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ORIGINAL RESEARCH

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Vestibular function after cochlear implantation: A test battery and case-by-case approach

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Abstract

Objectives: The purpose of this study was to assess the effects of cochlear implantation on the functional integrity of the horizontal semicircular canal using multiple methodologies, and to discuss and highlight the limitations of using isolated vestibular tests to assess vestibular function in surgical ears.

Methods: Ten cochlear implant patients were consented to undergo a preoperative and 3-month postoperative vestibular assessment. The horizontal semicircular canal (SCC) was assessed using three different vestibular test measures that assess function using different stimuli and at different frequencies ranges: caloric testing, sinusoidal harmonic acceleration testing in the rotary chair, and video head impulse testing in the plane of the horizontal SCC. Data was analyzed using different methods: descriptive, statistical, and by an examination of individual case studies.

Results: Each analysis method yielded a different interpretation. Statistical analysis showed no significant group mean differences between baseline pre-op vestibular test results and 3-month post-op vestibular test results. Descriptive analysis showed 30% of individuals presented with postoperative abnormal vestibular testing findings. A case study examination showed that only one patient presented with a post-op decrease in vestibular function in the implanted ear.

Conclusions: There are several limitations of conventional vestibular testing in post-surgical cochlear implant patients. A test-battery approach, including case history, and test interpretation made on a case-by-case basis is needed to determine whether the patient has undergone vestibular damage, is at risk for falling, or in need of further management.

Level of Evidence: 2b individual cohort study.

KEYWORDS

caloric testing, cochlear implants, VEMP, vestibular, vHIT

1 | INTRODUCTION

After cochlear implants (CI) began to be implanted worldwide and on a large group of individuals, concerns regarding post-surgical dizziness arose. In fact, symptoms of dizziness, vertigo, and imbalance are commonly reported following CI surgery.[1-5] However, symptoms are often short-lived and it is not clear whether symptoms are due to vestibular damage secondary to the surgical procedure or due to other nonvestibular causes.[6] Some individuals who undergo cochlear implantation will have concomitant vestibular system damage, and it is important to identify these patients as impaired vestibular function can have detrimental consequences, such as falls and injuries. In fact, the risk of falls increases in some older patients after cochlear implantation.[7] Thus, examination of vestibular function post CI surgery has become increasingly important. Despite numerous studies examining vestibular function postoperatively, our understanding regarding the extent to which vestibular dysfunction occurs as a result of cochlear implantation remains unclear and the best test protocol to assess vestibular function post-CI surgery is not known.

1.1 | Limitations of vestibular testing in CI patients

Recent meta-analyses have shown that the caloric test and cervical vestibular evoked myogenic potential (cVEMP) are the most commonly used indices of vestibular end organ function and change in CI patients.[6,8] cVEMPs assess the functional integrity of the saccule and its afferent pathway via the inferior vestibular nerve. Given its proximity to the cochlea, the saccule is presumed to be the vestibular end organ most vulnerable to damage secondary to CI surgery. However, reported saccule impairments, as measured using air conduction (AC) elicited cVEMPs, range from 9% to 86%.[9-13] Reasons for the discrepancy in the literature may be that, (a) cVEMP testing is not standardized, (b) cVEMPs elicited with an air conducted stimulus are contraindicated in the presence of conductive hearing loss (CHL), and (c) responses are often absent in older adults. First, electrode placement, transducer placement, and monitoring of the electromyographic activity of the sternocleidomastoid muscle are not standardized, yet all contribute to response variability.[14] Also, most clinical cVEMP studies utilize a 500 Hz air-conducted (AC) tone burst, but others use clicks or bone conduction, and there is great variability in the intensity level of the stimulus used.[14,15] Second, the use of an AC stimulus may be contraindicated in post-CI patients due to the potential for CHL that is not routinely measured (or, if hearing is not preserved, cannot be measured). The presence of CHL in CI patients with residual hearing has been reported,[16] as has evidence of reduced static admittance, measured via tympanometry, in children post-CI.[17] Finally, cVEMP responses elicited using a 500 Hz air-conducted tone burst stimulus, as is the most common clinical practice at this time, are not reliable in older patients,[18] and are commonly absent in individuals over the age of 60.[19] Thus, it is not clear whether abnormal AC cVEMPs are due to differences in cVEMP testing techniques, inadequate stimulation secondary to CHL and/or abnormal middle ear function, a consequence of age, or truly indicative of an otolith impairment.

The caloric test assesses the functional integrity of the horizontal semicircular canal (SCC) and is the most utilized test of vestibular function in post-CI patients. A recent literature review estimates 34% of post-CI patients show new caloric asymmetries, but the range across studies is staggering, with reports between 0% and 77%.[2,6,20-22] Interpretation of caloric irrigation results post-CI are confounded by altered temporal bone anatomy which makes it difficult to know if the change in caloric results post-CI surgery reflects changes to underlying vestibular function or alterations in thermal conduction due to anatomical changes in the mastoid cavity. Patki et al. (2016) used temporal bone modeling to estimate anatomical contributions to the caloric response and demonstrated that 69% of the variability of caloric responses could be accounted for by anatomical differences in the temporal bone.[10] This would suggest that alterations to the mastoid would alter the heat transfer properties of the caloric test. These factors are magnified in patients with surgical ears, specifically CI patients, because most undergo mastoidectomies. Additionally, patient alertness can affect the caloric test results, and the test is conducted in the dark where visual cues are removed. For a CI patient with moderate or greater hearing loss, this may result in great difficulty keeping the patient alert during testing. For these reasons, caloric testing may not be ideal for monitoring vestibular status, especially in post-CI ears.

Other tests of horizontal SCC function include rotational testing and video head impulse testing. Very little has been reported on the effects of CI on rotary chair results. An advantage of rotary chair testing is its high test-retest reliability because a precise, computer generated stimuli is applied each time.[23] For this reason, it is often recommended for monitoring or serial testing such as in cases of ototoxicity monitoring.[24] Another advantage is the test is not affected by changes in temporal bone anatomy since a physiological stimulus of rotation in the yaw axis is employed to stimulate the vestibular system. One disadvantage of the rotary chair, and possibly why rotary chair results are so infrequently reported in the CI literature, is the cost associated with the chair. Thus, testing is not readily available. Another disadvantage is that patient alertness also impacts rotary chair responses. Similar to caloric testing, rotary chair testing is performed in the dark; however, a CI patient is often able to continue use of their CI or hearing aid during testing. A final disadvantage is that the test provides information regarding both vestibular labyrinths together and does not differentiate between right and left ear impairments well; but this can be remedied by comparing it to results from other tests of the horizontal SCC including caloric testing and the video head impulse test (vHIT).

More recently, vHIT has been used to quantify horizontal semicircular canal function.[25] The vHIT test is a quick measure that is easily tolerated, and unlike caloric testing, does not rely on thermal conduction through the temporal bone. Several studies have utilized vHIT to quantify vestibulo-ocular reflex (VOR) function in the cochlear implant population.[13,26,27] Earlier work using scleral search coil recordings during head impulse testing[20,28] showed minimal changes to VOR gain

pre and post cochlear implantation. Recent review studies study suggested that vHIT is the least affected vestibular test post-CI[6,8]; however, vHIT is limited to testing a high frequency range of vestibular function,[25] and may miss some vestibular impairments.[29] Further, reliability is hindered by a lack of standardization and user-technique, including things such as hand placement.[30]

A subjective measure often utilized to assess post-CI vestibular changes is the Dizziness Handicap Inventory (DHI[31]). The DHI is a measure of self-reported dizziness handicap and disability and is frequently measured as a measure of subjective dizziness post-CI.[6,8] DHI and vestibular test results in CI patients are often conflicting, that is abnormal vestibular test results are often reported in patients who self-report no dizziness handicap.[8] However, numerous studies show that DHI does not correlate with any objective measure of vestibular function in patients with a variety of pathologies (eg, [32]). It is no surprise that the DHI does not correlate with vestibular test measures in CI patients.

1.2 | Difficulties in vestibular test interpretation

Though each vestibular test has specific limitations in CI patients and vestibular testing techniques differ between studies, there are additional issues in interpreting vestibular tests in a serial manner to assess pre-op and post-op vestibular function. Mainly, the definition of "significant change" is different between studies. Some studies conduct a statistical comparison of mean responses pre-op compared to post-op testing. Others may define a significant change as post-op test results that fall outside the normal limits specified by that specific lab. Very few consider the minimal detectable change needed in a test to interpret the change as clinically significant.

Each method of test interpretation has a weakness. A significant change in the group mean data, or nonsignificant change, can be examined using significance testing, for example a *t* test. However, a statistically significant mean difference indicates whether the result is not likely due to sampling error. It does not indicate how strong the mean difference is nor does it indicate clinical importance for an individual. Alternatively, data may be interpreted based on clinical lab norms, meaning patients whose values fell within normal limits or outside normal limits based on pre-set criteria. However, these values will differ between labs. Further, most vestibular testing norms are based on a single test administration, not serial testing, and do not accurately assess whether the magnitude of a change in a test result is reliable. For example, Piker and colleagues demonstrated that the minimal detectable change, as a measure of absolute reliability, for a unilateral weakness in the caloric test is 23% in healthy ears.[11] Therefore, a statistically significant mean difference may be observed, but individual responses may not represent a true change in function if they fall within the known variability for the caloric test (ie, change in unilateral weakness <23%). Additionally, the dizziness handicap inventory (DHI) score may be statistically different between pre-op and post-op administrations, but clinical research shows that an 18+ point difference is needed for a clinically significant change.[31] These differences in test interpretation and data analyses may contribute to the inconsistences across studies with regards to the effects of cochlear implantation on vestibular function.

Herein we present a prospective study examining the effects of cochlear implantation on the functional integrity of the horizontal semicircular canal (SCC) using three different vestibular test measures that assess function using different stimuli and at different frequencies ranges: caloric testing, sinusoidal harmonic acceleration testing in the rotary chair, and vHIT in the plane of the horizontal SCC. We analyzed the data in two different ways, examining both mean differences pre-op compared to post-op and the percentage of patients with post-op results that were outside our clinical lab norms. Analyses are followed by a series of case studies, highlighting the complexity of vestibular testing and test interpretation in CI patients.

2 | MATERIALS AND METHODS

2.1 | Participants

Sixteen participants were recruited and enrolled in the current study. Individuals were included in the current study if they were 18 years or age or older, undergoing unilateral cochlear implant surgery, and being implanted with a MED-EL Flex28 cochlear implant device. Individuals were excluded if they were less than 18 years of age, did not receive a baseline preoperative vestibular evaluation within 90 days prior to implantation, or if they were implanted with a cochlear implant other than the MED-EL Flex28 device. This study was approved by the institutional review board at Duke University Medical Center (IRB # Pro00060216), and all individuals signed an informed consent form prior to participation in the study. The participants were given nominal payment for their time.

2.2 | Surgical approach

All participants underwent cochlear implantation using soft surgical techniques. They received 10 mg of decadron IV prior to the surgery as well as a transtympanic injection of decadron at the beginning of the surgery. A standard mastoidectomy and facial recess approach was performed and the round window was exposed. When the round window membrane was opened, Healon was placed over the opening to prevent leakage of perilymph. The electrode was inserted slowly over 3 minutes.

2.3 | Vestibular laboratory measures

Participants underwent an evaluation at baseline and at a 3-month postoperative follow up visit. The evaluations included an assessment of the horizontal semicircular canal using caloric testing, sinusoidal harmonic acceleration testing in the rotary chair, and vHIT in the plane of the lateral canal. Table 1 shows the predetermined laboratory norms and clinical cut-offs for each of these assessments.

TABLE 1 Laboratory norms and clinical cut-off values used in the current study

Vestibular test/test parameter	Cut-off value for abnormal
Caloric test, unilateral weakness	≥25%
Caloric test, total response	<25 deg/sec
SHA, phase 0.01 Hz	>52 deg
SHA, gain 0.01 Hz	<0.15
vHIT, right	Gain < 0.8, or presence of OS or CS
vHIT, left	Gain < 0.8, or presence of OS or CS
DHI	No handicap = 0–15 points Mild handicap = 16-34 points Moderate handicap = 36-52 points Severe handicap = 54+ points

Abbreviations: CS, covert corrective saccades present; deg, degrees; DHI, dizziness handicap inventory; OS, overt corrective saccades present; SHA, sinusoidal harmonic acceleration; vHIT, video head impulse test.

Prior to caloric testing, participants underwent a search for spontaneous nystagmus in a vision denied condition. For the caloric irrigations, participants were placed in the supine position with their head elevated 30° to align the horizontal canal in the vertical plane. Caloric water irrigations consisted of 250 mL of water for 30 seconds (delivered via the Micromedical Aqua Stim irrigator). Standard caloric temperatures of 44°C and 30°C were administered for warm and cool irrigations respectively. Warm water irrigations were performed first followed, and if responses were >11 deg/sec each and the difference between the right and left were <10%, testing was deemed normal and terminated.[33] Otherwise, warm irrigations were followed by cool irrigations. All caloric results were measured in the vision denied condition with mental alerting tasks to minimize central suppression. Total eye speed and unilateral weakness using Jongkees formula were calculated.

Rotary chair testing using the Neurokinetics I-Portal Neuro-Otologic Test Center (NOTC). Sinusoidal harmonic acceleration (SHA) was performed at the frequencies of 0.01 Hz, 0.08 Hz, and 0.32 Hz on each participant. Additional frequencies were performed as needed for clinical interpretation. For the purposes of this analysis, gain and phase were evaluated at 0.01 Hz which has been reported to be the most sensitive frequency, and the most sensitive measures, to identify peripheral impairment.[34]

Video head impulse testing was performed using the *EyeSeeCam* (Interacoustics, Munich Germany). The EyeSeeCam vHIT goggles are lightweight, video goggles that are affixed to the participant's head using an elastic band. The goggles consist of a high-speed camera and an accelerometer. Participants were seated in a chair 1.5 m from the wall. Standard manufacturer recommended calibration was performed prior to head impulses. Following calibration, a visual fixation target was placed in front of the participant. Participants were asked to relax his/her head and neck and to remain fixated on the visual target in front of them. Head impulses were generated by trained examiners for all participants. Impulses were produced by having the participant focus on the fixation target while the examiner stood behind the participant with his/her hands firmly gripping the participant's jawline. Eye movements were recorded to passive lateral head impulses (head displacements approximately 10° to 20°) to the left and right. A total of 15 leftward impulses and 15 rightward impulses were completed. Impulses were random in presentation direction and onset. Head impulses were accepted if the velocity of the head movements exceeded 150°/sec. vHIT results were considered abnormal if the gain was less than 0.8 or with the presence of corrective saccades. Isolated corrective saccades (ie, saccades in the presence of normal gain) were also considered abnormal.[35,36]

The DHI was administered to examine perceived handicap due to dizziness.[31] The DHI contains 25 items and individuals rate their responses on a "yes" (4 points), "sometimes" (2 points), or "no" (0 points) scale. Total scores range from 0 (no handicap) to 100 (severe handicap). An 11 point or greater difference between the DHI scores would be needed for an individual's score to be considered significantly different from a previous score with 95% confidence.[31]

2.4 | Statistical analyses

Statistical analyses were performed using SPSS (version 26). Descriptive statistics were used to examine the distribution and frequencies for the outcome variables. Difference scores, between baseline pre-op measures and 3-month post-op measures were inspected. When assessed by inspection of a boxplot, 2 outliers were detected for the right vHIT and 1 outlier was detected or the left warm caloric irrigation. Inspection of their values did not reveal them to be extreme and they were kept in the analysis. The difference scores were normally distributed, as assessed by Shapiro-Wilk's test (P = .07-.957), with the exception of the difference in DHI scores (P = .05). For normally distributed outcomes, paired sample t tests were used to determine whether the mean difference between paired vestibular test results, baseline test results and post-op test results, were statistically significantly different from zero. For the DHI, the Wilcoxon signed-rank test was used. Participants were also categorized as normal/abnormal, based on predetermined clinical cut-offs described above, at baseline and post-op. The percentage of participants who changed impairment status, between preoperative measurements and three-month post-operative follow up were also calculated.

3 | RESULTS

3.1 | Participants

Sixteen participants were enrolled in the current study with a mean age of 62 years (range = 26-85 years). There were 4 females and 12 males. Seven participants were implanted on the left side and 9 participants were implanted on the right side. Of the 16 patients enrolled, 14 returned for 3-month follow up testing. Complete data were available on 10 participants and the other four participants had

TABLE 2 Preoperative baseline and follow up vestibular results for individual participants that completed calorics, SHA, and video head impulse testing at both sessions

		Baseline							3 month follow up						
Subject	Implant ear	Total eye speed	UW (%,ear)	vHIT right gain (saccades present)	vHIT left gain (saccades present)	SHA gain 0.01 Hz	SHA phase 0.01 Hz	DHI	Total eye speed	UW (%,ear)	vHIT right gain (saccades present)	vHIT left gain (saccades present)	SHA gain 0.01 Hz	SHA phase 0.01 Hz	DHI
4	L	116	12(R)	1.06	0.93	0.41	43	0	126	5(R)	1.08	0.90	0.42	46	0
5	R	25	12(L)	0.93	0.78	0.18	61	0	23	22(L)	0.92	0.87	0.23	65	0
6	R	25	4(L)	1.07	1.07	0.22	63	0	31	3(L)	0.98	1.06	0.29	54	0
7	L	15	76(R)	0.18(OS)	0.57(OS)	0.18	86	DNE	2	N/A[b]	0.31(OS)	0.66(OS)	0.11	83	8
8	R	41	12(R)	0.96	0.95	0.18	62	4	26	46(L)	0.94	0.98 (CS,OS)	0.10	68	18
10	R	36	11(R)	0.96	0.99	0.25	35	0	33	39(R)	0.97	0.98	0.43	32	24
12	L	50	21(L)	1.08	1.02	0.33	55	0	41	12(L)	1.12	1.06	0.33	52	0
14	L	53	13(L)	1.09	0.97	0.21	47	0	58	7(L)	1.08	0.95	0.17	67	0
15	R	61	11(R)	1.05	0.83	DNE	DNE	0	38	0	1.14	0.94	DNE	DNE	18
16	R	93	10(L)	1.06	1.07	0.25	62	36	62	10(L)[a]	1.18	1.06	0.38	59	46

Abbreviations: CS, covert corrective saccades present; DHI, dizziness handicap inventory; DNE, did not evaluate; L, left ear; OS, overt corrective saccades present; R, right ear; SHA, sinusoidal harmonic acceleration; UW, unilateral weakness; vHIT, video head impulse test.

[a]Only monothermal (warm) caloric irrigation performed.

[b]In light of minimal nystagmus generated, comparison between ears is not meaningful.

TABLE 3 Group mean data of preoperative baseline and follow-up vestibular results, including the mean difference between preoperative and follow-up testing as well as 95% confidence intervals of the difference

Vestibular test	Mean (*SD*)		Mean difference (pre-op—post-op)	95% confidence interval of the difference	
				Lower	Upper
Caloric right warm	Pre-op	16.10 (10.9)	1.20	−0.78	4.21
	Post-op	14.90 (12.0)			
Caloric left warm	Pre-op	14.90 (11.0)	1.00	−2.41	2.98
	Post-op	13.90 (13.0)			
Caloric UW	Pre-op	11.78 (4.3)	−4.22	−14.54	3.15
	Post-op	16.0 (16.4)			
Caloric total response	Pre-op	51.5 (31.7)	7.50	−5.48	11.19
	Post-op	44.0 (33.5)			
SHA phase 0.01 Hz	Pre-op	57.11 (14.6)	1.33	−0.062	0.035
	Post-op	55.8 (15.1)			
SHA gain 0.01 Hz	Pre-op	0.25 (0.08)	−0.028	−0.095	0.040
	Post-op	0.27 (0.13)			
vHIT gain right	Pre-op	0.94 (0.27)	−0.03	−0.077	0.021
	Post-op	0.97 (0.25)			
vHIT gain left	Pre-op	0.92 (0.15)	−0.03	−0.065	0.009
	Post-op	0.95 (0.12)			
DHI	Pre-op	4.4 (11.9)	−7.33	−14.585	−0.082
	Post-op	11.8 (16.2)			

Abbreviations: DHI, dizziness handicap inventory; SHA, sinusoidal harmonic acceleration; UW, unilateral weakness; vHIT, video head impulse test.

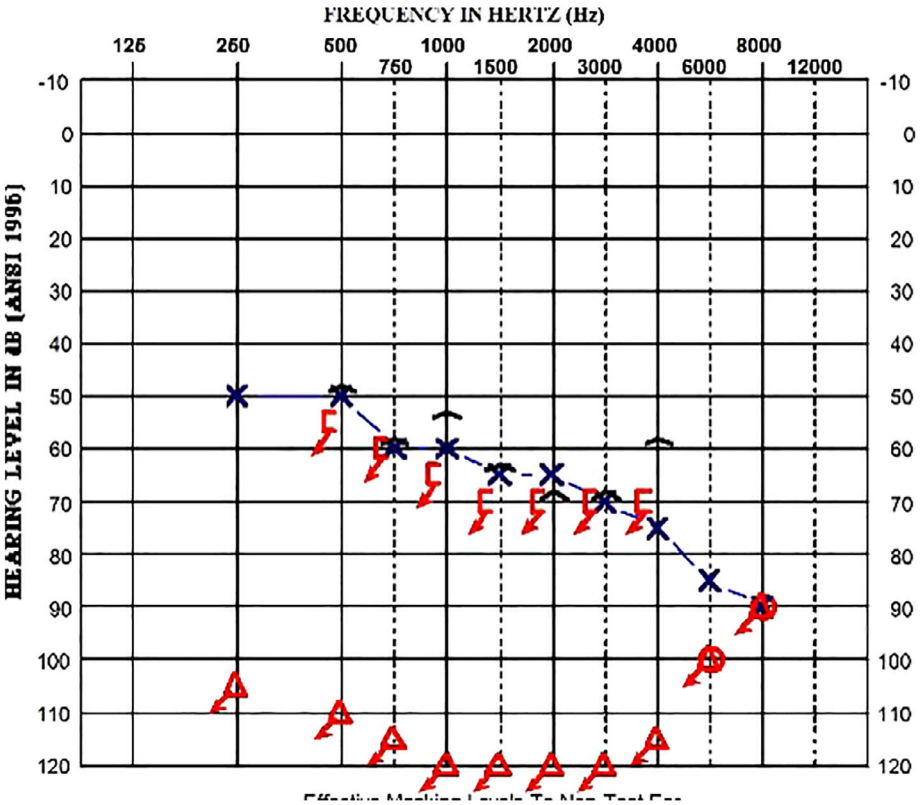


FIGURE 1 Baseline audiogram for participant 7

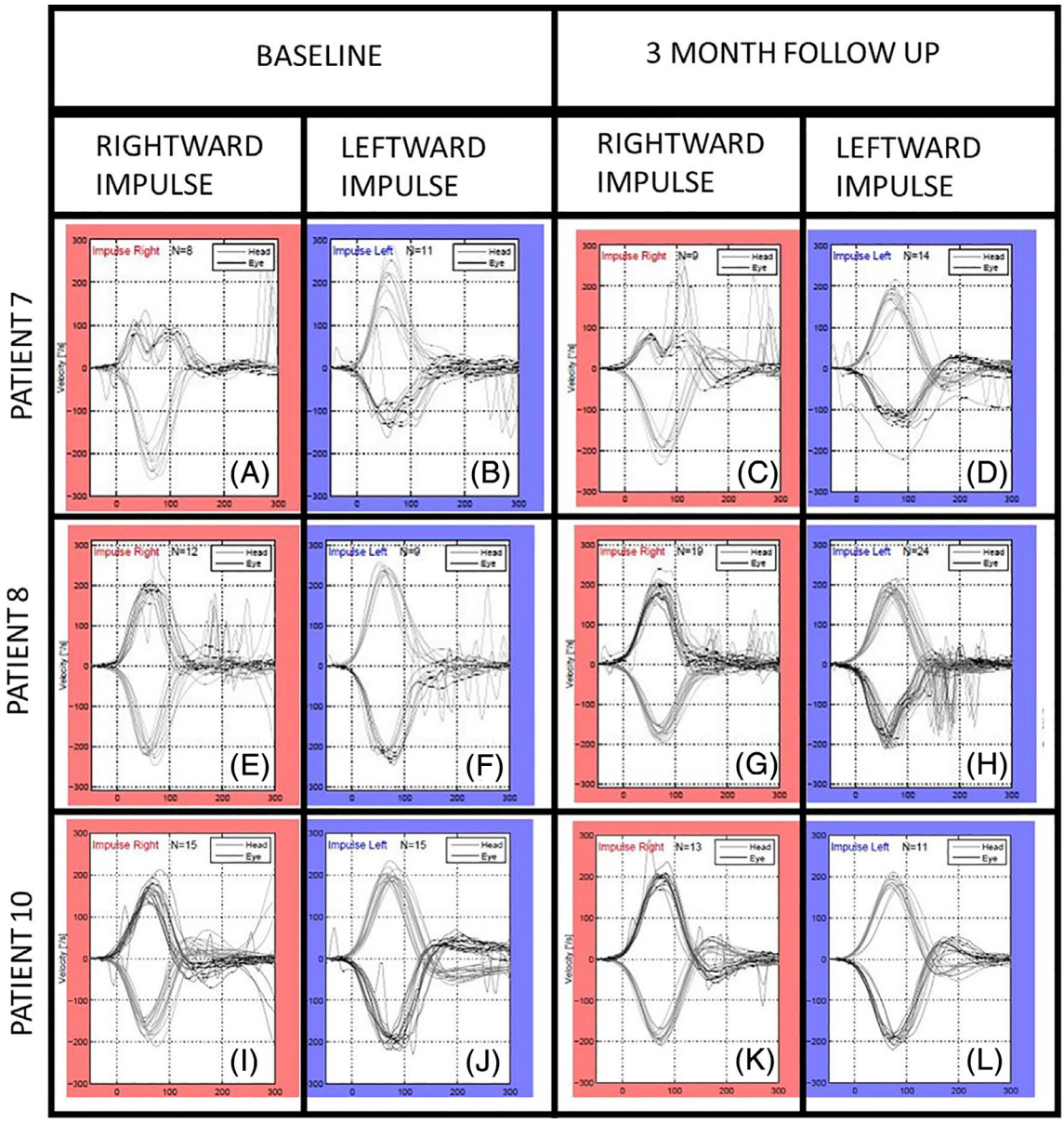


FIGURE 2 Preoperative and postoperative vHIT results for participants 7, 8, and 10. (A) and (B) are the preoperative vHIT tracings and (D) and (C) are the postoperative vHIT tracings for Patient 7. (E) and (F) are the preoperative vHIT tracings and (G) and (H) are the postoperative vHIT tracings for Patient 8. (I) and (J) are the preoperative vHIT tracings and (K) and (L) are the postoperative vHIT tracings for Patient 10

either missing caloric, rotary chair, or vHIT data at one session. Of these 10 participants, the etiology of hearing loss was unknown for 7/10, one participant was diagnosed with bilateral Meniere's disease, one suspected to have auto-immune inner ear disease, and one with a sudden sensorineural hearing loss. The duration of hearing loss was reported to be 20 years or greater for 9/10 participants and 3 years for the participant with the sudden hearing loss.

3.2 | Descriptive analyses and clinical norms

Individual results from the 10 participants with complete data from both the baseline/pre-op assessment and the post-op 3-month follow-up testing are shown in Table 2.

As shown in Table 2, for the baseline condition 1 participant (participant 7) had an abnormally reduced total eye speed (ie, total response of 15°/second for all caloric irrigations), along with reduced gain and a phase lead at 0.01 Hz in the rotary chair, and abnormally low gain with corrective saccades during vHIT testing. No other patient demonstrated evidence for vestibular dysfunction prior to surgery and 7/10 patients reported DHI score of 0 (no dizziness handicap).

During the 3-month follow-up, 3 individuals (participant numbers 7, 8, 10) presented with abnormal vestibular testing findings. One of those participants (participant 7) showed consistent evidence of a bilateral weakness pre-op and post-op. Two of those individuals (participants 8 and 10) had normal vestibular test results preoperatively but presented with a change post-op. These three participants will be discussed in detail below.

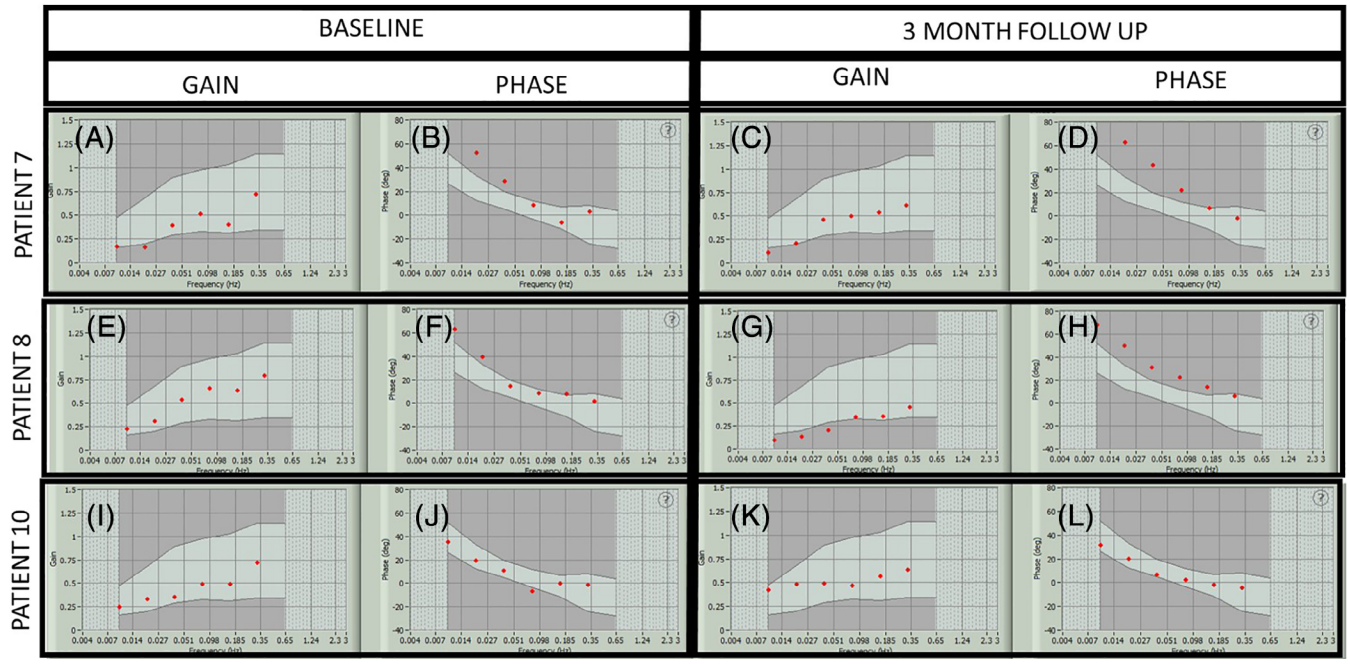
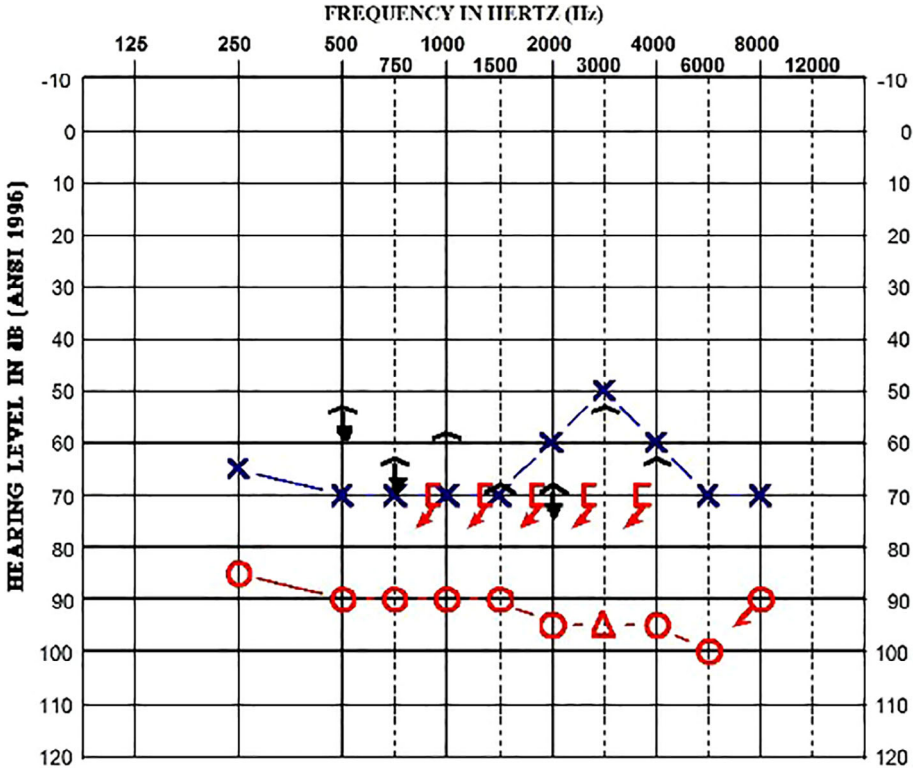


FIGURE 3 Preoperative and postoperative rotary chair results for participants 7, 8, and 10. (A) and (B) are the preoperative gain and phase values and (D) and (C) are the postoperative gain and phase values for Patient 7. (E) and (F) are the preoperative gain and phase values and (G) and (H) are the postoperative gain and phase values for Patient 8. (I) and (J) are the preoperative gain and phase values and (K) and (L) are the postoperative gain and phase values for Patient 10

FIGURE 4 Baseline audiogram for participant 8



3.3 | Statistical analyses

Group mean data, with mean difference between pre-op and post-op as well as 95% confidence intervals of the difference, are presented in Table 3.

Paired samples *t* tests were conducted for all normally distributed continuous outcome variables and showed no statistically significant differences between baseline pre-op vestibular test results and 3-month post-op vestibular test results. Specifically, there was no significant difference in the results of the caloric UW ($t = -.770$, $df = 9$, $P = .464$), total

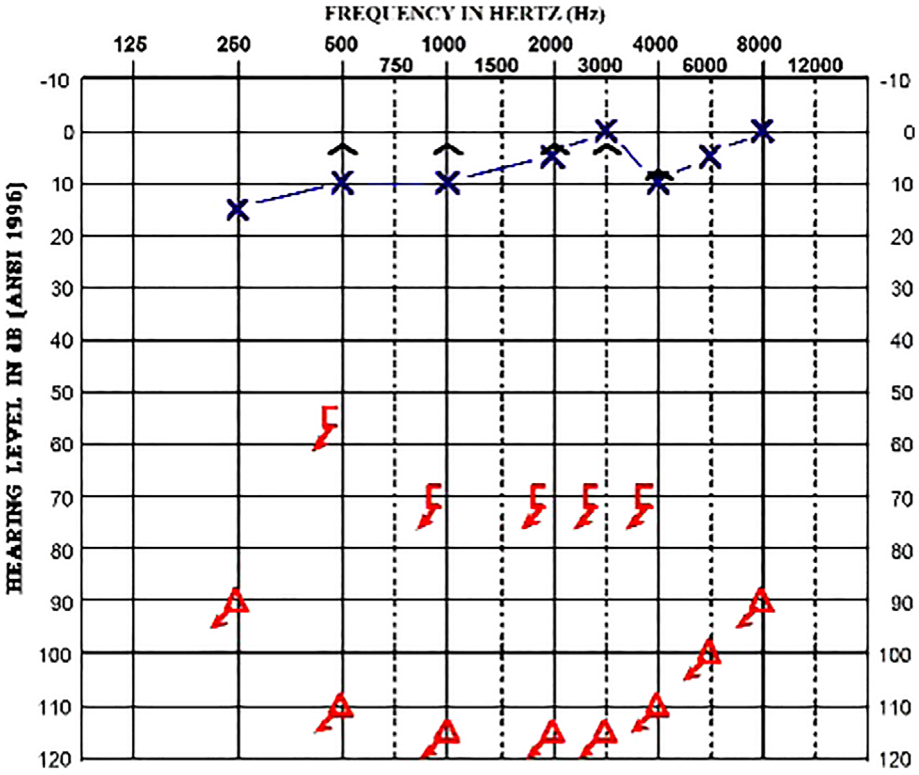


FIGURE 5 Baseline audiogram for participant 10

caloric response (t = 1.792, df = 9, P = 1.07) or for individual warm irrigations in the right ear (t = 1.078, df = 9, P = .309), or left ear (t = .674, df = 9, P = .517). There was no significant difference in the results from the rotary chair for either phase (t = .848, df = 8, P = .421) or gain (t = −.941, df = 8, P = .374) at 0.01 Hz. There was no significant difference in vHIT gain for the head thrusts to the right (t = −1.291, df = 9, P = .229) or to the left (t = −1.695, df = 9, P = .124). The Wilcoxon signed-rank test was used to assess the DHI scores and there was no significant difference (z = 1.826, P = .068).

4 | CASE STUDIES

4.1 | Participant 7

Participant 7 was an 85-year-old male with a known right sided vestibular schwannoma (1.9 cm) and a history of transient ischemic attack. His audiometric testing was consistent with profound hearing loss in the right ear and severe to profound hearing loss in the left ear. His preoperative baseline audiogram is shown in Figure 1. Given the right sided vestibular schwannoma, the left ear was implanted.

During the preoperative baseline caloric irrigations, there was no response to traditional warm and cool caloric irrigations in the right ear. Although there were responses in the left ear, the responses from both the warm and cool irrigations from the left ear only totaled 15°/sec. His preoperative baseline vHIT results are shown in Figure 2 and rotary chair results are shown in Figure 3. His preoperative baseline vHIT test results were abnormal, showing bilateral but asymmetrically (right poorer than left) reduced gain with corrective saccades. This was further corroborated by the rotary chair results showing reduced gain and an abnormally large phase leads at several frequencies. DHI scores were not obtained at baseline.

His 3-month postoperative follow-up results are also shown in Figures 2 and 3. Minimal nystagmus was generated in either ear during caloric testing. His vHIT results continued to show reduced gain with large corrective saccades bilaterally and his rotary chair continued to show grossly reduced gain and phase leads and multiple frequencies consistent with bilateral vestibular hypofunction. Surprisingly, his postoperative DHI score was 8 points, indicating no dizziness handicap. Thus, his vHIT and rotary chair tests consistently showed bilaterally reduced responses both pre-op and post-op, his caloric test results were significantly reduced after cochlear implantation, but the reduction in his caloric test results was not consistent with any other observed changes in function or his self-reported dizziness handicap.

4.2 | Participant 8

Participant 8 was a 56-year-old male with a diagnosis of bilateral Meniere's disease. His preoperative audiogram is shown in Figure 4. He was asymptomatic at the time of his preoperative baseline testing, which showed normal caloric results (12% UW on the right side), low frequency phase leads in an otherwise normal rotary chair study, normal vHIT gain, and a DHI of 4 points. His vHIT and rotary chair results are shown in Figures 2 and 3.

The patient underwent cochlear implantation on the right side. At his 3-month follow up he was symptomatic for dizziness and aural fullness in the *left* ear. His caloric irrigations showed a 46% UW in the left ear. As shown in Figures 2 and 3, rotary chair results continued to show low frequency phase leads but now also showed reduced VOR gain in the low frequencies, and corrective saccades were noted during head

impulses to the left; consistent with a vestibular impairment in the left ear. Without knowledge of the patient's history of bilateral Meniere's disease, the post-op finding of a vestibular impairment in the nonimplanted ear would be unexpected. The patient's history was needed to appropriately interpret these test findings.

4.3 | Participant 10

Participant 10 was a 39-year-old male with a history of profound sudden sensorineural hearing loss in the right ear with tinnitus and vertigo that occurred 1 year prior to cochlear implantation. He has normal hearing in the left ear (Figure 5).

At his pre-op baseline vestibular assessment, he was asymptomatic for dizziness. His caloric irrigations, vHIT, and rotary chair were all completely normal (Figures 2 and 3) and his DHI was 0 points.

At his post-op follow-up appointment, he demonstrated a clinically significant change in perceived handicap with a DHI of 24 points as well as a caloric weakness of 39% on the right side, the side of implantation. However, his vHIT and rotary chair continued to be within normal limits and unchanged (Figures 2 and 3).

5 | DISCUSSION

One of the major issues in testing vestibular function is that there is no gold-standard for a general population, and the lack of gold-standard extends to those who have undergone ear surgery. There are advantages and disadvantages to every available vestibular test in CI patients and many nonvestibular factors that affect vestibular test results. In the current study, we analyzed tests of the horizontal SCC using different methods (ie, descriptive, statistical, individual case studies), which all yielded a different interpretation. Statistical results suggest cochlear implantation using the MED-EL Flex28 has no significant effect on function of the horizontal SCC or on self-reported dizziness handicap at 3-months post-op. A more descriptive analysis tells a different story. That is, 30% (3/10) of patients presented with vestibular test results that were outside the range of normal in the post-op condition and suggestive of a post-CI vestibular impairment. A closer examination of those cases, including interpretation of results as a test battery (including case history), provides the context needed to interpret the vestibular test results. Only 1 participant (participant 10) showed a decrease in vestibular function in the implanted ear with a concomitant increase in dizziness handicap. The dizziness handicap was reportedly mild (24 points) and only the caloric test showed a significant change with vHIT and rotary chair results remaining unchanged and within normal limits. The full vestibular test battery suggests the impairment identified during caloric testing is statically and dynamically compensated.

Given the variability in vestibular test results and limitations of vestibular tests, investigators have looked to large systematic reviews and meta-analyses to help determine the extent of vestibular impairments post-CI and to define the best testing protocol for detecting vestibular impairments in CI recipients. Ibrahim et al. (2017) conducted a meta-analysis to determine the effects of CI surgery on vestibular function. Through a series of forest plots, they illustrated the great variability across studies, and they discussed the differences in the methodology, criteria to determine normal/abnormal, and differences in test techniques across studies. Ultimately, they concluded that CI surgery may affect the results of caloric testing and cVEMP testing more so than vHIT; but as stated previously, there are limitations to caloric and cVEMP testing in CI patients.[6]

Abouzayd et al. (2017) conducted a meta-analysis in an attempt to define the best testing protocol for the evaluation of vestibular function in CI patients. They calculated the true positive, false positive, true negative, and false negative values of various vestibular tests using patient-reported symptoms as the gold-standard. That is, if the patient reported symptoms then the test was classified as a true positive if it showed an impairment. If it did not, it was classified as a false negative. In asymptomatic patients, a normal test was classified as a true negative and an abnormal test was classified as a false positive. Using this classification, they determined the sensitivity of the caloric test to be 21%, the cVEMP to be 32%, and vHIT to be 50%.[8] However, the problem still remains that vestibular tests rarely correlate with patient symptoms, are tests of vestibular *function*, and have never been presented as tests of patient symptoms, so the significance of measuring sensitivity in this way is unclear. Further, within their meta-analysis, the authors were unable to control for time since surgery. This limitation would certainly impact the interpretation of symptom presentation which makes the classification scheme to determine sensitivity problematic. Finally, the authors reported great variability between studies in both methodology and results, and ultimately concluded that no single vestibular test is particularly sensitive in this population and that a battery of tests should be available on a case-by-case basis. Other recent reviews on the topic of vestibular function in CI patients also consistently report great variability between studies.[37-39]

The presented series of case studies provide evidence of the difficulty in interpreting vestibular tests in postoperative patients. The cases illustrate that group mean differences often miss significant findings in individual patients and how, in isolation, a single vestibular test cannot provide adequate information about the whole vestibular system. An examination of vHIT and rotary chair results show that patient 7 maintained a bilateral weakness pre-op and post-op and he reports no dizziness handicap. If only his caloric tests were obtained it may appear that the CI surgery resulted in new vestibular damage in the post-op condition. Participant 8 presented with seemingly conflicting findings where the nonimplanted ear showed a post-op impairment that was consistent across vestibular testing. Examination of the participant's case history (ie, bilateral Meniere's disease) explains these results, which were unrelated to the CI surgery. Participant 10 appears to have reduced vestibular function in the post-implant ear, but different tests of the horizontal SCC reveal different findings with calorics showing an impairment and vHIT and rotary chair showing normal results. It may be that the impairment is localized to the low frequencies, thus vHIT and rotary chair results remain normal, or

it may be that the caloric results are inaccurate due to the surgical ear. In either case, the DHI significantly changed, is within the range of mild, and the patient's symptoms need to be addressed. Thus, a combination of tests, in context of that specific patient, is needed to make a determination of vestibular function and its effect on the individual.

There are several limitations to the current study. First, the study utilized a small sample size and included patients with known vestibular impairments. Second, our testing focused on measures of horizontal semi-circular canal function and did not account for otolith function or the function of the vertical semicircular canals. These measures may have provided additional information that would have helped to clarify the clinical picture, especially since the saccule may be most at-risk during implantation due to its proximity to the cochlea. Third, our study completed follow up testing at 3 months. This time frame neither reflects an immediate/acute postoperative period nor does it reflect the long-term follow-up period. The time postoperative testing is completed is an important consideration as the central compensation mechanisms will reduce symptoms associated with an acute change in vestibular function. Fourth, the attrition rate of our study was high. Even though 14 out of 16 participants returned for post-op testing, only 10 participants elected to complete all the assessments. Fifth, our study did not utilize any measures of physical function (eg, dynamic visual acuity, measures of balance and gait) that may have provided evidence for functional impacts associated with vestibular changes due to cochlear implantation.

6 | CONCLUSION

Given the limitations of conventional vestibular testing in a postsurgical population, a test-battery, including case history, and a case-by-case approach is needed to determine whether the patient is at risk for falling or in need of treatment. At this time, patient report may be the best clinical indicator because if the patient is not symptomatic nor functionally impaired, they will probably not undergo management or treatment. That is, the majority of patients will not need vestibular testing post-CI, but those who present with vestibular or balance symptoms may need an assessment consisting of a battery of tests and a thorough case history. However, patient-reported symptoms and self-reported handicap may underestimate the true prevalence of vestibular dysfunction due to central compensation mechanisms, leaving gaps in knowledge regarding vestibular physiology in post-implanted ears. Future studies should examine alternative measures that go beyond reflex testing and are not subject to postsurgical anatomical changes, such as vestibular psychophysics and more systematic quantification of motion perception, as these measures have potential to yield new and insightful information in this population.

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CONFLICT OF INTEREST

The authors report no financial or nonfinancial conflicts of interest.

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