

Investigating Long-Term Effects of Cochlear Implantation in Single-Sided Deafness: A Best Practice Model for Longitudinal Assessment of Spatial Hearing Abilities and Tinnitus Handicap

*†Brian C. Gartrell, †Heath G. Jones, †Alan Kan, ‡Melanie Buhr-Lawler,
*†Samuel P. Gubbels, and *†Ruth Y. Litovsky

**Division of Otolaryngology, Department of Surgery; †Waisman Center and ‡Department of Communication Sciences and Disorders, University of Wisconsin-Madison, Madison, Wisconsin, U.S.A.*

Objectives: To evaluate methods for measuring long-term benefits of cochlear implantation in a patient with single-sided deafness (SSD) with respect to spatial hearing and to document improved quality of life because of reduced tinnitus.

Patient: A single adult male with profound right-sided sensorineural hearing loss and normal hearing in the left ear who underwent right-sided cochlear implantation.

Methods: The subject was evaluated at 6, 9, 12, and 18 months after implantation on speech intelligibility with specific target-masker configurations, sound localization accuracy, audiologic performance, and tinnitus handicap. Testing conditions involved the acoustic (NH) ear only, the cochlear implant (CI) ear (acoustic ear plugged), and the bilateral condition (CI+NH). Measures of spatial hearing included speech intelligibility improvement because of spatial release from masking (SRM) and sound localization. In addition, traditional measures known as “head shadow,” “binaural squelch,” and “binaural summation” were evaluated.

Results: The best indicator for improved speech intelligibility was SRM, in which both ears are activated, but the relative locations of target and masker(s) are manipulated. Measures that

compare performance with a single ear to performance using bilateral auditory input indicated evidence of the ability to integrate inputs across the ears, possibly reflecting early binaural processing, with 12 months of bilateral input. Sound localization accuracy improved with addition of the implant, and a large improvement with respect to tinnitus handicap was observed.

Conclusion: Cochlear implantation resulted in improved sound localization accuracy when compared with performance using only the NH ear, and reduced tinnitus handicap was observed with use of the implant. The use of SRM addresses some of the current limitations of traditional measures of spatial and binaural hearing, as spatial cues related to target and maskers are manipulated, rather than the ear(s) tested. Sound testing methods and calculations described here are therefore recommended for assessing performance of a larger sample size of individuals with SSD who receive a CI. **Key Words:** Cochlear implantation—Single-sided deafness—Sound localization—Spatial hearing—Spatial release from masking.

Otol Neurotol 00:00–00, 2014.

Address correspondence and reprint requests to Ruth Y. Litovsky, PhD, Professor, Communication Sciences and Disorders, and Division of Otolaryngology, Head and Neck Surgery, 1500 Highland Ave., Madison, WI 53726; E-mail: litovsky@waisman.wisc.edu

This study was funded by NIH-NIDCD (5R01 DC003083, Litovsky) and also in part by a core grant to the Waisman Center from the NICHD (P30 HD03352).

The project described was also supported by the Clinical and Translational Science Award (CTSA) program, by the National Center for Advancing Translational Sciences (NCATS), grant 9U54TR000021. The content is solely the responsibility of the authors and does not necessarily represent the official views of the NIH. S. P. G. receives support from NIH 1 R03 DC012432-01.

This work was approved by the University of Wisconsin–Madison institutional review board.

The authors disclose no conflicts of interest.

Unilateral cochlear implantation has become a common treatment option for bilaterally deaf patients and has been shown to improve speech communication. However, these patients still exhibit hearing deficits such as difficulties segregating speech in noise and poor sound localization abilities (1). Bilateral cochlear implantation was introduced in an attempt to improve these abilities (2–5) and has been shown to be highly beneficial for many patients (3). Recently, cochlear implants (CIs) have also been used in the treatment of severe unilateral tinnitus in individuals with single-sided deafness (SSD) (6,7), and research over short-term time frames after surgery has demonstrated the success of this approach in reducing tinnitus severity (8). More recently, it has been realized that patients with SSD who

undergo cochlear implantation represent a unique opportunity for investigating the ability of patients to integrate inputs across the ears, in an electric-acoustic configuration, because these patients have audiologically NH in 1 ear.

Assessments of spatial hearing can serve as indicators of how well the auditory system is able to integrate and use information from the 2 ears. Three measures of spatial hearing, summation, squelch, and head shadow have been traditionally referenced in the literature. The benefit gained from listening to the ear with the better signal-to-noise ratio (SNR) is known as the head shadow effect. It is important to note that this phenomenon results from a physical effect related to the mass of the head and not due to true binaural processing. Binaural summation results from the auditory system receiving redundant information from both ears, whereas binaural squelch refers to the advantage of adding an ear with a poorer SNR compared with listening with only the ear with the better SNR alone. Auditory mechanisms in which input from the 2 ears is integrated have functional importance, such as improvements in sound localization and recognition of speech, especially in noisy environments. To date, studies in speech-in-noise understanding in patients with SSD who undergo cochlear implantation suggest that at 12 months after activation of the CI, binaural squelch only occurs in patients who use a hearing aid in the ear contralateral to the CI (6). When no hearing aid is worn, no squelch has been observed. Binaural summation has not been demonstrated either at 6 months (7) or 12 months post-CI activation (6) in any of these patients. However, it remains unclear if binaural processing strategies will develop with continued use of the implant over time, and longer-term follow-up studies will be important to address this topic. It is important to note that this study, and others in the field, do not necessarily differentiate between auditory mechanisms that require only the binaural pathway to be activated versus more generalized pathways that also depend on monaural input.

Although current work in the SSD population indicates little to no benefit from cochlear implantation for speech-in-noise testing (7), there are several disadvantages in the assessments conducted in previous studies, which focused on binaural squelch and summation. These calculations are based on comparisons between monaural and bilateral listening conditions. Hence, for the same stimulus condition, the patient's performance with the hearing ear is compared with performance with the use of both ears. This method is problematic, as it does not represent the patient's newly natural listening condition in which both ears are used. Furthermore, it has been recently documented that the presence of tinnitus in the deaf ear can elevate speech reception thresholds in the opposite ear when the implant is inactivated in these patients, which may confound the audiologic performance of the patient in the NH-only listening condition (9) and therefore make it more difficult to interpret results from these aforementioned comparisons. A final difficulty with previous research on this topic is that comparisons have previously been made between performance when patients use the NH ear alone to the bilateral listening condition (6,7,10). No assessments have been

attempted by making the observation in which performance using only the CI (NH ear plugged) is compared with the bilateral condition. Thus, the frame of reference in which CI use alone (with NH ear plugged) is compared with the bilateral condition has not previously been tested. Assessment of this listening condition is important because it may potentially reveal the extent to which the implant is functional relative to the NH ear.

As these issues demonstrate, the most effective methods to assess long-term performance in patients with SSD receiving a CI are not currently known, and a specific testing paradigm to evaluate long-term performance in these individuals may be useful. This study investigated these questions in an individual with SSD who underwent implantation for severe tinnitus. We provide longitudinal data up to 18 months regarding performance on spatial hearing tasks, audiologic performance, and tinnitus improvement. We also describe the use of a free-field sound testing method used to determine spatial release from masking (SRM) and discuss how this concept may provide a new and useful testing method to address some of the current limitations of traditional measures of binaural processing.

METHODS

Subject

The subject was a 53-year-old male with right-sided tinnitus and profound right-sided sensorineural hearing loss after a head trauma without temporal bone fracture sustained during a bicycle accident. Audiometric thresholds of his left ear were within normal limits, as he demonstrated a preoperative 4-frequency PTA (average of 500, 1,000, 2,000, and 3,000 Hz) of 17 dB HL in the NH ear. After the accident, tinnitus in the right ear became severe and refractory to multiple medical therapies including pharmacologic treatments, behavioral interventions, and masking devices. The patient selected to proceed with implantation of the right-side with a Cochlear Nucleus 5 implant (Cochlear Ltd., Sydney, Australia). Full insertion of the Contour Advance electrode was achieved using the advance off stylet technique through a cochleostomy approach.

Study Design

Free-field testing involving sound localization and speech-in-noise tasks was conducted at 6, 9, 12, and 18 months postactivation. Free-field testing was conducted with the acoustic ear alone (NH), CI activated and acoustic ear plugged (CI), and in the bilateral condition (CI+NH). The listener was seated with their head in the center of an array of 19 loudspeakers, spaced 10 degrees apart, positioned in the horizontal plane on an arc with a 1.2-m radius (Fig. 1A). All stimulus presentations and data acquisition were achieved through the use of custom MATLAB software (Mathworks, Inc., Natick, MA, USA).

Sound localization accuracy was assessed using a task in which the subject identified the source direction of a train of 4 pink noise bursts, each 170 ms in duration with an interburst interval of 50 ms, played at a sampling rate of 48,000 Hz. The output sound level was 50 dB SPL. A ± 4 dB level and ± 10 dB spectrum rove were applied to minimize the availability of monaural level cues and to compensate for minor differences in the spectral characteristics of the loudspeakers. Testing levels were determined based on the expected compression range of

the CI (near 65 dB). Because a ± 4 dB level and ± 10 dB spectrum rove were applied, the sound output level of 50 dB SPL was determined to be the maximum sound level that could be tested while avoiding compression. On each trial, the patient indicated the perceived location of the sound source on a graphical interface that displayed a continuous arc representing the loudspeaker array. For each of the 19 locations, 20 repetitions were tested in a random order. Benefits of speech understanding were evaluated in a speech-in-noise task, whereby the subject identified a single word, randomly chosen from a set of fifty possible alternatives (CNC corpus) on each trial. Target words were spoken by a male talker, presented from the loudspeaker in front (0 degree) of the subject. Maskers were 2 overlapping sentences from the Harvard IEEE corpus spoken by a female talker (11). As shown in Figure 1B, 4 masker configurations were tested: colocated (both maskers from 0 degree, i); symmetrical, spatially separated (one masker at +90 degrees and the other at -90 degrees, ii); asymmetrical, spatially separated (both maskers at either -90 degrees or +90 degrees, iii and iv, respectively). Presentation of maskers began 250 ms before and stopped 250 ms after the presentation of the target word. The level of each masker was 50 dB SPL, and the presentation level of the target speech was varied to present different signal-to-noise ratios (SNRs) at each spatial configuration (30 trials per SNR). The masker intensity level of 50 dB was chosen to be consistent with the intensity level used in the sound localization task. The data obtained in each spatial configuration were fit with a psychometric function, and the 50% correct threshold was estimated. These thresholds were then used to estimate head shadow, binaural summation, and binaural squelch benefits (12). Three listening conditions (NH, CI, and CI+NH) were tested for each of the 4 spatial configurations.

Audiologic evaluation was performed before implantation and at 6-, 9-, 12-, and 18-month intervals after activation of the implant. Evaluation consisted of audiometric threshold measurements, the Hearing in Noise Test (HINT), Consonant-Nucleus-Consonant test (CNC), and the IEEE sentence test. Stimuli were presented at 60 dB SPL; percent correct was scored for each test at each condition. All tests were performed in a sound attenuated booth.

Longitudinal performance on tinnitus containment was also evaluated. The Tinnitus Reaction Questionnaire (TRQ; 13), Tinnitus Handicap Inventory (THI; 14), and Tinnitus Questionnaire (TQ; 15) were completed by the patient preoperatively, 1 week after surgery, monthly for the next half-year, then bimonthly for the following 10 months.

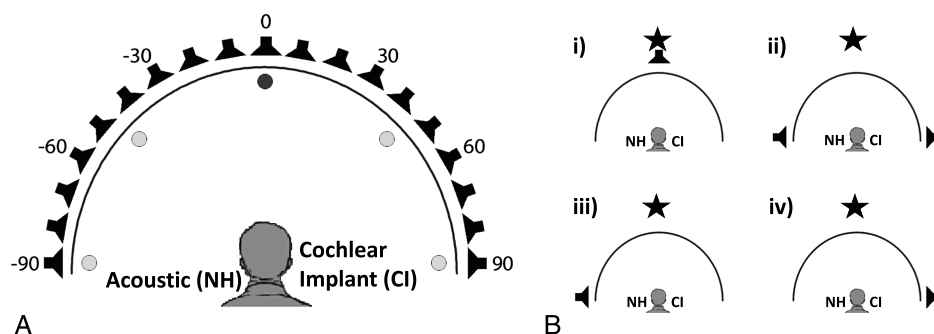


FIG. 1. A, A schematic view of the setup used in the localization and speech-in-noise tasks. For the localization task, the subject was positioned at the center of an arc of loudspeakers with a 1.2-m radius. The positions of each loudspeaker were concealed by a curtain. Nineteen loudspeakers were placed at 10-degree intervals. B, The spatial configurations tested in the speech-in-noise task. Target speech (★) was always presented from 0-degree azimuth. Maskers (▲) were presented from (i) 0 degree, (ii) ± 90 degrees, (iii) -90 degrees, or (iv) $+90$ degrees. Three listening conditions (cochlear implant alone [CI], acoustic [normal-hearing] ear alone [NH], and bilateral [CI+NH]) were tested in each of the 4 spatial configurations.

RESULTS

Localization

Figure 2 shows root mean square (RMS) error values between the target and response locations for each listening condition (CI, NH, and CI+NH) at each testing interval. Compared with the acoustic-only condition, RMS errors in the CI+NH condition improved by 5 degrees. A 1-way analysis of variance was performed to assess differences between performance on the 3 listening conditions at the 18-month testing interval. Results suggest a significant overall effect [$F_2 = 217.31$, $p < 0.001$]. Follow-up pairwise tests with Bonferroni correction suggested that performance was significantly better in the bilateral versus either monaural conditions ($p < 0.05$) and that performance was better in the NH monaural condition than the CI monaural condition ($p < 0.05$). It should be noted that RMS error in the NH-ear only listening condition was found to be lower than would be expected in a monaural listening condition at all testing periods. This finding suggests a higher degree of localization accuracy than would be expected in this listening condition. This observation was postulated to be related to the presence of spectral cues that may have been available, as the sound booth design allowed for these cues to be minimized but not eliminated entirely. Because the NH ear has greater spectral resolution than the CI ear, it would be more adept at using these cues, thus resulting in the findings observed during testing.

Speech-in-Noise

Benefits for understanding speech-in-noise were assessed by comparing percentage correct scores for different target-masker spatial configurations (Table 1). Overall, binaural benefits depended greatly on the spatial configuration of the maskers relative to the NH acoustic or CI ear. The head shadow effect (Fig. 3A) was generally small during the first 9 months of CI use; however, after 12 and 18 months of experience, a large head shadow effect was observed (12.98 dB) when the acoustic ear was “added”

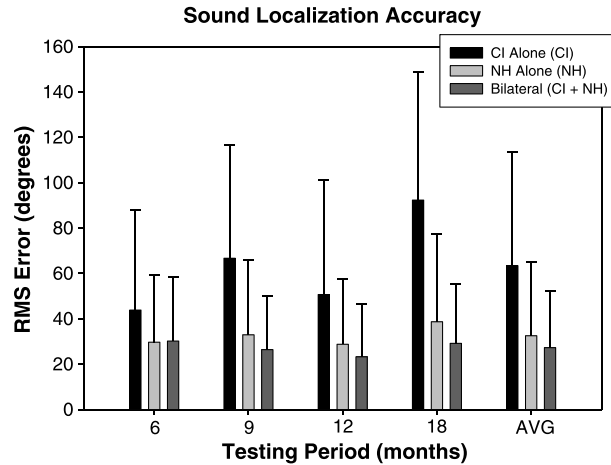


FIG. 2. Sound localization results. Root-mean squared (RMS) localization error is shown as a function of postactivation time for the CI-only (normal-hearing ear plugged, black bars), acoustic-only (light bars), and bilateral (gray bars) conditions. For each of the 3 listening condition at all 4 testing periods, 20 trials were performed for each of the 19 speaker locations in a random order (380 trials per condition). Error bars represent the standard deviation from the mean for each of these testing conditions at each period. For reference, an RMS error of 90 degrees represents localization accuracy no greater than chance alone. CI = cochlear implant with opposite ear plugged, NH = acoustic (normal-hearing) ear, CI+NH = bilateral listening condition, AVG = average RMS error over all 4 testing periods.

to the monaural, CI-only listening condition. Similar effect sizes and trajectories were observed for binaural summation (Fig. 3B; 9.88 dB) and binaural squelch (Fig. 3C; 4.38 dB). These findings were observed when comparing performance in conditions with the NH acoustic ear plugged while using the CI to conditions with the NH ear unplugged. Thus, the bilateral conditions represent the needed input from the NH ear (Fig. 3, A–C, black circles). This change in performance between the 9- and 12-month testing periods may therefore represent early evidence of binaural processing. Although this change is somewhat large and may not be representative of the increment that is observed in all patients, it is within the measured range of effect sizes reported in literature related to spatial unmasking (1,16). However, the findings observed from the opposite frame of reference in which performance using only the NH ear was compared with the bilateral condition suggest that the addition of auditory input provided by a CI in the other ear does not provide benefits and may even have a small detrimental effect (Fig. 3, A–C, white circles).

Perhaps the most effective approach for measuring benefit from the addition of the CI can be observed in Fig. 3D, where SRM calculations are shown. SRM calculations always included conditions with both ears activated, as opposed to the aforementioned conditions in which comparisons were made between performance in monaural and bilateral conditions. This method of determining SRM was performed to simulate the patient's natural listening condition in which both ears are used, but the masker positions are varied. The only condition in which benefits of approximately 4 dB were observed long term (6, 9, 12, and 18 months postactivation) was the condition with the masker positioned toward the right (near the ear with the CI; Fig. 3D, triangles). In other conditions, SRM was positive but small at initial testing intervals and remained consistently near 0 dB at the longer intervals (Fig. 3D, squares and crosses). These data indicate that when the patient received bilateral auditory input in complex listening environments with competing background noise, the greatest benefit from spatial separation of target and maskers

TABLE 1. Calculations made for binaural benefits

Spatial speech measure	Condition	Calculation
SRM	Bilateral	$Bil(T0^{\circ}M0^{\circ}) - Bil(T0^{\circ}M+/-90^{\circ})$
	Masker Right	$Bil(T0^{\circ}M0^{\circ}) - Bil(T0^{\circ}M+90^{\circ})$
	Masker Left	$Bil(T0^{\circ}M0^{\circ}) - Bil(T0^{\circ}M-90^{\circ})$
Binaural summation	NH Frame of Reference	$CI(T0^{\circ}M0^{\circ}) - Bil(T0^{\circ}M0^{\circ})$
	CI Frame of Reference	$NH(T0^{\circ}M0^{\circ}) - Bil(T0^{\circ}M0^{\circ})$
Head shadow	NH Frame of Reference	$CI(T0^{\circ}M+90^{\circ}) - Bil(T0^{\circ}M+90^{\circ})$
	CI Frame of Reference	$NH(T0^{\circ}M-90^{\circ}) - Bil(T0^{\circ}M-90^{\circ})$
Binaural squelch	NH Frame of Reference	$CI(T0^{\circ}M-90^{\circ}) - Bil(T0^{\circ}M-90^{\circ})$
	CI Frame of Reference	$NH(T0^{\circ}M+90^{\circ}) - Bil(T0^{\circ}M+90^{\circ})$

Spatial release from masking was calculated for the symmetric and asymmetric masker conditions. Binaural summation, head shadow, and binaural squelch were calculated with respect to the acoustic ear or the implanted ear.

Bil indicates bilateral; NH, acoustic ear; CI, CI ear; T0°, target speech located at 0-degree azimuth; M, masker location.

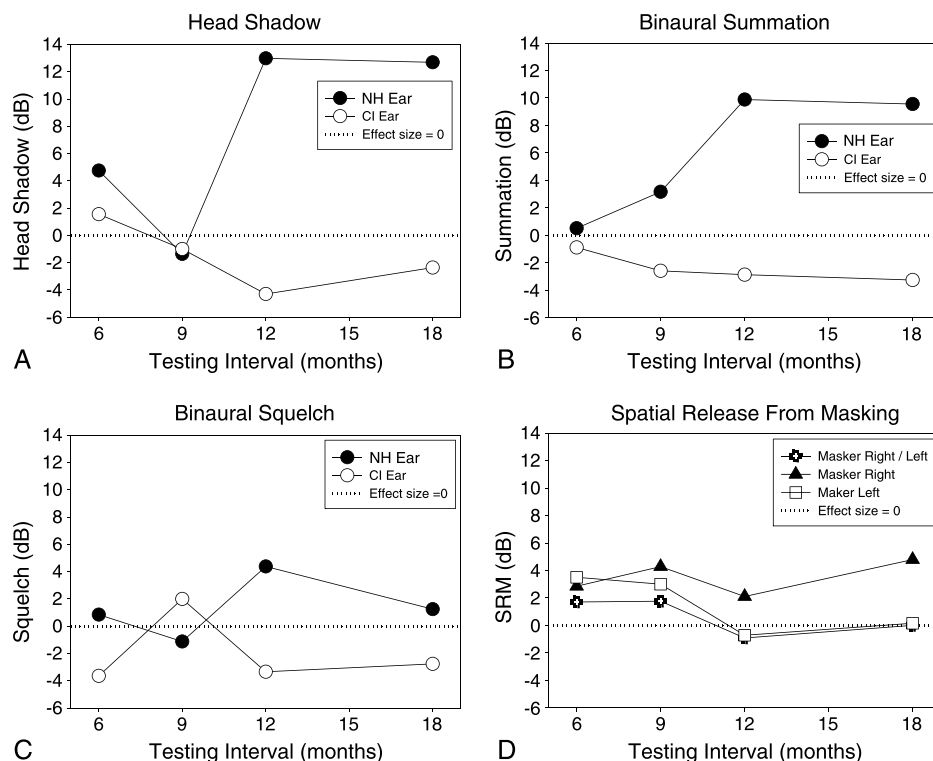


FIG. 3. Results of the binaural benefit calculations are shown for (A) head shadow, (B) binaural summation, and (C) binaural squelch. Calculations were made with respect to the NH (acoustic) ear (black circles) and the implanted (CI) ear (white circles). D, SRM was calculated for the symmetric masker (crosses) and asymmetric masker (to right, triangle; to left, square) conditions. Normal values for binaural hearing measures are as follows: head shadow 3 to 10 dB; binaural squelch 3 dB; binaural summation 6 to 10 dB (20). Normal range of SRM in normal-hearing adults is as follows: masker left or right 6 to 7 dB; maskers left and right 2 to 3 dB (19).

occurred with the masker located on the side of the implanted ear. In contrast, similar effects of spatial separation were not observed when the masker was positioned on the side nearest the NH ear. This finding may have implications for clinical fittings, as discussed below.

Audiologic

At the first testing period (6 months postactivation), a PTA of 16 dB HL was documented in the NH ear (CI turned off), and a 23 dB HL PTA was demonstrated in the implanted ear with the NH ear plugged. HINT scores were 99% using the CI alone (NH ear plugged) and 100% using only the NH ear. Whole word and phonemic identification was at 66% and 85%, respectively, in the CI-only listening condition as measured on the CNC word lists. At 18 months postactivation, performance improved to 88% on whole-word identification ($p = 0.002$) and 95% on phonemic identification ($p < 0.001$). On all other audiologic tasks, the patient correctly identified between 90% and 100% of target speech in all listening conditions (CI, NH, and CI+NH) at all 4 testing periods.

Tinnitus

The subject reported marked tinnitus reduction upon activation of the CI and while the CI was on. This

effect remained constant over the 16-month period, postactivation (Fig. 4).

DISCUSSION

The data presented here are important for several reasons. First, this information highlights the potential ways in which an individual with SSD may benefit from cochlear implantation in the deaf ear. For example, the individual tested here demonstrated a marked benefit with respect to tinnitus handicap when the implant was activated, consistent with previous reports (7,17). A statistically significant improvement in sound localization was also observed 9 months after activation and later, also in agreement with previous work (6,18). Although the 5-degree improvement in localization observed in the bilateral condition may have minimal benefits in real-world settings, it is important to point out that this finding may be evidence of the integration of bilateral auditory input, and longer-term follow-up is required to evaluate whether localization accuracy will improve with continued experience using the implant. In addition, a subject with SSD using a CI may demonstrate binaural effects not previously realized. This was highlighted here by the observations that binaural squelch, head shadow, and binaural

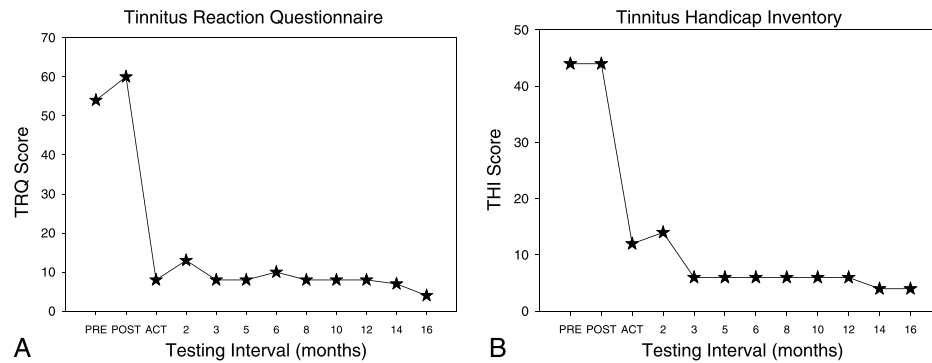


FIG. 4. Results for (A) the Tinnitus Reaction Questionnaire (TRQ) and (B) the Tinnitus Handicap Inventory (THI). The scores were obtained at 1 week preimplantation (PRE), 1 week postimplantation (POST), 1 week postactivation (ACT) of the implant, and at 2-month intervals thereafter. After activation of the implant, TRQ scores decreased into the normal range (normal <17) and remained stable over the 16-month period after activation (see A). After activation of the implant, the patient's THI scores decreased from a moderate Grade 3 handicap (score of 38–56) to a slight Grade 1 handicap (score of 0–16) and remained stable over the 16-month period after activation (see B).

summation were all seen at the 12-month testing period and at later periods, but only when the NH acoustic ear was added to the CI-only listening condition. In contrast, in the reverse case, there was a small disruptive effect of adding the CI to the acoustic ear. This finding may offer new insight into how auditory cues are integrated from each ear after cochlear implantation in other subjects who have SSD. Previous studies in this patient population have only shown a binaural squelch effect in these individuals at 12 months and only if a hearing aid is worn in the contralateral ear (6). No other binaural mechanisms have been described in these patients at follow-up of 1 year or less (6,7,10), and no binaural mechanisms have been observed in any of these patients if the opposite ear has normal hearing (6). Although it is possible that an individual with SSD and normal hearing in the opposite ear who utilizes a CI may never demonstrate benefits with respect to spatial hearing, our findings indicate that auditory stimuli from both ears is being centrally integrated when comparisons are made between the CI-only listening condition and the bilateral condition. This finding is demonstrated by the observation that binaural squelch and summation were demonstrated at 12 and 18 months when the CI-only listening condition was compared with the bilateral listening condition. Further research with a larger group of patients will shed light on the effect sizes observed in this unique population. This relationship has not been previously described, as these comparisons have only been made in the reverse order between the NH ear and the bilateral listening condition in previous work (6,7,10). This finding may indicate that binaural processing strategies are evolving as experience is gained using the implant and that a longer period using the implant may be required in order for binaural squelch and summation to emerge with respect to the NH ear. There are no studies in the literature documenting assessments of squelch or summation at longer-term intervals; however, our data indicate that it may require use of the implant for greater than 18 months to demonstrate these abilities. This is supported by the observation that squelch and summation were not demonstrated at

this period in our subject. Taken as a whole, these observations suggest that further investigations of binaural hearing in this patient population should have a longer follow-up period to better clarify these findings.

The unique nature of the measures made here is in SRM, which may be useful in assessment of spatial hearing outcomes in patients with SSD who receive a CI. Although SRM is not currently a component of previously reported hearing assessments in this patient population, SRM has already been shown to be a useful measure to assess spatial hearing performance in normal-hearing subjects and in those with bilateral CIs (1,19). Our findings indicate that measurement of SRM provides new information beyond that which can be determined if only squelch or summation are calculated as in previous reports on implanted subjects with SSD (6,7). For example, although our subject did not demonstrate evidence of binaural squelch or summation when the NH-only condition was compared with the bilateral listening condition, the SRM effect demonstrated a benefit of spatial separation of target and masker stimuli on the order of 4+ dB. This effect was consistent for the condition with masker on the right (toward the ear with the CI), suggesting that the auditory system of this individual was particularly facile at using spatial cues to segregate speech from maskers when the maskers were near the implanted ear. There may be clinical implications to be considered, such as clinical fittings of microphones and/or noise cancelling signal processing algorithms for these patients.

Although the measurement of “binaural squelch” in this individual involved the use of this same masker configuration, these spatial hearing benefits would not have been realized if only squelch (and not SRM) had been measured, as has been conducted in previously reported studies. Furthermore, an additional benefit of SRM is that all calculations are made with both ears activated, as opposed to comparing performance between a monaural and the bilateral listening condition in a given masker configuration as is done with binaural squelch and summation (6,7). This is important because the presence of

TABLE 2. Summary of suggested binaural measures to be used in the assessment of individuals with SSD who have undergone cochlear implantation

Spatial measure	Description	Applicability	Example	References
Head shadow	Comparing monaural to bilateral listening performance by adding ear with better SNR	Assessment of listener's performance when the second ear is in a favorable listening condition	Subject demonstrates better performance in the bilateral listening condition because the second (added) ear is positioned opposite to the masker	Litovsky et al. 2006 (21)
Binaural squelch	Comparing monaural to bilateral listening performance by adding ear with worse SNR	Assessment of listener's performance when the second ear is in an unfavorable listening condition	Subject demonstrates better performance in the bilateral listening condition because the second (added) ear allows for binaural processing in which the brain allows for attenuation of masking noise	Amdt et al. 2011 (7) Firszt et al. 2012 (18) Litovsky et al. 2006 (21)
Binaural summation	Comparing monaural to bilateral listening performance when target and masker are located from the same position in space (typically in front)	Assessment of performance in complex listening environments when a talker is located at the same position as background noise	Subject demonstrates better performance in the bilateral listening condition because the second (added) ear provides additional auditory input which assists in recognition of target speech	Vermeire et al. 2009 (6) Amdt et al. 2011 (7) Firszt et al. 2012 (18) Litovsky et al. 2006 (21)
SRM	Comparison of performance in bilateral listening condition when target and masker are co-located vs. spatially separated	Assessment of any potential improvement in listening accuracy when background noise is separated from a target sound. Test assumes that patient has bilateral auditory input	If a subject has bilateral auditory input and demonstrates binaural processing, listening performance will be better when target speech is separated in space from one or more sources of background noise	Vermeire et al. 2009 (6) Amdt et al. 2011 (7) Firszt et al. 2012 (18) Hawley et al. 2004 (16) ^a Misurelli and Litovsky 2012 (1) ^a Jones and Litovsky 2011 (19) ^a

SNR indicates signal-to-noise ratio; SRM, spatial release from masking.

^aNo studies exist in the literature documenting SRM for individuals with SSD who undergo cochlear implantation. These articles reference SRM in normal-hearing individuals and those with bilateral profound hearing loss undergoing cochlear implantation.

tinnitus in an implanted ear of patients with SSD has been shown to elevate speech reception thresholds in the normal-hearing ear when the implant is deactivated (9). Because the CI is always activated when determining SRM, this confounding effect is eliminated.

The data suggest that several important factors be considered when assessing binaural hearing outcomes in patients with SSD who receive a CI. First, when performing traditional monaural to bilateral calculations (squellch and summation), these calculations should be made both by comparing the NH-only listening condition to the bilateral listening condition and by comparing the CI-only listening condition to the bilateral condition, as our data indicate that in this individual, binaural benefits were seen first at 12 months when the NH ear was added to the CI-only listening condition. These assessments should also be performed at follow-up periods of greater than 18 months, as our data suggest that longer time periods may be required to assess for these binaural benefits. Next, calculation of SRM overcomes many of the current limitations with the assessment of traditional binaural hearing measures and should be performed as a component of the assessment of binaural hearing in these patients. As these calculations are always performed in the bilateral listening condition with the masker positions varied, they represent real-world listening situations in which the position of background noise commonly changes around the patient. SRM is also useful as it controls for the effect of tinnitus on speech reception thresholds in the acoustic-hearing ear as the implant is always activated during these tasks. As cochlear implantation continues to be investigated as a means of restoration of binaural hearing in patients with SSD, we suggest that these novel measurements (see Table 2) be considered as a best-practice in future spatial hearing investigations in this patient population. Finally, we acknowledge that here, and in numerous previous studies, the differentiation of mechanisms in the auditory pathways that rely purely on binaural processing, versus the integration of spatial cues that arise from monaural cues as well, is not clear and needs to be better understood (21).

Acknowledgment: The authors thank Daniel Bolt for assistance with statistical analyses performed in conjunction with this article.

REFERENCES

- Misurelli SM, Litovsky RY. Spatial release from masking in children with normal hearing and with bilateral cochlear implants: effect of interferer asymmetry. *J Acoust Soc Am* 2012;132:380–91.
- Van Hoesel RJ. Exploring the benefits of bilateral cochlear implants. *Audiol Neurootol* 2004;9:234–46.
- Litovsky RY, Parkinson A, Arcaroli J. Spatial hearing and speech intelligibility in bilateral cochlear implant users. *Ear Hear* 2009;30:419–31.
- Godar SP, Litovsky RY. Experience with bilateral cochlear implants improves sound localization acuity in children. *Otol Neurotol* 2010;31:1287–92.
- Litovsky RY, Goupell MJ, Godar S, et al. Studies on bilateral cochlear implants at the University of Wisconsin's Binaural Hearing and Speech Laboratory. *J Am Acad Audiol* 2012;23:476–94.
- Vermeire K, Van de Heyning P. Binaural hearing after cochlear implantation in subjects with unilateral sensorineural deafness and tinnitus. *Audiol Neurootol* 2009;14:163–71.
- Arndt S, Aschendorff A, Laszig R, et al. Comparison of pseudo-binaural hearing to real binaural hearing rehabilitation after cochlear implantation in patients with unilateral deafness and tinnitus. *Otol Neurotol* 2011;32:39–47.
- Arts RA, George EL, Stokroos RJ, et al. Review: cochlear implants as a treatment of tinnitus in single-sided deafness. *Curr Opin Otolaryngol Head Neck Surg* 2012;20:398–403.
- Mertens G, Kleine Punte A, De Ridder D, Van de Heyning P. Tinnitus in a single-sided deaf ear reduces speech reception in the nontinnitus ear. *Otol Neurotol* 2013;34:662–6.
- Buechner A, Brendel M, Lesinski-Schiedat A, et al. Cochlear implantation in unilateral deaf subjects associated with ipsilateral tinnitus. *Otol Neurotol* 2010;31:1381–5.
- IEEE Subcommittee on Subjective Measurements: IEEE Recommended Practices for Speech Quality Measurements. *IEEE Transactions on Audio and Electroacoustics* 1969;17:227–46.
- Garadat SN, Litovsky RY, Yu G, Zeng FG. Role of binaural hearing in speech intelligibility and spatial release from masking using vocoded speech. *J Acoust Soc Am* 2009;126:2522–35.
- Wilson PH, Henry J, Bowen M, et al. Tinnitus reaction questionnaire: psychometric properties of a measure of distress associated with tinnitus. *J Speech Hear Res* 1991;34:197–201.
- Newman CW, Sandridge SA, Jacobson GP. Psychometric adequacy of the tinnitus handicap inventory (THI) for evaluating treatment outcome. *J Am Acad Audiol* 1998;9:153–60.
- Hallam RS, Jakes SC, Hinchcliffe R. Cognitive variables in tinnitus annoyance. *Br J Clin Psychol* 1988;27(Pt 3):213–22.
- Hawley ML, Litovsky RY, Culling JF. The benefit of binaural hearing in a cocktail party: effect of location and type of interferer. *J Acoust Soc Am* 2004;115:833–43.
- Van de Heyning P, Vermeire K, Diebl M, et al. Incapacitating unilateral tinnitus in single-sided deafness treated by cochlear implantation. *Ann Otol Rhinol Laryngol* 2008;117:645–52.
- Firszt JB, Holden LK, Reeder RM, Waltzman SB, Arndt S. Auditory abilities after cochlear implantation in adults with unilateral deafness: a pilot study. *Otol Neurotol* 2012;33:1339–46.
- Jones GL, Litovsky RY. A cocktail party model of spatial release from masking by both noise and speech interferers. *J Acoust Soc Am* 2011;130:1463–74.
- Firszt JB, Reeder RM, Skinner MW. Restoring hearing symmetrically with two cochlear implants or one cochlear implant and a contralateral hearing aid. *J Rehabil Res Dev* 2008;45:749–68.
- Litovsky R, Parkinson A, Arcaroli J, Sammeth C. Simultaneous bilateral cochlear implantation in adults: a multicenter clinical study. *Ear Hear* 2006;27:714–31.