Impact of Cochlear Implantation on Canal and Otolith Function

*Belinda Y. C. Kwok, *†Sally M. Rosengren, ‡§||Jonathan H. K. Kong, ‡¶#**Catherine S. Birman, †Emma Hoskisson, ††Allison S. Young, *††Emma C. Argaet, ††Luke Fratturo, ††Cheryl Rivas, ‡‡Simon L. Greenberg, §||Alex J. Saxby, and *†Miriam S. Welgampola

*Central Clinical School, Faculty of Medicine and Health; †Department of Neurology and Institute of Clinical Neurosciences; ‡Department of Otolaryngology, Royal Prince Alfred Hospital; §Discipline of Surgery, Sydney Medical School; ||Department of Otolaryngology, Head and Neck Surgery, Macquarie University, North Ryde; ¶Faculty of Medicine and Health, University of Sydney, Camperdown; #Sydney Cochlear Implant Centre, Royal Institute of Deaf and Blind Children, Gladesville, NSW; **Department of Clinical Medicine, Macquarie University, North Ryde; ††The Balance Clinic and Laboratory, Sydney; and ‡‡Department of Otolaryngology, St George Hospital, Kogarah, Australia

Objective: To quantify the impact of cochlear implantation (CI) on all five vestibular end-organs and on subjective ratings of post-CI dizziness.
Methods: Seventy-two patients undergoing unilateral CI were recruited for the study. All participants completed pre- and post-CI three-dimensional video head-impulse tests (3D vHITs) to assess semicircular-canal (SC) function, air- and bone-conducted (AC and BC) cervical and ocular vestibular-evoked myogenic potentials (cVEMPs and oVEMPs) to assess otolith-function and the dizziness handicap inventory (DHI) to measure self-perceived disability.
Results: Nineteen percent of patients reported new or worsened dizziness postsurgery. Post-CI abnormalities (new lesions and significant deteriorations) were seen in the AC cVEMP (48%), AC oVEMP (34%), BC cVEMP (10%), and BC oVEMP (7%); and lateral (L) (17%), posterior (P) (10%), and anterior (A) (13%) SC vHITs. CI surgery was more likely to affect the AC cVEMP compared with the other tests (χ^2 test, $p < 0.05$). Fifty percent of patients reported no dizziness pre- and postsurgery. In the implanted ear, normal pre-CI vHIT gain was preserved in lateral semicircular canal (LSC) (69%), anterior semicircular canal (ASC) (74%), and posterior semicircular canal (PSC) (67%), and normal reflex amplitudes were found in AC cVEMP (25%), AC oVEMP (20%), BC cVEMP (59%), and BC oVEMP (74%). Statistically significant decreases were observed in LSC vHIT gain, AC cVEMP amplitude, and AC oVEMP amplitude postsurgery ($p < 0.05$). There was a significant moderate positive correlation between change in DHI scores and the summed vestibular deficit postsurgery ($r_{(51)} = 0.38$, $p < 0.05$).
Conclusion: CI can impact tests that assess all five vestibular end-organs and subjective ratings of dizziness. These results support pre and post-surgical vestibular testing and assist preoperative counseling and candidate selection.
Key Words: Canal and otolith function—Cochlear implantation—Dizziness handicap inventory—Vestibular function—Video head impulse testing.

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Cochlear implantation (CI) represents an effective and life-changing intervention for individuals with moderately-severe to profound sensorineural hearing loss. While much is known about the effects of CI on residual cochlear function, little is known about the impact on vestibular function.

The vestibular system is made up of three angular accelerometers (semicircular-canals: SCs) and two gravity sensors (otolith organs). It stabilizes the visible world upon the retina by fast oligosynaptic connections with the extraocular muscles (vestibulo-ocular reflex: VOR). It also supports a range of balance activities from the very simple to the complex by powerful oligo- and polysynaptic projections to the neck, trunk, and limbs (vestibulospinal reflexes: VSR). Due to the anatomical proximity of the cochlea and vestibular end-organs, vertigo and imbalance have been reported post-CI surgery with prevalence rates ranging from 0 to 32% (1–4).

Existing literature has examined the impact of CI on vestibular function through objective methods such as the

Address correspondence and reprint requests to Miriam S. Welgampola, Ph.D., Institute of Clinical Neurosciences, Royal Prince Alfred Hospital, Central Clinical School, University of Sydney, Sydney, Australia; E-mail: miriam@icn.usyd.edu.au

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cervical vestibular-evoked myogenic potential (cVEMP), caloric testing, clinical head impulse test (cHIT), and sclerical HIT with diverse outcomes. Colin et al. (5) reported abnormal cHIT, lateral canal hypofunction on caloric testing and absent cVEMPs in the implanted ear postsurgery in 59, 58, and 86% of patients respectively. Conversely, Melvin et al. (1) reported a significant drop in caloric testing, saccular function, and sclerical HIT gain for all three SCs for 6.3, 31, and 3.6% of patients respectively. Studies have also examined changes in subjective perceptions of dizziness pre- and post-CI via the dizziness handicap inventory (DHI) reporting both increases (worsening) and decreases (improvements) in dizziness handicap postsurgery (1,6). However, there is no clear correlation between the DHI and outcomes of objective balance tests (7). The recent introduction of three-dimensional video HIT (3D vHIT) has made it possible to efficiently assess the integrity of all three SCs (6). It also presents as a viable alternative to the gold standard caloric testing, with Bassaletti et al. (8) showing that caloric testing could be avoided in 46% of cases when using their newly defined vHIT parameter evaluating vHIT gain and saccade presence.

Given the increasing numbers of cochlear implants performed in all age-groups and the rise of bilateral implantation, there is an interest and need to quantify the full effects of CI on the entire vestibular system. Thus, the current study aims to evaluate the impact of CI on all five vestibular end-organs and subjective DHI scores and explore the relationship between subjective symptoms and objective measures of vestibular loss. These findings will be valuable in guiding pre- and post-surgical counseling and rehabilitation of cochlear implant recipients.

MATERIALS AND METHOD

Patients undergoing unilateral CI were recruited from the neuro-otology outpatient clinic, Royal Prince Alfred Hospital from November 2013 to September 2019 (Sydney, Australia). The study was approved by the local ethics committee (Protocol X18-0087) and conducted in accordance with the Declaration of Helsinki. Written informed consent was obtained from 55 patients and data from 17 patients were included as per existing waiver of consent.

Surgery was conducted by one of four surgeons (authors J.K., C.B., S.G., and A.S.). The standardized round window (RW) approach was used consisting of a normal mastoidectomy with posterior tympanotomy, followed by RW insertion after removal of the RW lip. Cochleostomy was performed in one patient. Cochlear and MED-EL branded implants with different electrode arrays were inserted according to the patient's requirements.

All patients completed the DHI (9) and balance assessment comprising of 3D vHITs and air- and bone-conducted (AC and BC) cervical and ocular VEMPs (cVEMP and oVEMPs) before and after surgery. Patients undergoing explant/reimplantation were excluded from the study. Only the implanted ear was analyzed.

Equipment and Materials

DHI

The DHI was administered pre- and postsurgery. Patients were instructed to answer each item as it pertains to any problems of dizziness. The total DHI score was calculated by assigning scores of four, two, or zero for answers, ''yes,'' ''sometimes,'' or ''no,'' respectively. The total DHI score ranges from 0 to 100 with scores categorized as follows: 16 to 34 (mild handicap); 36 to 52 (moderate handicap); and greater than 54 (severe handicap).

vHIT

vHIT testing was performed to assess the function of all three SCs. The standardized testing protocol was conducted using ICS Impulse (GN Otometrics, Taastrup, Denmark) video goggles and OTOsuite Vestibular Software Version 4.00. Twenty head impulses were conducted in each SC plane, for both ears.

VEMPs

cVEMPs (saccular function) and oVEMPs (utricular function) were recorded using a Medelec Synergy EMG system (ViasysHC, Old Woking, UK) and software (version 15). The protocol has previously been detailed by Taylor et al. (10). VEMPs were recorded in response to AC and BC stimuli. AC stimuli were 0.1 ms clicks of alternating polarity presented at 140 dB peak-SPL monaurally through TDH-49 headphones at a rate of 5/s. BC stimuli were 1 ms vibration-pulses of condensation polarity, 20 V peak amplitude, delivered to the forehead (Fz) with a Bruel and Kjaer 4810 minishaker at a rate of 5/s. cVEMP amplitudes were reported as corrected amplitudes (CA), i.e., raw peak-to-peak amplitude divided by sternocleidomastoid muscle contraction (refer to Taylor et al. (10)), and oVEMP peak-to-peak amplitudes were measured in microvolts (μV).

For cVEMPs, a minimum run of 125 AC clicks and 100 BC skull taps were administered. For oVEMPs, a minimum run of 100 AC clicks and 50 BC skull taps were administered. For all VEMPs, if initial recordings were poor, a second run was conducted, and the better waveform selected for analysis.

Data Analysis

For the DHI, a score indicating a mild handicap or above was classified as abnormal. A change in total DHI score of 18 points or more was accepted as a reliable change (9) and will be referred to as ''significant'' in future.

vHIT and VEMP data were analyzed for the implanted ear only. The lower limit of normal gain for vHIT, was calculated with respect to age, ear, and canal based on data reported in Pogson et al. (11), see supplementary table 1, http://links.lww.com/MAO/B395. A reliable change in gain post-CI was defined as a gain change greater than two standard deviations (SD) for each canal. These values are listed in supplementary table 1, http://links.lww.com/MAO/B395 as the ''significant gain change value.'' A decrease/increase in gain exceeding these values will be referred to as a significant deterioration/improvement in future. However, any significant change in gain in which both values were within the normal range was considered an artefact of goggle slip or visual acuity and was not counted as a significant change.

Abnormal VEMPs were those with low amplitude compared with laboratory normal data in normal control subjects, or those which were absent. For cVEMPs the cutoff value was less than 0.5 CA and oVEMPs were either absent or present ($>0\ \mu$V). Peak latency was not included as a test variable. To determine a reliable change in VEMP amplitudes postsurgery we calculated the degree of percentage change in VEMP amplitudes in the non-implanted ear across the two test sessions (amplitude change/pre-op amplitude $\times$ 100) and computed the 95th percentile of these scores. A percentage change in the VEMP amplitudes of the implanted ear exceeding this value was considered a significant decrease/improvement in VEMP amplitude.

Data was analyzed using SPSS version 26 (IBM Corp 1989, 2019). We conducted paired samples *t* tests to examine statistically significant changes in the seven vestibular function tests (VFTs) pre- and postsurgery and a χ^2 test to determine whether the frequency of new lesions postsurgery differed across the seven VFTs. To examine the prevalence of new vestibular deficits across the VFTs, we ascribed a value of 1 where there was a deficit and 0 where there was none. The total number of deficits was summed to arrive upon a summed vestibular deficit, with seven representing a new abnormality affecting all seven tests. Pearson's correlation coefficient was used to examine the relationship between change in DHI scores and the summed vestibular deficit postsurgery. A significance level of 0.05 was applied in all analyses. Changes in the seven VFTs postsurgery were categorized as no change (0 abnormal VFTs), mild change (1–2 abnormal VFTs), moderate change (3–4 abnormal VFTs), and severe change (5–7 abnormal VFTs).

RESULTS

Demographics

Seventy-two patients were recruited for the study (29F, 43M; aged 59 ± 16 years at the time of postoperative testing). Causes of hearing loss are listed in Table 1. Surgery was performed in the right ear (50%) and left ear (50%). Electrode array type was known for 40 of the 72 patients: 83% lateral wall electrodes and 18% perimodiolar arrays (supplementary table 2, http://links.lww.com/MAO/B396). Postoperative assessments were conducted at a mean of 197 days postsurgery (range, 15–1191 days, median: 105 days, 75th percentile: 7 months). To reduce inhomogeneity, sub-analyses were conducted for those who had postoperative assessment within 3 months and 1 year of surgery (Table 2). While the DHI scores demonstrated changes as described below, most VFT results remained comparable for all time windows.

TABLE 1. *Hearing loss etiologies*

Etiology	Number of Patients	Percentage (%)
AIED	1	1%
Bilateral LVAS + Menière's disease	1	1%
Codeine	1	1%
Congenital hearing loss	7	10%
LVAS	4	6%
Menière's disease	8	11%
NIHL + progressive SNHL	7	10%
Otosclerosis	1	1%
Progressive SNHL	10	14%
Radiation therapy	3	4%
SSNHL	9	13%
SSNHL and vertigo	6	8%
Stapedectomy	1	1%
Trauma	1	1%
Unknown	10	14%
Vestibular schwannoma	2	3%

AIED indicates autoimmune inner ear disease; LVAS, large vestibular aqueduct syndrome; NIHL, noise induced hearing loss; SNHL, sensorineural hearing loss; SSNHL, sudden sensorineural hearing loss.

DHI

Fifty-seven patients completed the DHI pre- and postsurgery. The mean DHI scores pre- and postsurgery were 17 and 20 points respectively. Fifty percent of patients reported no dizziness both pre- and postsurgery; 19% experienced new or worsened dizziness postsurgery at the mild level or above (32% for those within 3 months and 22% for those within 1 year of surgery); and 25% showed a significant change for better or worse in DHI scores postsurgery.

Of those that showed a significant change (15 patients), nine demonstrated increased DHI scores (increased handicap) postsurgery. Six of the nine patients reported a new occurrence of at least mild dizziness postsurgery (range pre: 0–10, post: 28–60) and three demonstrated an enhancement of pre-existing subjective dizziness (range pre: 38–46, post: 58–66). The mean increase of DHI scores across these nine patients was 36 ± 6 points. Six of the 15 patients demonstrated a decrease in DHI scores (reduced handicap) postsurgery. Of these, three changed from reporting mild handicap to no significant dizziness; one from moderate to mild; and two from severe to moderate. The mean decrease of DHI scores across these subjects was 22 ± 3 points.

Six patients showed a dissociation between subjective and objective vHIT findings (Fig. 1). Five of these patients experienced new or worsened dizziness postsurgery but reported normal/improved function on two or more of the SC tests. This suggests that vestibular function tests are not the sole contributor to subjective reports of dizziness. Conversely, one patient showed significantly improved dizziness postsurgery but had new abnormalities on all three SCs. This patient has Menière's disease and experienced labyrinthectomy during CI surgery. Ablation of the vestibular end-organs thus served to improve subjective reports of dizziness.

VFT Overview

Thirty-nine percent of patients showed no change in VFTs postsurgery; 44% showed a mild change, 13% showed a moderate change, and 4% showed a severe change. New abnormalities postsurgery (new lesions and significant deteriorations) were seen in the following proportions for each test: 48% (AC cVEMP), 34% (AC oVEMP), 17% (lateral semicircular canal [LSC]), 10% (posterior semicircular canal [PSC]), 13% (anterior semicircular canal [ASC]), 10% (BC cVEMP), and 7% (BC oVEMP) of patients. Excluding the patients that had absent VEMPs before surgery, new abnormalities were: AC cVEMPs and AC oVEMPs (72%), followed by BC cVEMPs (13%) and BC oVEMPs (9%). χ^2 testing showed a significant difference in frequency of abnormalities across the seven VFTs ($\chi^2 = 35.70, p < 0.05$). Assessment

TABLE 2. *Sub-analysis for those that had postoperative assessment within 3 months and 1 year compared with the entire group*

	n			% New Abnormalities		
	3 months	1 year	Entire Group	3 months	1 year	Entire Group
DHI	19	45	57	32	22	19
AC cVEMP	23	59	71	48	49	48
AC oVEMP	23	56	68	35	36	34
BC cVEMP	23	58	70	4	10	10
BC oVEMP	23	60	72	4	8	7
LSC	23	60	72	13	17	17
ASC	23	60	72	13	15	13
PSC	23	60	72	13	12	11

AC cVEMP indicates air-conducted cervical evoked myogenic potential; AC oVEMP, air-conducted ocular evoked myogenic potential; ASC, anterior semicircular canal; BC cVEMP, bone-conducted cervical evoked myogenic potential; BC oVEMP, bone-conducted ocular evoked myogenic potential; DHI, dizziness handicap inventory; LSC, lateral semicircular canal; PSC, posterior semicircular canal.

of the adjusted residuals showed that CI surgery is more likely to affect the AC cVEMP compared with the other VFTs, which showed similar abnormalities to each other. Statistically significant decreases in function postsurgery were observed for the LSC (mean change: 0.07 gain; Cohen's $D = 0.26$), AC cVEMP (mean change: 0.60 CA; Cohen's $D = 0.85$), and AC oVEMP (mean change: 3.47 μV; Cohen's $D = 0.66$). Overall, normal function presurgery remained unchanged in the following proportions: 69% (LSC), 74% (ASC), 67% (PSC), 25% (AC

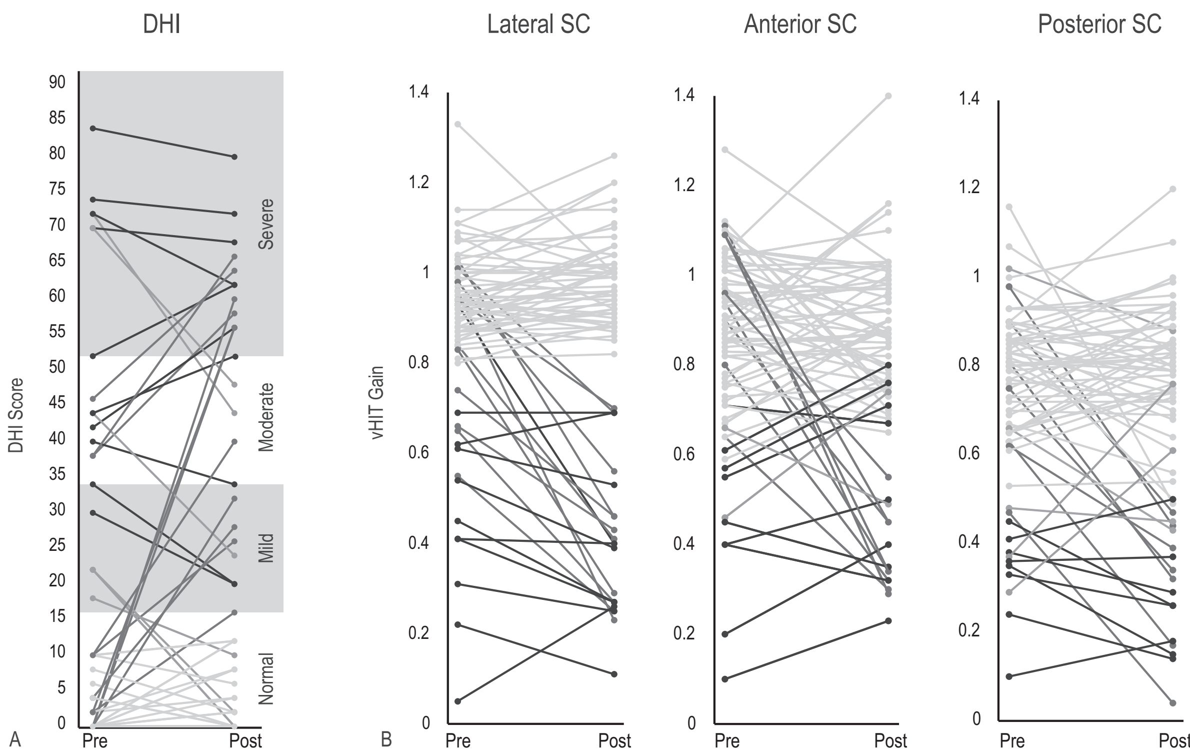

FIG. 1. Individual DHI scores and vHIT gain pre- and postsurgery. *A*, Individual DHI scores pre- and postsurgery (n = 57). Blue lines indicate patients who showed no dizziness handicap; red lines indicate those who reported a new occurrence of dizziness/a significant increase in pre-existing dizziness as demonstrated by a significant increase in DHI scores (increased handicap); green lines indicate those who showed a significant decrease in DHI scores (reduced handicap)/return to no handicap; and black lines indicate those who had pre-existing dizziness which remained relatively unchanged postsurgery. *B*, Individual vHIT gain scores across all three SCs pre- and postsurgery (n = 72). Blue lines indicate patients who showed normal function pre- and postsurgery. Red lines indicate patients who acquired a new lesion postsurgery/who experienced a significant deterioration of pre-existing dysfunction; orange lines indicate patients who acquired a new lesion postsurgery but did not demonstrate a significant change; green lines indicate those who showed a significant improvement; and black lines indicate those who had pre-existing dysfunction and demonstrated no significant change post-surgery. DHI indicates dizziness handicap inventory; vHIT, video head-impulse tests.

cVEMP), 20% (AC oVEMP), 59% (BC cVEMP), and 74% (BC oVEMP) of patients.

vHIT

Twelve patients (17%) experienced a significant deterioration in LSC function postsurgery (mean gain reduction: 0.41 ± 0.15). Of these, eight acquired new lesions and four had a significant deterioration of a pre-existing dysfunction (Fig. 1B).

Eight patients (11%) experienced a significant deterioration in ASC function postsurgery (mean gain reduction 0.56 ± 0.17). This excludes one patient who acquired new lesions postsurgery but did not show a significant change (e.g., normal gain of 0.66 presurgery which decreased to an abnormal gain of 0.49 postsurgery). Seven of these patients acquired new lesions and one displayed a significant deterioration of a pre-existing dysfunction. Interestingly, one patient showed a significant improvement and regained normal ASC function. However, this patient sustained posttraumatic hearing loss and a fractured cochlea presurgery. Thus, this improvement may reflect spontaneous recovery of the vestibular end-organs rather than a positive effect of cochlear implantation.

Seven patients (10%) experienced a significant deterioration in PSC function postsurgery (mean gain reduction 0.43 ± 0.10). This excludes three patients who acquired new lesions postsurgery but did not show a significant change. Six of the seven patients acquired new lesions and one a significant deterioration of a pre-existing dysfunction. Interestingly, two patients (3%) with pre-existing dysfunction showed significant improvement postsurgery, regaining normal posterior SC function. One patient had a diagnosis of endolymphatic hydrops and the other hearing loss of unknown origin.

AC cVEMP

Thirty-four patients (48%) demonstrated a significant decrease in cVEMP peak-to-peak amplitude. Twenty-seven of the 35 patients experienced complete AC cVEMP loss postsurgery (mean change: 1.1 ± 0.5 CA). Eight of the 35 patients demonstrated a significant decrease in AC cVEMP amplitude (mean change: 1.19 ± 2.33 CA). Twenty-four patients (36%) had absent AC cVEMPs presurgery which remained unchanged postsurgery. Two patients appeared to regain AC cVEMP function postsurgery. However, these cVEMP reflexes were small (0.4 CA) and it is possible that the stimulus intensity was close to their reflex thresholds on both occasions (Fig. 2).

BC cVEMP

Seven patients (10%) experienced complete BC cVEMP loss postsurgery. Sixteen patients (23%) had absent BC cVEMPs presurgery which remained unchanged postsurgery. Six patients (10%) regained normal BC cVEMP function postsurgery. Amongst 40 patients (56%) with present BC cVEMPs pre- and postsurgery three patients demonstrated a significant improvement in BC cVEMP amplitude (mean change: 1 ± 0 CA) and no patients experienced a significant deterioration (Fig. 2).

AC oVEMP

Eighteen patients (26%) experienced complete loss of the AC oVEMP reflex postsurgery. Thirty-seven (54%) patients had absent AC oVEMPs presurgery which remained unchanged postsurgery. Twelve patients (17%) had present AC oVEMPs pre- and postsurgery. Of these, five experienced a significant decrease in AC oVEMP amplitude (mean change: $10.06 \pm 5.80\ \mu V$). No patients showed an improvement in AC oVEMP amplitude postsurgery (Fig. 2).

BC oVEMP

Five patients (7%) experienced complete BC oVEMP loss postsurgery. Fourteen patients (19%) had absent BC oVEMPs presurgery, which remained unchanged postsurgery. Amongst 54 (74%) patients with present BC oVEMPs pre- and postsurgery, six patients experienced a significant improvement in BC oVEMP amplitude (mean change: $11.65 \pm 5.21\ \mu V$) with no patients demonstrating a significant deterioration (Fig. 2).

Relationship between DHI and VFTs

There was a significant moderate positive correlation between change in DHI scores and the summed vestibular deficit postsurgery, $r_{(51)} = 0.38$, $p < 0.05$. As the number of VFT deficits increased, DHI scores (worsened handicap) also increased.

Fourteen patients (19%) with paired data for all seven VFTs recorded a significant change in DHI scores postsurgery (Table 3). Eight of these patients (57% of the sample) experienced a deterioration in handicap. All these patients experienced vestibular loss postsurgery with four showing a mild change in VFTs postsurgery, three a moderate change, and one a severe change. New lesions postsurgery were most prevalent for AC cVEMP (five patients); followed by AC oVEMP (four patients); LSC and ASC (both three patients); BC cVEMP and BC oVEMP (both two patients); and PSC (one patient).

Six patients (43% of the sample) demonstrated an improvement in DHI scores postsurgery. Of these, three patients showed no change across all seven VFT results postsurgery, one regained normal ASC and PSC function postsurgery (patient 9); one acquired new lesions on both AC cVEMP and AC oVEMP (patient 14); and one acquired new lesions on all VFTs postsurgery except the BC cVEMP and AC oVEMP (patient 10, Fig. 3). This patient had a diagnosis of Menière's disease and it is possible that surgery served to ablate the vestibular end-organs and reduce subjective reports of dizziness/vertigo.

Thirty-nine (54%) patients demonstrated no significant change in the DHI scores postsurgery (see supplementary table 3, http://links.lww.com/MAO/B397). Of these, 28% showed no change in VFTs postsurgery, 62% mild change, 8% moderate change, and 3% severe change. In this group, new lesions post-surgery were 11% (AC cVEMP), 10% (AC oVEMP), 9% (PSC vHIT), 8% (LSC vHIT), 2% (ASC vHIT), and 1% (BC cVEMP and BC oVEMP).

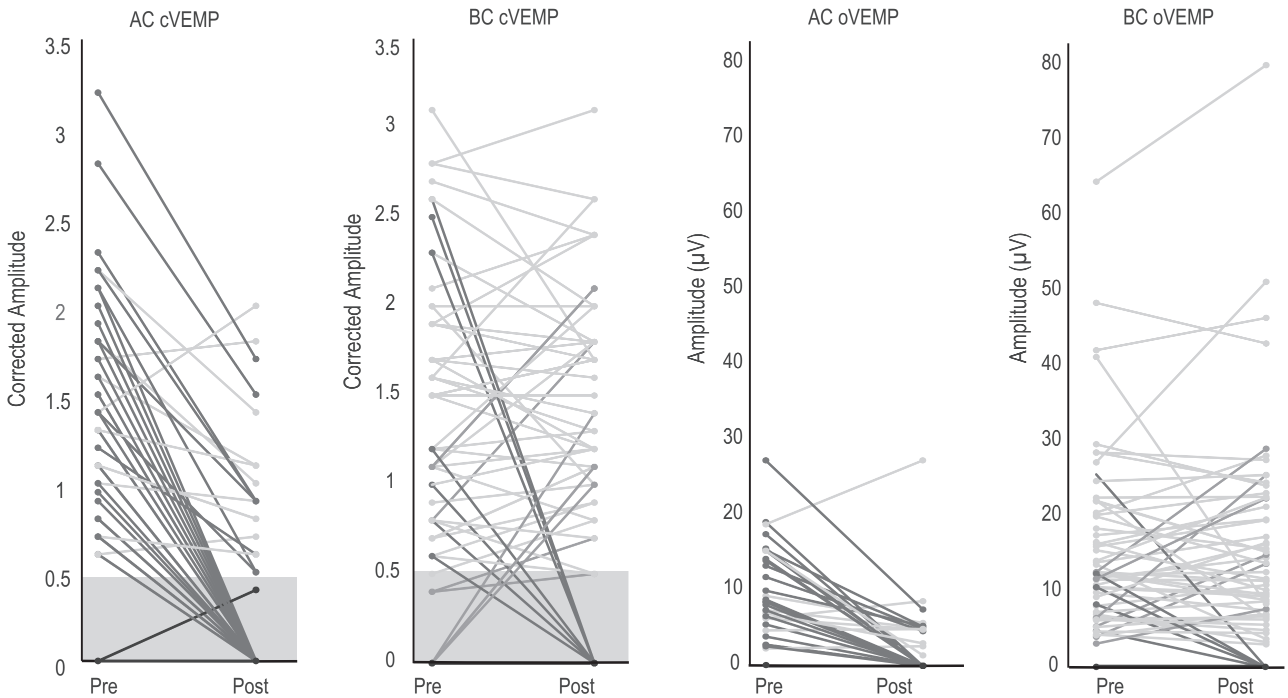

FIG. 2. Individual VEMP amplitudes pre- and postsurgery. Blue lines indicate patients who showed normal function pre- and postsurgery. Red lines indicate patients who experienced complete loss postsurgery/a significant decrease in VEMP amplitude; green lines indicate those who showed a significant increase in VEMP amplitude or regained normal function; and black lines indicate patients who had pre-existing dysfunction and demonstrated no significant change postsurgery. The grey shaded area indicates cVEMP amplitudes that were abnormal. For each test, the numbers of patients with paired data recorded were: AC cVEMP (n = 71), BC cVEMP (n = 70), AC oVEMP (n = 70), BC oVEMP (n = 72). AC indicates air-conducted; BC, bone-conducted; cVEMPs, cervical vestibular-evoked myogenic potentials; oVEMPs, ocular vestibular-evoked myogenic potentials.

DISCUSSION

Cochlear implant surgery has an impact on both subjective ratings of dizziness and objective vestibular end-organ function. Postsurgery, 19% of patients experienced new or worsened reports of dizziness. These results are comparable to Zawai et al. (12) and Kubo et al. (13) who reported new post-CI onset rates of vertigo of 10 and 16%

TABLE 3. *Detailed view of patients with a significant (≥18 points) deterioration or improvement in the dizziness handicap inventory (DHI) and corresponding vestibular test impairment postsurgery*

Patient ID	Age	Etiology	DHI	LSC vHIT	ASC vHIT	PSC vHIT	AC cVEMP	BC cVEMP	BC oVEMP	AC oVEMP
1	78	Menière's disease	54 ↑	A	A	N	A	PD	PD	PD
2	58	NFC radiation therapy	28 ↑	PD	N	A	PD	PD	PD	PD
3	83	Progressive SNHL	18 ↑	N	N	N	N ↑	N ↑	N	A
4	49	SSNHL	20 ↑	N	A	N	PD	N	N	PD
5	62	SSNHL and Vertigo	24 ↑	N	N	N	A	N	N	A
6	78	Unknown	32 ↑	PD	A	N	A	A	A	A
7	49	Unknown	60 ↑	A	N	N	A	A	N	A
8	55	Vestibular Schwannoma	30 ↑	N	N	N	A	PD	A	PD
9	38	Menière's disease	20 ↓	A	A	A	A	A	A	PD
10	45	Menière's disease	28 ↓	N	N	N	N	N	N	N
11	73	Progressive SNHL	22 ↓	N	N	N	PD	N	N	PD
12	45	SSNHL	20 ↓	N	N	PD	A	N	N	A
13	25	Trauma	22 ↓	PD	N ↑	N ↑	PD	PD	PD	PD
14	72	Unknown	22 ↓	PD	PD	PD	PD	PD	PD	PD

(xx)↑ indicates increase in DHI scores by (xx) points indicating a significant deterioration in dizziness handicap; (xx)↓, decrease in DHI scores by (xx) points indicating a significant improvement in dizziness handicap; A, new abnormality; AC cVEMP, air-conducted cervical evoked myogenic potential; AC oVEMP, air-conducted ocular evoked myogenic potential; ASC, anterior semicircular canal; BC cVEMP, bone-conducted cervical evoked myogenic potential; BC oVEMP, bone-conducted ocular evoked myogenic potential; DHI, dizziness handicap inventory; LSC, lateral semicircular canal; N, Normal; N↑, regain normal function from pre-existing dysfunction; PD, Pre-existing dysfunction; PSC, posterior semicircular canal; SNHL, sensorineural hearing loss; SSNHL, sudden sensorineural hearing loss.

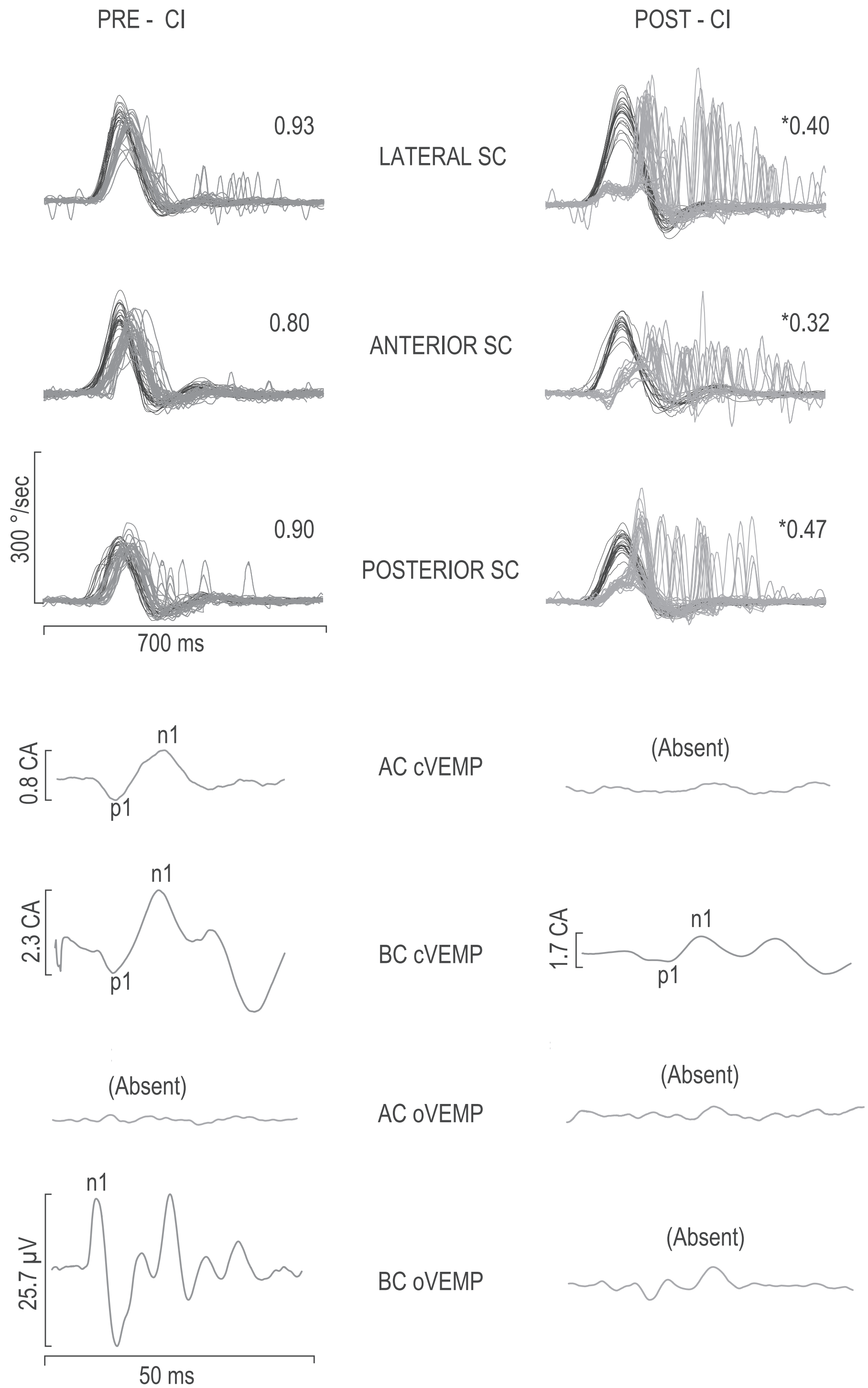

FIG. 3. Patient 10: vHIT and VEMP results pre- and postsurgery. Results show essentially normal vestibular-end organ function (except AC oVEMP) presurgery. Postsurgery abnormal vHIT gains are recorded for all three SCCs and all VEMPS are absent except the BC cVEMP which was preserved. Blue traces indicate normal function and orange traces indicate abnormal function. AC indicates air-conducted; BC, bone-conducted; cVEMPs, cervical vestibular-evoked myogenic potentials; oVEMPs, ocular vestibular-evoked myogenic potentials.

respectively, predominantly mild in nature. However, six of our patients showed significant subjective improvements. Stultiens et al. (14) also reported improved DHI scores post-CI in 13 of their 144 patients. Two of our improvers had Menière’s disease and one experienced labyrinthectomy during CI surgery. Thus, ablation of the vestibular end-organs may have led to complete abolition of vertigo and reduction in dizziness handicap. Another improver regained ASC and PSC function postsurgery. This patient had hearing loss due to trauma and it is possible that their improvement is due to spontaneous recovery.

All three SCs were affected by CI surgery. New abnormalities (new lesions and significant deteriorations) were observed in LSC (17%), ASC (13%), and PSC (10%). To our knowledge, only two other studies (6,14) have reported vHIT results for all three SCs in cochlear implant recipients. Unlike Dagkiran, et al. (6) who reported the PSC (11.9%) to be more affected than LSC (7.1%) at 3 days postsurgery with RW insertion, our results concur more with Stultiens et al. (14) who observed that all three SCs were equally affected at a mean follow-up interval of 7.9 months (insertion technique unspecified). Whether electrode insertion technique could account for these differences is unknown. When comparing RW and cochleostomy approaches, Todt et al. (4) showed that the RW approach was better at preserving vestibular function as measured by caloric and AC VEMPs, while Korsager et al. (15) demonstrated no significant difference in vHIT and DHI results with either approach. Discrepancies could therefore be due to variations in mean follow up time postsurgery and different criteria used to determine normal/abnormal results. A strength of the current study is the use of local normative data for all tests including age-, side-, and canal-specific norms for the vHIT. We also used objective methods for determining partial deterioration (or improvement).

The present study recorded both cVEMPs and oVEMPs to both AC and BC stimuli in a large group of CI recipients. Existing literature has mainly focused on examining cVEMP function using AC stimuli, revealing significant impacts of CI surgery on saccular function (6,16,17). When we excluded patients who had absent VEMPs before surgery, the proportion of patients with new abnormalities were equally high for AC cVEMPs and AC oVEMPs (72%). Temporal bone studies of implanted ears (18) showing the saccule to be most affected post-CI surgery suggests increased saccular dysfunction due to anatomical proximity to the round window. However, other studies purport the creation of an ''air-bone gap'' postsurgery rather than a true vestibular loss (19). Since AC cVEMPs are considered a predominantly saccular test and AC and BC oVEMPs are predominantly utricular tests (20,21), the equal impact on AC VEMPs and relative preservation of BC VEMPs postsurgery favors conductive losses as the chief mechanism of apparent otolith dysfunction.

Study Limitations

Postoperative testing was conducted at a mean of approximately seven months. During this period, patients could have acquired other new vestibular disorders making it challenging to isolate changes in vestibular end-organ function from CI surgery itself. However, at 3 months and one year, the percentage prevalence of abnormal VFT results were comparable. Patients also had a wide range of hearing loss etiologies, some of which could impact vestibular function before and/or after surgery (e.g., Menière's disease, vestibular schwannoma, and radiotherapy). To account for this, we only examined significant changes in DHI and vestibular end-organ function in those that had pre-existing dysfunction.

CONCLUSION

CI can have an impact on tests that interrogate all five vestibular end-organs and on subjective ratings of dizziness handicap. New or worsened reports of dizziness occurred in 19% of patients; the three SCs were relatively equally affected and AC VEMPs were more likely to be affected compared with BC VEMPs. These results provide a comprehensive overview of the impact of CI on vestibular function and will be valuable in guiding pre- and postoperative counseling. Future studies should examine the interactions between vestibular dysfunction and age/hearing loss etiology to further assist CI candidate selection and counseling.

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