework of one unifying statistical model. In addition, we use a linear mixed model with random subject and random slope effects to account for within subject correlation due to the repeated measures nature of the data. We did examine simpler statistical models and more complex statistical models searching for a model that adequately fits the data while not being too complex using the Akaike Information Criterion for model selection. The piecewise linear model was superior to a linear model and polynomial models in fitting the data for PTA and CNC. For AzBio Sentences in noise, the linear mixed model included a quadratic effect in time. Each of the models included fixed effects for time. The piecewise model comprised two time variables with one before 0.5 years and a separate one for time after 0.5 years. The quadratic model for AzBio included both a linear time trend and a quadratic time trend, allowing the modeled mean of AzBio to curve as a function of time.

Each model also included as fixed effects a categorical variable for device type, plus interactions between device type and time. There were random effects for intercept, and slope, as well as covariances between them. The random effects allow each individual to have his/her own trajectory in the model, and accounts for longitudinal correlation. Main effects were tested with a chi-square test. T-tests with a Tukey-Kramer adjustment were used to determine differences between device types at specific years. SAS v9.4 was used for the model, and R v3.3.1 was used for computing probabilities based on model results.

The linear mixed model that was used assumed that data are missing at random (MAR). This means that all participants were included in the analysis, that we observed the individual pattern, and that the reason for data being missing depends only on data that were observed. In an effort to confirm this assumption, we examined baseline PTA for those who had a return visit after 2 years versus those whose last visit was prior to 2 years, and compared them with a two-sample t-test. Including all participants with baseline data, those who returned beyond 2 years (mean=62.9) had significantly poorer hearing than those who did not return (mean=39.9) ($p<0.01$). Examining only S8, those who returned (mean=61.5) had significantly worse hearing than those who did not return (versus 35.2) ($p<0.01$). Examining S12 and L24 together, there was no significant difference between those who returned (mean=64.4) and those who did not (mean 53.1) ($p=0.26$).

Results

In Figure 1, we show individual and modeled longitudinal hearing preservation using a three-frequency PTA from 125 to 500 Hz. Panel A shows PTAs for the S8 subjects; Panel B for the S12 subjects; and Panel C for the L24 subjects. Panel D shows the modeled PTAs for each of the Hybrid groups over time. The PTA of hearing that is unusable to stimulate acoustically was considered non-functional⁵ and was stimulated electrically. The individual PTAs show that 83% of the S8 subjects maintained longitudinally functional hearing (Panel A) and 92% of the S12 (Panel B) and 86% the L24 subjects (Panel C) maintained longitudinally functional hearing. A total of 7 subjects developed a non-functional PTA at some point following initial activation (IA) of their device. Four subjects (N=2 S8, N=1 S12, N=1 L24) lost their hearing by .25 years (3 months) post-activation; two subjects (N=1 S8 and N=1 L24) lost their hearing at 2 years post-activation; and 1 subject (n=1 S8) lost her hearing at 6 years post-activation. Total loss of hearing was recorded as 120 dB HL. The seven subjects that did not maintain functional hearing on the implanted ear were followed as bimodal listeners (CI and a HA on the opposite ear). None of the subjects were explanted and reimplanted.

In Figure 1, Panel D, we show predicted change in PTA over time for the three hybrid groups using a piecewise linear mixed model. Within the piecewise linear model we used the 6 month postoperative time point as the joint for the model. As shown in Panel D, there is a linear trend that exists preoperatively until 0.5 years postoperatively, and then the linear trend sharply changes after this time point. The model included fixed effects of time before 0.5 years, time after 0.5 years, a categorical variable for type, and interactions between time and type. The analysis showed random effects for intercept and before and after 0.5 years slopes. There were also co-variances between the intercept and the before and after 0.5 year

slopes. We did find significant changes over time between implantation and 0.5 years ($p=0.026$). There was no significant interaction between time and group before 0.5 years ($p=0.57$) or after 0.5 years ($p=0.53$). Thus, we can conclude that there was no significant difference in trajectory between the three groups. As shown by the black dashed lines in Panels A-C, the preoperative to IA shift in PTA for the S8 and S12 groups was 9 dB HL and 8 dB HL for the L24 group. The average IA to 0.25 year shift in PTA was 6 dB HL for the S8 group, 12 dB HL for the S12, and 8 dB HL for the L24 group.

Using the model results, we also were able to predict the PTA score longitudinally. In our analysis, the average S8 user will have a predicted PTA of 47dB HL at 0.5 years. The average S12 user will have a predicted PTA of 54 dB HL at 0.5 years and the average L24 user will have a predicted PTA of 56 dB HL at 0.5 years. The average S8 user who has an average PTA of 50 dB HL or better at 0.5 years has an 88% probability to maintain functional low-frequency hearing (PTA=90 dB HL or better) at 9 years. For the average S12 user who has an average PTA of 50 dB HL or better at 0.5 years, they have a 94% probability of maintaining functional low-frequency hearing at 4 years. For the average L24 user who has an average PTA of 50 dB HL or better at 0.5 years, they have a 93% probability of maintaining functional low-frequency hearing at 4 years. Table 2 shows probabilities based on various 0.5 year PTAs. In essence, a poorer PTA at 0.5 years indicates a lower probability of having a functional hearing PTA at the longitudinal time point. Nonetheless, these data demonstrate that it is likely if you have functional hearing at 0.5 years that you will keep that for several years.

Figure 2 displays the most recent post-operative individual thresholds from 125–500 Hz. Panel A shows thresholds for the S8 subjects; Panel B for the S12 subjects; and Panel C for the L24 subjects. Panel D displays the averaged preoperative and most recent postoperative thresholds from 125–500 Hz for each of the Hybrid groups. As can be seen from the individual data, some subjects have functional thresholds at all three of the frequencies while others have functional hearing at only 125 and 250 Hz. Even when functional hearing is not maintained at all low-frequency thresholds, we still find significant benefits of amplifying any low-frequency thresholds that can be effectively aided^{5,21}. Even for the L24 subject who has functional acoustic hearing only at 125 Hz, she still chooses to have her processor programmed to allow for acoustic hearing at that threshold because she subjectively hears benefit. In fact, in recent reports with both a 16 mm Hybrid implant (L24) or a 10mm electrode with 6 or 10 channels (Hybrid S8, S12) the same improvement in speech perception in quiet and noise can be achieved if the residual acoustic hearing pure-tone average (PTA) is in the mild, moderate or severe range^{5,21}.

In Figure 3, we show individual and modeled longitudinal speech perception outcomes for CNC words in the Combined listening condition (bilateral hearing aids and the CI). Panel A shows scores for the S8 subjects; Panel B for the S12 subjects; and Panel C shows for the L24 subjects. Subjects who lost their residual hearing on the implanted ear were tested in the Bimodal listening condition (the CI reprogrammed to provide both low- and high-frequency information in one ear and hearing aid in the contralateral ear). Ninety percent of subjects showed significant (using the binomial model) improvement when comparing each subject's pre-operative bilateral hearing aid score to their most-recent post-operative combined score

(for those that lost all residual hearing post-operatively, the bimodal score was used). Two subjects showed an improvement in performance post-operatively, but it was not significant. Two subjects did significantly poorer at their most-recent post-operative visit. And one subject showed no change. Both subjects that scored significantly poorer had functional low-frequency hearing in the implanted ear. One of the subjects had a significant improvement post-operatively through 6 years, but at the most recent visit, her score dropped. This subject did not simultaneously experience a drop in hearing. Equipment was checked and the subject is coming in soon for a follow-up appointment. The other subject with a significant decline in hearing struggled post-operatively longitudinally. This subject was older at the time of implantation (80 years) and perhaps that played a role in performance.

The averaged individual data for each group in Figure 3, Panels A–C, show the greatest improvement in scores by 0.25 to 0.5 years post implantation and remain stable. The S8 subjects had an average score of 36% on CNC words using bilateral hearing aids preoperatively and improved to 65% in the Combined condition at 0.5 years postoperative. The S12 and L24 subjects had an average preoperative bilateral hearing aid CNC score of 54% and 34% and improved to 81% and 83% in the Combined condition at 0.5 years postoperative.

Figure 3, Panel D, shows the modeled preoperative CNC score using bilateral hearing aids and longitudinally following implantation for each of the subjects in the Hybrid groups. Statistical analysis demonstrated a significant improvement in CNC scores after initial activation ($p < 0.01$) through 0.5 years and then scores start to reach their maximum. Although we do not find significant interactions less than 0.5 years ($p = 0.79$) nor after 0.5 years ($p = 0.81$), we do find a significant difference between the groups ($p = 0.05$). Using a Tukey-Kramer adjustment, the CNC scores for the S8 group are significantly poorer than the S12 users at 0.25 years ($p = 0.03$), 0.5 years ($p = 0.02$), and 1 year ($p = 0.02$), and 2 years ($p = 0.03$). These two groups are no longer significantly different at 3 years ($p = 0.05$) or 4 years ($p = 0.09$) post implantation. The CNC scores for the S8 group are significantly poorer than the L24 group at 0.25 years ($p = 0.03$), 0.5 years ($p = 0.01$), 1 year ($p = 0.01$), 2 years ($p = 0.01$), 3 years ($p = 0.004$), and 4 years ($p = 0.01$). There was no significant difference in CNC scores between the S12 or L24 groups.

In Figure 4, we show we show individual and modeled longitudinal speech perception outcomes for AzBio Sentences in Noise in the Combined listening condition. Panel A shows scores for the S12 subjects and Panel B shows scores for the L24 subjects. The S8 group is not included in this analysis as this test was not yet available during the early years following their implantation. The averaged individual data for both groups show the greatest improvement in scores by 0.25 to 0.5 years post implantation.

Eighty-five percent of the S12 and L24 subjects in Figure 4, Panels A and B, showed a significant improvement when comparing each subject's pre-operative score with bilateral hearing aids to their most-recent post-operative combined score (bimodal score was again used for those that lost all residual hearing). Four subjects did poorer in noise post-operatively. One of these subjects is the same subject who had a drop in her CNC word score at her most-recent visit. Consistent with her score in quiet, we also saw a similar trend in

noise; she was performing better post-operatively and at her last visit, her score dropped. This same trend was indicated for one other subject in noise. The other two subjects who performed poorer post-operatively performed similarly to their pre-operative scores longitudinally. Interestingly, both of these two subjects showed nice improvements with words in quiet.

Figure 4, Panel C, shows the modeled preoperative AzBio Sentences in noise score using bilateral hearing aids and longitudinally in the combined condition following implantation for each of the subjects in S12 and L24 Hybrid groups. The linear mixed model included a quadratic effect for year, but no regression spline. The analysis showed significant changes over time with a significant effect for time ($p=0.04$), but no significant quadratic effect ($p=0.07$). There was also a significant main effect for group ($p=0.02$) and a significant interaction between group and year ($p=0.03$). Thus, the group effect is changing over time. The L24 group scored better than the S12 group on the AzBio Sentences in noise pre-operatively ($p=0.03$), 0.25 years ($p=0.03$), and 0.5 years ($p=0.04$) postoperatively. That that difference then disappears with no significant difference between groups at 1 year ($p=0.07$), 2 years ($p=0.23$), 3 years ($p=0.61$), and 4 years ($p=0.92$).

Discussion

This manuscript is the first to demonstrate longitudinal trends of more than 2 years for individuals implanted with a short electrode cochlear implant. When the hybrid concept was initially being discussed, one of the biggest concerns was normal progression of low-frequency hearing loss over time as a result of the aging process. One study showed that that showed the long-term rate of decline per year in acoustic low-frequency thresholds in patients who were not implanted, but had hearing loss that met the hybrid candidacy, averaged 1.05 dB³⁷. This demonstrated that if hearing could be preserved during the short electrode cochlear implant surgical procedure that hybrid hearing could be a long-term solution to individuals with high-frequency hearing loss. This longitudinal paper further confirmed that finding by showing maintenance of functional hearing in 86% of the subjects for up to 15 years following implantation.

The greatest shift in hearing for the subjects in this study occurred between surgery and the initial activation of the cochlear implant. This likely is a result of the surgical procedure despite the fact that the surgeons have employed techniques for hearing preservation¹⁶. While the IA PTA shift in this dataset appears to be better than that noted in the Gantz et al.⁵ and Roland et al.²¹ multi-center Hybrid Clinical Trial data, it should be noted that the PTA calculated in this paper used 125–500 Hz and the PTA calculated in the multi-center clinical trial data used thresholds from 125–1000 Hz. Furthermore, while our data did not show a significant between-group difference in low-frequency hearing PTA preoperatively and at initial activation, other research has suggested that depth of insertion could be a predictor of hearing loss; the farther an electrode is advanced into the cochlea, the greater the risk to residual acoustic hearing^{30,31}.

A second shift in hearing was also demonstrated between initial activation and .25 to .5 years following the initial activation and then hearing appears to maintain stable for the

majority of the subjects. The cause of this second shift in hearing is unknown, but one research finding suggests that the hearing loss might be related to intra-cochlear changes. Recently, a long-term research participant at our Center continued his commitment to research posthumously by donating his temporal bone for histopathologic evaluation. This subject had used a short electrode device (10 mm) for 9 years, but had lost residual acoustic hearing between one and four months following device activation. The temporal bone evaluation revealed extensive fibrotic changes and bone debris associated with creating a cochleostomy within the scala tympani³⁸. These changes suggest that dampening of the acoustic traveling wave by intra cochlear fibrosis represents a potential mechanism contributing to the low-frequency hearing loss. Interestingly, the hair cell counts and ganglion cell survival in the implanted and non-implanted ears were similar.

Other potential mechanisms of acoustic hearing loss following initial activation could be excitotoxic changes within the cochlea similar to excitotoxicity associated with noise trauma^{39,40}. While recent research suggests that electric charge levels do not appear to be related to subsequent loss of residual low-frequency hearing⁴¹, perhaps the electrical current plus acoustic amplification is introducing a stress reaction within the cochlea⁴². Nevertheless, we also now consider a range of demographic factors during the evaluation process that we have linked to residual hearing loss such as gender, etiology of hearing loss, tobacco use, and medical co-morbidities such as hypertension, hyperlipidemia, diabetes mellitus, obesity, and cardiovascular disease⁴³. Regardless of all of these possible links to causes of hearing loss, we have reported that the inner ear might be more robust than once thought as we were able to remove a failed Hybrid S12 (10 mm) implant and replace it with the Hybrid L24 (16 mm) and maintained residual hearing through these 2 separate procedures³².

Speech perception results from this study and data from our previous research has demonstrated that access to low-frequency acoustic information provides a significant advantage in noise^{17,19,44}. The averaged data in this study demonstrate large improvements in speech perception within the first 0.5 years post activation which then plateau and, importantly, remain stable over time. Interestingly, this pattern is observed despite a radical difference between electrode location in the cochlea and the pitch to what would be observed with natural hearing or used in a standard CI. Consequently, listeners must learn a tonotopic representation that differs markedly from that found with the cochlea. As a result, the success of Hybrid CI users implies a fairly plastic system which is able to remap pitch to new parts of the cochlea⁴⁵.

It worthwhile to point out that in the seven Hybrid subjects who lost functional acoustic hearing and listen in a bimodal condition, we found no significant difference in CNC performance between those users compared to the Hybrid users in the Combined condition ($p=0.28$) (Fig 5). Furthermore, we also found no significant difference in performance when comparing the Hybrid bimodal users to a group of 28 users at our Center who use a standard-length electrode in a bimodal situation ($p=0.21$) or those with simultaneous bilateral standard-length electrodes used in a separate study⁴⁶ from our Center ($p=0.78$) (Fig 5). The standard unilateral users from a separate study at our Center⁴⁶, were found to be significantly poorer than all of the other groups ($p<0.05$). Interestingly, when comparing

performance for the Hybrid listeners in the Combined condition to the simultaneous bilateral users, the Hybrid users performed significantly better ($p < 0.05$). This suggests that having acoustic hearing in the implanted ear might provide better speech understanding in quiet; there are also benefits of hearing with two ears over only hearing with one, as is demonstrated with the poorer overall results with the standard unilateral cochlear implant users.

It is important to point out that while most subjects demonstrated a significant advantage to speech perception in quiet and in noise, it is not always consistent among users. It appears that this variability might be more evident in noise. One possibility for this finding might be attributed, at least in part, to differences in pre-implantation neural substrate survival (both peripheral and central) and subject demographic factors (e.g. age, duration of deafness) between the three populations. In the Hybrid S12 and L24 users, subjects were limited at our center to 65 years of age and younger and with fewer than 30 years of high frequency hearing loss. We have found that these selection criteria predict better outcomes^{19,43}. However, a better understanding how other variables, such as central cognitive and personal factors might have an impact on outcomes is needed.

Conclusion

This longitudinal study demonstrates that A+E hearing preservation and speech understanding benefits in both quiet and in noise can be accomplished and sustained for many years with a short electrode cochlear implant. Even those that have lost their hearing on the implanted ear benefit from the combined use of acoustic and electric (bimodal) technology on opposite ears.

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Figure 1.

Individual and modeled longitudinal hearing preservation using a three-frequency pure-tone-average (PTA) from 125 to 500 Hz. Panel A shows PTAs for the S8 subjects; Panel B for the S12 subjects; and Panel C for the L24 subjects. Panel D shows the modeled PTAs for each of the Hybrid groups over time. The light gray dashed line in each of the panels represents the threshold that is considered to be non-functional hearing. The black dashed line represents the averaged PTA longitudinally.

Figure 2.

Individual most recent post-operative thresholds from 125–500 Hz. Panel A shows thresholds for the S8 subjects; Panel B for the S12 subjects; and Panel C for the L24 subjects. Panel D shows the averaged preoperative and most recent postoperative thresholds from 125–500 Hz for each of the Hybrid groups.

Figure 3.

Individual and modeled longitudinal speech perception outcomes for CNC words in the Combined listening condition (bilateral hearing aids and the CI). Panel A shows scores for the S8 subjects; Panel B for the S12 subjects; and Panel C shows for the L24 subjects. The gray dashed lines within each panel show the outcomes for the subjects that lost their residual hearing. These patients were tested in the Bimodal listening condition (the CI reprogrammed to provide both low- and high-frequency information in one ear and hearing aid in the contralateral ear). The black dashed line within Panels A-C show the averaged outcomes at each time point. Panel D shows the modeled preoperative CNC score using bilateral hearing aids and longitudinally in the Combined condition following implantation for each of the subjects in the Hybrid groups.

Figure 4.

Individual and modeled longitudinal speech perception outcomes for AzBio Sentences in Noise in the Combined listening condition. Panel A shows scores for the S12 subjects and Panel B shows scores for the L24 subjects. The gray dashed lines within each panel show the outcomes for the subjects that lost their residual hearing. These patients were tested in the bimodal condition. The black dashed line within Panel A and B show the averaged outcomes at each time point.

Figure 5.

Averaged CNC performance for Hybrid users (N=43) in the Combined condition, Hybrid subjects who lost hearing in the Bimodal condition (N=7), standard-length electrode bimodal users (N=28), simultaneous bilateral standard-length electrode users (N=33), and standard-length electrode unilateral users (n=33).

Table 1

Hybrid cochlear implant device description.

Name	Number of electrode contacts	Length (mm)	Insertion Approach
Nucleus Hybrid S8	6	10	Cochleostomy
Nucleus Hybrid S12	10	10	Cochleostomy
Nucleus Hybrid L24	22	16	Cochleostomy (N=8) Round Window (N=6)

Table 2

Probability of having functional PTA 9 years (S8) and 4 years (S12 and L24) post-implantation as a result of PTA at 6 months post-implantation.

Group	PTA at 6 months (dB HL)	Probability of Functional Hearing (%)
S8	50	88
	60	78
	70	64
	80	48
S12	50	94
	60	88
	70	78
	80	64
L24	50	93
	60	85
	70	73
	80	58