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Hearing-in-Noise Benefits After Bilateral Simultaneous Cochlear Implantation Continue to Improve 4 Years After Implantation

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Abstract

Objective—The purpose of this 4-year longitudinal study was to assess the stability of the binaural benefits of head shadow, summation, and squelch for bilateral cochlear implant recipients and to quantify these benefits for the understanding of speech in noise.

Design—This is a prospective study of 9 patients who received simultaneous bilateral insertion of MED-EL COMBI +40 cochlear implants in a single-stage operation at the University of North Carolina, Chapel Hill, NC. Each patient had postlingual deafness of short duration before insertion of the device. Each year, the patients were tested for word recognition using consonant-nucleus-consonant words in quiet and speech perception in noise using City University of New York sentences. These tests were administered using direct audio input to the implants. Head-related transfer functions were used to simulate speech in noise testing in a spatial environment. Speech was always presented at midline (0), and the noise masker was presented at either side or midline (−90, 0, +90 degrees).

Results—The binaural benefits of head shadow and summation effects developed early in the postoperative period and remained stable throughout the follow-up period. Squelch developed more slowly and was first demonstrated at 12 months after implantation but continued to increase beyond the first year of follow-up.

Conclusion—Benefits of head shadow and summation emerge early and remain stable. However, squelch has the most protracted period of development, with increasing benefit after a year or more of implant experience. These data support the idea that binaural integration continues several years after insertion of bilateral cochlear implant devices.

Keywords

Bilateral cochlear implant; Binaural hearing; Speech discrimination

Unilateral cochlear implantation has become a standard practice in the management of severe and profound hearing loss. This procedure has allowed many patients direct access to auditory information that would otherwise be outside their reach. However, even the best-performing cochlear implant users have difficulty with speech comprehension in noisy environments. In normal-hearing listeners, speech comprehension in noise is improved by having access to information from both ears, an effect described as the binaural benefit. Research on hearing aid users has shown an analogous improvement in speech comprehension with binaural as compared with monaural amplification (1). These

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observations suggest to some that the next step to improve the performance of patients with cochlear implants is to provide bilateral stimulation.

Preliminary research has demonstrated a binaural benefit in bilateral cochlear implant recipients (2–6). If neural survival differs across ears, it is possible that bilateral implantation could improve performance simply by ensuring that the “better ear” receives stimulation; this source of benefit could be particularly important in light of the fact that preoperative data have not been successful at predicting which ear will perform better after implantation (7). Alternatively, if the ears differ in the types of speech cues that they can encode, then bilateral implantation could improve performance by virtue of providing complementary cues across ears. Another possibility is that interaural time and intensity differences useful in sound localization are used to obtain this benefit.

Measures that quantify the binaural benefit include head shadow, summation, and squelch (Fig. 1). The most robust binaural effect reported in the literature for bilaterally implanted listeners is the head shadow effect, which ranges between 4 and 7 dB (5–8). Head shadow refers to the benefit obtained when the target signal and a concurrent masking noise originate from different points in the horizontal plane such that the head attenuates the noise reaching the target ear. This effect can be calculated as the difference in speech recognition threshold comparing 2 unilateral listening conditions: threshold with just the active implant ipsilateral to the noise source minus the threshold with the active implant contralateral to the noise source. Binaural summation is the benefit of signal presentation to both ears as compared with either ear alone. This effect can be calculated as the difference between the speech recognition thresholds obtained with just 1 active implant minus the threshold with bilateral input, where both sides receive identical input. This effect is usually reported as a moderate binaural benefit on the order of 1.5 to 2.9 dB in implanted listeners (5 – 8). Finally, the squelch effect is a relatively modest binaural benefit. Unilateral and bilateral performances are compared for target speech and masking noise that originate from different locations on the horizontal plane; a positive squelch is an improvement in performance comparing the better unilateral condition based on the input from “shadowed” side or side furthest from the noise source to the bilateral listening condition. This effect is believed to result from interaural time and intensity differences, which in turn aid sound source segregation and auditory scene analysis. The squelch effect is small even in normal-hearing listeners, on the order of 3 dB, and has been reported in only approximately half of listeners tested with bilateral cochlear implants (3,5–7).

This study reports on the speech performance abilities of a cohort of 9 bilaterally implanted listeners followed once a year over 4 years. Study participants were originally enrolled in a multicenter bilateral cochlear implant trial that followed a larger cohort of bilaterally implanted adults over a single year of follow-up (2). In that study, Buss et al. (2) demonstrated that the binaural benefits from head shadow and summation were significant early in the follow-up period and remained constant through 1 year of follow-up. Interestingly, the squelch effect was not evident at the first measurement interval but rather emerged between the 6-month and 1-year test intervals. Squelch is thought to rely on the same binaural cues that give rise to localization of sound sources in space such as interaural time difference cues. The association between squelch and localization was assessed by Buss et al. (2) using localization data collected at 5-months postimplantation and described in detail by Grantham et al. (9). For the patients tested in that protocol, there was a significant correlation between localization error and the magnitude of squelch but no correlation between localization error and either summation or head shadow. The association between localization error and magnitude of the squelch effect supports the conclusion that the cues underlying these 2 binaural processing tasks are related. The purpose of the present study was to determine whether the growth in squelch between 6-months and 1-year postimplantation would continue after 1 year of listening experience.

MATERIALS AND METHODS

Listeners

Nine patients underwent single-staged bilateral cochlear implantation with the MED-EL COMBI 40+ device between August 2001 and January 2003 at the University of North Carolina, Chapel Hill, NC. Participants were adults aged 26 to 76 years (mean, 56.8 yr). All had severe to profound sensorineural hearing loss bilaterally, with a pure-tone average (PTA) of greater than or equal to 70 dB hearing loss at 0.5, 1, and 2 kHz. None of the listeners showed benefit from hearing aids, with preoperative scores of less than or equal to 40% on hearing in noise test sentences under auditory-only testing conditions, and as such met eligibility criteria for unilateral cochlear implantation. All patients had functional duration of deafness of less than or equal to 15 years and a mismatch across ears of less than or equal to 10 years in onset of deafness. All were fully literate and fluent in English. Exclusion criteria included prelingual onset of deafness, radiographic evidence of cochlear malformation preventing a full electrode insertion, abnormal neuroanatomy, poor physical or mental health, or past experience with cochlear implants. In addition, all patients agreed to participate in a 1-year follow-up testing protocol in exchange for receipt of the second implant free of charge; all patients volunteered to continue following the testing protocol after the initial 1-year follow-up period. The University of North Carolina-Chapel Hill Institutional Review Board approved all study procedures.

Procedures

Listeners were implanted bilaterally in a single surgery with the MED-EL COMBI 40+ internal device and the standard 31-mm electrode. They returned 2 to 4 weeks after surgery for initial stimulation of their devices. At this visit, a map was generated for each of a pair of TEMPO+ speech processors using a continuous interleaved sampling processing strategy (10). Standard unilateral mapping procedures were followed. Electrodes were turned off for a variety of reasons, including facial stimulation and failure to attain sufficient loudness. Mapping parameters such as pulse duration, pulse rate, and number of active electrodes were allowed to vary across ears. Processor maps were updated at each follow- up visit as needed to maximize performance. Speech testing was performed using the map favored by the listener before remapping, a procedure adopted to ensure sufficient familiarity with the stimulation parameters.

Speech Testing

Direct audio input was used for presentation of all test stimuli. Test materials were recorded onto a compact disc (CD) and presented to the listeners using a battery-operated CD player. The CD player was plugged directly into each of the 2 speech processors using a specially designed audio cable. All testing was completed in a soundproof booth. To simulate free-field testing conditions, stimuli were processed with KEMAR-based head-related transfer function filters computed in the absence of pinna cues. These filters simulate the effect of the head and torso on the sound reaching the microphones of a bilaterally implanted listener in a free-field environment. Speech data will be reported for 4 test intervals corresponding to postimplantation Years 1 to 4. At the beginning of a speech testing session, the listener was asked to select the map preferred for listening in a noisy environment and to adjust the levels on each speech processor so that bilateral speech stimuli were comfortably loud and "balanced" between ears. Each test session lasted approximately 6 hours and included the 2 test types: identification of words in quiet using consonant-nucleus-consonant (CNC) words and recognition of sentences in noise with City University of New York (CUNY) sentences.

There were 10 CNC lists of 50 words each and 72 CUNY lists with 12 sentences each. At the beginning of the first testing session, a random list number was selected, and lists were used in sequence from that point on. Within the 2 tests, conditions were presented in a random order to prevent practice or fatigue from having nonuniform effects.

The CNC words were presented with a simulated position of 0 degree azimuth. Percent correct was computed based on a 50- word list for each of 3 conditions presented in random order: with only the left implant active (left-only), with only the right implant active (right-only), and with both implants active (bilateral). Testing with CUNY sentences involved 9 conditions. The signal was always presented from the front (simulated 0 degree azimuth). The position of the masking noise ranged from −90, 0, or +90 degrees in the azimuthal plane. Percent correct was computed as the average of 4 lists for each of 3 conditions: left-only, right-only, and bilateral.

The first step in masked CUNY testing was to determine an appropriate signal-to-noise ratio (SNR) for that session, a procedure that was adopted to ensure that percent correct scores did not hit the ceiling or the floor. Starting at an SNR of +1.8 dB, percent correct was measured for 2 lists in each of 2 conditions, the noise-left/bilateral and the noise-right/ bilateral conditions. The SNR was then adjusted in 5-dB increments until the listener performed between 40 and 80% correct. This step was undertaken for each listener at the start of the CUNY testing for each testing interval. Therefore, the SNR was not necessarily constant across time points within listeners. Once an appropriate SNR had been identified, listeners completed each of the 9 conditions interleaved such that one list was completed in each condition before going through conditions a second time.

RESULTS

Some data points were unavailable due to listener illness, lack of transportation, equipment failure, or technical difficulties. For the CUNY sentence test, 2 listeners at 2-year and 1 listener at 4-year intervals are lacking data points. For the CNC word test, 3 listeners at 2-year and 1 listener at 4-year intervals are lacking data points. Data were available for all listeners at the 1-year and 3-year time periods.

CNC Words in Quiet

Figure 2 shows mean percent correct for CNC words in quiet over time. Data were categorized into 3 bins: worse unilateral listening condition, better unilateral listening condition, and bilateral listening condition. Mean scores improved in all 3 bins between 1-year and 4-year measurement intervals.

The percent correct scores for 6 listeners with complete data were transformed into rationalized arcsine units (11) and analyzed using repeated-measures analysis of variance. The transformation into arcsine units helps to normalize the distribution of percent correct data. There were 4 levels of interval (1, 2, 3, and 4 years) and 2 of condition (better unilateral listening condition and bilateral listening condition). There was a significant effect of interval ($F_{3,15} = 6.99$; $p < 0.05$) and condition ($F_{1,5} = 48.06$; $p < 0.05$), but no interaction ($F_{3,15} = 2.32$; $p = 0.32$). This is consistent with a parallel improvement of scores in the better unilateral listening condition and the bilateral listening condition, as well as superior performance in the bilateral listening condition when compared with the better unilateral listening condition. A linear regression was performed to assess the significance of changes in performance over time. Performance improved over time in all 3 cases: worse-performing unilateral listening condition ($\beta = 0.27$; $t_{22} = 2.62$; $p < 0.05$), better-performing unilateral listening condition ($\beta = 0.41$; $t_{22} = 3.65$; $p < 0.001$), and the bilateral listening condition ($\beta = 0.34$; $t_{22} = 2.79$; $p < 0.05$).

CUNY Sentences in Noise

Table 1 shows the SNR for CUNY sentence testing for each listener at each time point. The SNR tended to improve over time, with most listeners requiring a +6.8-dB level at Year 1 and all but one listener dropping to +1.8 dB by Year 4.

Figure 3 shows derived measures of binaural benefit plotted by patient number and shown separately for each of the follow-up intervals. In the case of head shadow and squelch, two estimates are shown for each listener at each time point; the left-pointing triangles corresponding to the value computed for the left side and the right-pointing triangles for the right side. Because summation is the difference between scores in the bilateral listening condition and the better of two unilateral conditions, only one value of summation is shown for each listener. We predicted an overall increase in binaural benefit over time and analyzed the data using linear regression. Individual listeners' data were represented with dummy variables to control for individual differences in performance, and the independent variable was interval in years. Because the prediction was directional, the significance of the interval variable was evaluated using a 1-tailed criterion. For the head shadow and squelch effects, where two estimates were computed at each interval, the two values were averaged before regression analysis.

Head shadow is defined as the difference in percent correct obtained in two unilateral stimulus conditions: with the noise presented ipsilateral to the active implant and with the noise presented contralateral to the active implant. The median values for head shadow in percent correct difference are 41.2% at 1 year, 42.1% at 2 years, 37.9% at 3 years, and 37.5% at 4 years. Regression analysis of the head shadow data indicates no significant increase in the head shadow effect after the first year ($\beta = -0.29$; $t22 = -1.52$; $p = 0.07$), with a non-significant trend for reduction in the overall head shadow effect over time. Over the follow-up period, the benefit of head shadow remains relatively constant, and the difference between the head shadow computed on each side fluctuates between 6 and 12%.

Summation is defined as the advantage associated with bilateral listening as compared with performance of the better ear alone when both ears receive identical input such as occurs in the noise-front conditions. The median values for summation are 8.3% at 1 year, 7.1% at 2 years, 6.9% at 3 years, and 11.5% at 4 years. Regression analysis of the summation data indicates no significant increase in the summation effect after the first year ($\beta = 0.01$; $t22 = 0.06$; $p = 0.48$).

Squelch is defined as the advantage associated with bilateral listening as compared with the shadowed ear alone in cases where the signal and masker are presented from different locations on the horizontal plane. The squelch effect is the benefit obtained by adding the information presented to the more severely masked ear. The median values for squelch are 8.2% at 1 year, 13.1% at 2 years, 11.8% at 3 years, and 18.1% at 4 years. Regression analysis of the average right and left squelch data indicates a significant increase in the squelch effect after the first year ($\beta = 0.35$; $t22 = 2.00$; $p < 0.05$).

Ear Dominance

Analysis of the preoperative audiograms was performed to identify the better-performing ear. Low-frequency pure- tone averages (low PTAs) were calculated from thresholds at 250, 500, and 1,000 Hz. In cases where there was no response at the limits of the audiometer, a value of 120 dB was included in the calculation of PTA. Table 2 shows preoperative pure-tone thresholds for each observer and the low PTA for each ear. Bone- conduction thresholds (not shown) were generally within 10 dB of air-conduction thresholds; the sole exception was the 1,000-Hz threshold for Listener 2, where the bone threshold was 15 dB lower. In one case (Listener 7), the left and right ears had the same low-frequency pure- tone threshold; in this case, the thresholds for 2,000 and 4,000 Hz were compared, and the ear with the lower thresholds at these additional frequencies was selected as the dominant ear. Based on these analyses, the right ear was dominant preoperatively for four listeners, and left ear was dominant for five listeners.

Preoperative ear dominance was then compared with postoperative ear dominance. The dominant ear for CNC words was defined as the unilateral condition with the higher percent correct score. For CNC data in each of the four follow-up intervals, preoperative and postoperative ear dominance was concordant in 39, 50, 61, and 56% of listeners. Ear dominance for CUNY testing was defined as the better unilateral condition where both the signal and noise were located in the front (0 degree azimuth). In these data, ear dominance was concordant in 56, 33, 78, and 56% of listeners at Years 1, 2, 3, and 4, respectively. These results indicate that the preoperative audiogram does not predict which ear will have better performance. In addition, examination of the data revealed that estimates of ear dominance at the postoperative test intervals seem to change over time.

DISCUSSION

Our data demonstrate a significant improvement in CNC word recognition in quiet for the bilaterally implanted listeners over 4 years of follow-up. In the bilateral condition, listener performance significantly exceeds the better ear unilateral performance. This indicates that in this population of patients with extensive binaural experience, use of bilateral implants results in superior performance as compared with the better unilateral condition at all testing intervals and continued improvement for listening tasks in quiet over time.

Unilaterally implanted listeners typically report the greatest difficulty for listening tasks with competing noise. The data demonstrate tolerance of increased noise in the CUNY sentence task over the 4-year follow-up period in bilaterally implanted listeners. Increased tolerance of noise in these listeners could improve functional performance in their daily use of these devices.

Head shadow and summation effects have been shown to be robust in implanted listeners and are often cited as reflecting the greatest benefit of bilateral stimulation (5–7). The benefit from head shadow remains stable through the extended follow-up period, and the median values for head shadow are comparable to those in the published literature (5,7). The benefit from summation is also constant over the 1- to 4-year follow-up period and is comparable with the published literature (5,6).

The most striking finding of the present data set is the growth in the squelch effect over the 4-year follow-up period. Our group previously demonstrated a growth in the squelch effect over the first year of bilateral cochlear implant use (2). The present data show that with further listening experience, the effect continues to grow. Regression analysis demonstrated a significant growth of squelch between Years 1 and 4. This finding suggests that to determine the full benefit of bilateral implantation, when considering the late-emerging squelch benefit, follow-up for these patients should be extended over years.

It has often been argued that squelch represents the only “true” binaural processing measure whereby listeners use the interaural difference cues to identify sound sources and construct an internal representation of the 3-dimensional sound scene (2). The growth of this benefit over time suggests that binaural processing continues to develop beyond the 1-year test interval. Recovery of higher-level binaural processing over time has previously been demonstrated in listeners with recurrent otitis media with effusion and in listeners with otosclerosis after surgical treatment. For example, Hall et al. (13) measured the masking level difference (MLD), a psychoacoustic estimate of auditory sensitivity to interaural difference cues of time and amplitude; they followed children with otitis media after placement of pressure equalization tubes over 3 years of follow-up. The MLD was reduced relative to normal controls in the early years after pressure equalization tube placement despite the finding of normal pure-tone thresholds, but the MLD recovered gradually over the 3-year follow up, a result that was interpreted as reflecting neural plasticity in binaural hearing. Similar recovery of MLD was seen in adult patients with otosclerosis after stapedectomy (14).

Further analysis indicates the better-performing ear is not consistent across preoperative and postoperative data, nor is the better-performing side postoperatively consistent over time. Therefore, in addition to binaural hearing, the bilaterally implanted listeners followed here seem to obtain benefits associated with ensuring that the better-performing ear receives stimulation. It is possible that we were unable to predict the better-performing ear because all 9 listeners had minimal residual hearing, making this type of estimation difficult. Further study of implant candidates with some residual hearing is needed to see if preoperative audiometric measures can be used to predict ear performance.

A potential weakness of this study is also a result of the extended follow-up. The lengthy follow-up interval resulted in some repetition of testing materials, with each CNC and CUNY list repeated once every 2 years. Previous research by examining learning effects with repeated presentation of sentence material separated by 5 days revealed little learning related to the tested material (12). In that study, listeners experienced little benefit from repetition of the test materials separated by 1 week. The testing materials in the present study included many more items than in the previous study, with 10 lists of CNC words and 72 lists of CUNY sentences compared with only 2 lists in the previous work. In addition, the 2-year delay between successive presentations makes it highly unlikely that familiarity with the test materials played a significant role in the data reported here.

CONCLUSION

Mounting data suggest that bilateral cochlear implantation provides functional benefit beyond that provided by unilateral implantation. The findings of this study suggest that the squelch effect, the smallest of the three binaural benefits, increases significantly beyond the first year, a trend that is consistent with previous data showing an increase in the effect of squelch over the first year of bilateral cochlear implant use (2). Increase of the squelch effect is interpreted as reflecting increased ability to make use of interaural difference cues in sound source segregation and auditory scene analysis. This finding may suggest that greater cortical integration of inputs from bilateral cochlear implants improves over a relatively protracted period of time.

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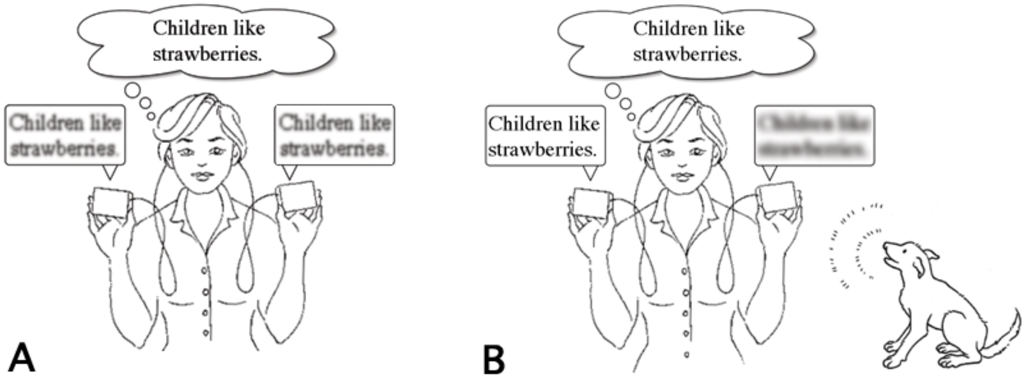

FIG. 1.

A diagram of the testing paradigm for summation and squelch. A, The stimulus configuration for assessing summation. In this image, the signal is presented with noise to the listener as if it were directly in front of her. The benefit is achieved through stimulation of both ears by the same target signal. B, The stimulus configuration used for estimating squelch. In this image, the signal is presented from the front, and the left ear is more heavily masked than the right. Squelch can be described as the benefit obtained by the addition of information from the masked side. Illustrations for Figure 1 were provided by Laura M. Buss.

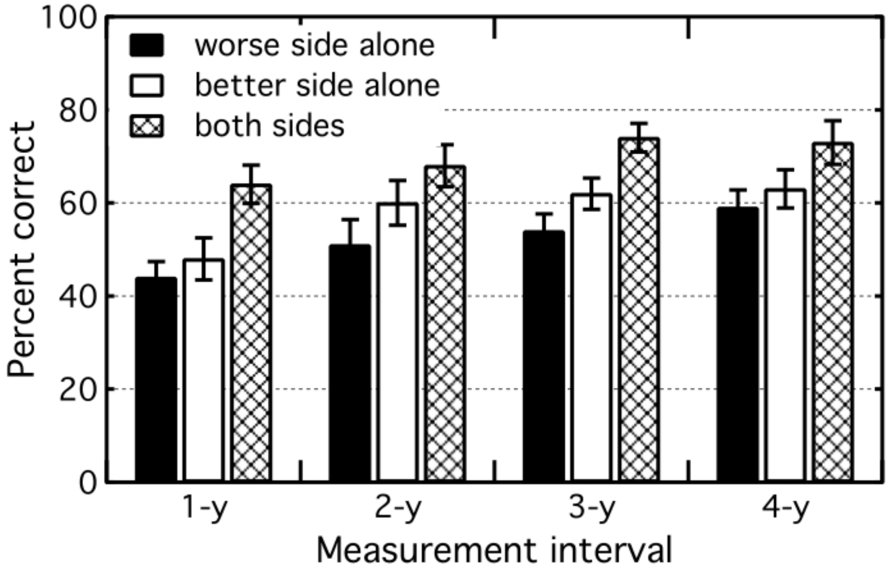

FIG. 2.

A comparison of percent correct for CNC words in quiet over time. Bar shading reflects listening condition: worse side alone (black), better side alone (white), or bilateral (hatched bars). Error bars show 1 standard error of the mean.

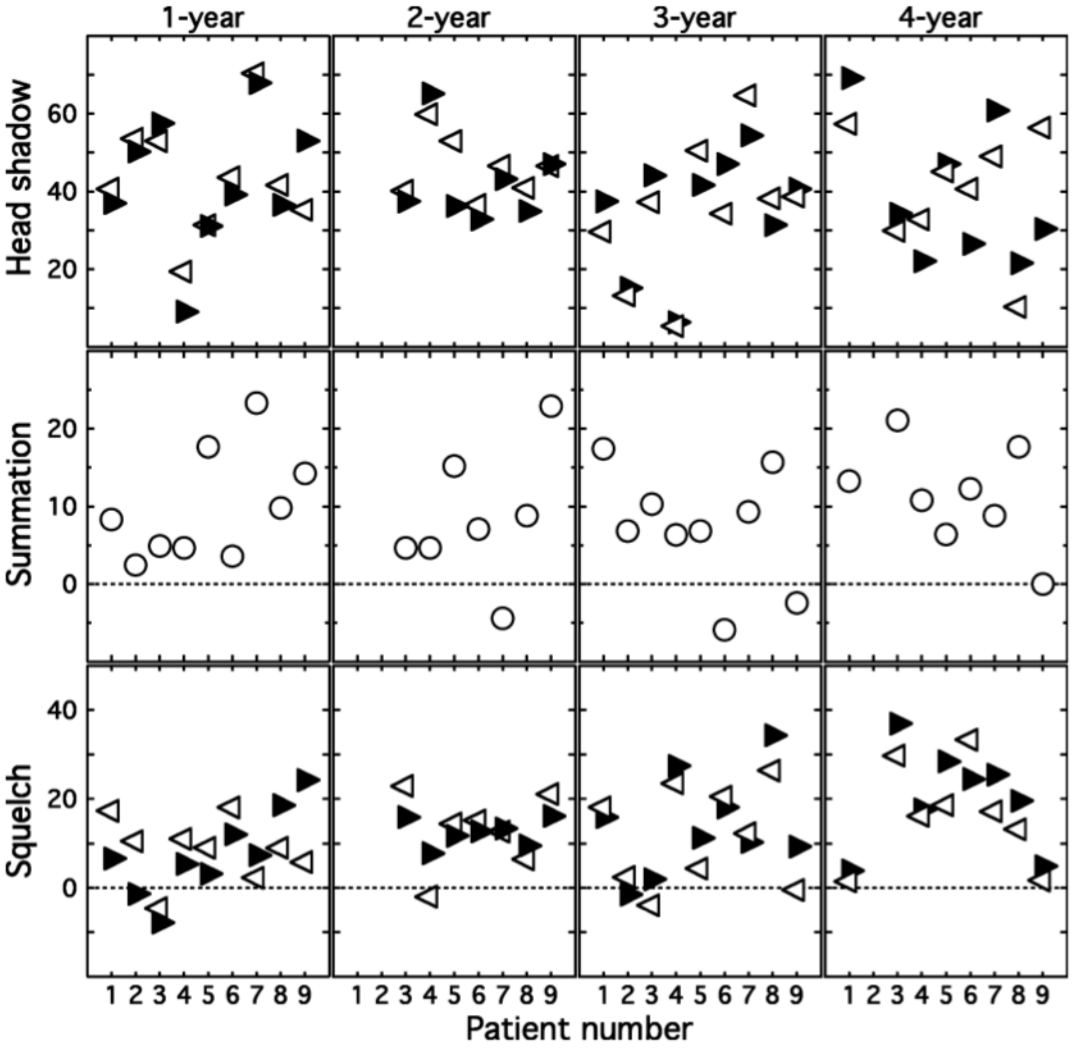

FIG. 3.

The derived measures of binaural benefit--summation, head shadow, and squelch--are plotted by patient number and shown separately for each of the follow-up intervals. In the case of head shadow and squelch, estimates are shown separately for the left and right side (left- and right-pointing triangles, respectively).

TABLE 1

Signal-to-noise ratio determined during CUNY testing for the listeners at each follow-up period

	Test interval			
Listener no	**1yr**	**2yr**	**3yr**	**4yr**
1	+6.8	NA	+6.8	+6.8
2	+6.8	NA	+1.8	NA
3	+6.8	+1.8	+1.8	+1.8
4	+1.8	+6.8	+1.8	+1.8
5	+1.8	+1.8	+1.8	+1.8
6	+6.8	+1.8	+1.8	+1.8
7	+1.8	+1.8	+1.8	+1.8
8	+6.8	+6.8	+6.8	+1.8
9	+6.8	+6.8	+1.8	+1.8

TABLE 2

Preoperative pure-tone air-conduction thresholds for 9 listeners

			Frequency, Hz				
Listener no.	**Dominant Low ear**	**PTA**	**250**	**500**	**1000**	**2000**	**4000**
1	R	120	NR	NR	NR	NR	NR
	L*	90	90	90	90	85	110
2	R*	83	80	80	90	NR	NR
	L	108	100	105	NR	NR	NR
3	R*	85	60	95	100	95	105
	L	93	65	95	NR	NR	NR
4	R	78	50	75	110	NR	NR
	L*	72	40	70	105	NR	NR
5	R	73	30	90	100	NR	NR
	L*	63	20	70	100	NR	NR
6	R	78	55	85	95	NR	NR
	L*	75	50	80	95	110	NR
7	R	97	85	95	110	120	120
	L*	97	85	95	110	115	NR
8	R*	67	40	60	100	120	NR
	L	73	40	70	110	NR	NR
9	R*	58	20	45	110	110	115
	L	80	50	80	110	110	NR

The “better ear” was identified based on the low-frequency PTA and is indicated with asterisks for each listener.

L indicates left; PTA, pure-tone average; R, right; NR, no response.