

Does cochlear implantation influence vestibular function and balance control?

(overview essay)

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***Abstract:** The contribution presents a literary review of the facts about cochlear implantation (CI) in association to balance control from studies over the past 5 years. CI has the potential risk for vestibular system and its functions. The vestibular system plays the main role in balance tasks, f. e. postural control, balance and spatial orientation. Vestibular problems have been reported after CI, but the literature indicates major discrepancies in the reported clinical impact. The aim of the contribution is to summarize studies that ask whether CI has an undesirable, improved or any impact on vestibular function and balance control.*

***Keywords:** cochlear implantation, vestibular function, balance, postural stability*

1 Introduction

The peripheral auditory analyzer, the inner ear, is stored in the temporal bone. It is a tube twisted into a rising spiral. The human ear snail has 3.5 threads and a length of 35 mm. The spiral tube is longitudinally divided into two floors (scala vestibule and scala tympani) by a cochlear septum called a scala. The organ of Corti is located on the basilar membrane. It is a membranous tunnel at the bottom with bearing cells that allow oscillation. The upper part of the labyrinth consists of three semicircular canals. Their extended parts register rotational movements of the body. Other parts of the vestibular system are two gravity vesicles (utricle and saccule). These parts transmit biopotential changes to the effectors of the equilibrium system (Hahn et al., 2019). The close anatomical connection of the auditory and equilibrium parts of the inner ear predisposes these areas in pathological frame to a common symptomatology. Rehabilitation of deafness is a standard clinical procedure, today. A child who is

born deaf or older individuals who lose their hearing has a very effective opportunity to return valuable auditory communication. The cochlear implant consists of an outer part (microphone, processor, power source) and an inner part (receiver, electrode, active intracochlear electrode unit). The microphone receives an audio signal. The audio signal with special software is processed in the processor and sent by high-frequency transcutaneous transmission to the receiver implanted in the temporal bone. The receiver sends a signal in the form of electrical pulses to the active electrode stored in the scala tympani of the inner ear. The electrical signal stimulates ganglion cells in the spiral ganglion cochleae (Corti) along the modiolus. The signal utilizes the tonotopic distribution of the ganglion cells along the cochlea and the speed of stimulation to optimally stimulate the auditory nerve. The signal is led along the auditory nerve to auditory centers in the brain stem and further to the auditory center in the temporal lobe. Indications for CI consist of both adults deaf (postlingually) due to inflammation, trauma, tumor, progressive perceptual disorder and so on. In these patients, it is relatively easy to determine the degree of hearing impairment and decide on the indication for CI. Another group is deaf older children and adults (prelingually). In the past, prelingual deafness of adults was a clear contraindication for CI. Today the criterion does not apply strictly. Prelingually deaf children include mainly children from 0–6 months. It is optimal to have the child implanted at the age of 1–2 years (Kubátová & Profant, 2012). The equilibrium mechanism has three basic functions in humans: a, Transmission of information from the vestibular inner ear system to those parts of the CNS that are responsible for controlling of spinal reflexes and that read just muscular activity, thereby ensuring upright posture; b, By guiding vestibular information to eye control centers, the position of the eyes is stabilized during head movement, thus reducing the displacement of the fixed point on the retina; c, Leading vestibular information to postural muscles and perception and processing of feedback information from them. The reactions of these structures involved in providing equilibrium are feedback. The equilibrium mechanism ensures balance and plays a great role in the subjective survival of movement and orientation in space. The vestibular receptors are in the upper part of the membranous labyrinth, in the vestibule and semicircular ducts, where there are five intrinsic strange elements of the equilibrium system (Hahn et al, 2015).

2 Selected current research surveys in the issue

2.1 Research surveys with reported undesirable impact of CI on the vestibular system and balance control

Wolter, Gordon, Papsin et al. (2015) determines the role of vestibular and balance dysfunction in children with cochlear implant failure. Thirty-five children with CI failure were compared to 165 children who did not experience CI failure. Vestibular function was compared between groups by horizontal canal function (measured by caloric, rotational, video Head Impulse Testing [vHIT]), saccular function (vestibular evoked myogenic potentials [VEMP]), and balance (measured by Bruininks-Oseretsky Test [BOT-2]). Twenty-one patients completed vestibular and balance testing. Patients with CI failure demonstrated significantly more abnormal horizontal canal function than those who did not experience CI failure (caloric: 81 vs. 47%, $p = 0.004$; rotational/vHIT: 71 vs. 35%, $p = 0.001$). Absence of bilateral horizontal canal function increased the odds of CI failure 7.6 times. A greater proportion of children with CI failure had abnormal saccular function compared to those without CI failure (81 vs. 46%, $p = 0.003$). Children with CI failure had significantly worse balance (BOT-2 score: 7.8) than children who did not experience CI failure (BOT-2 score: 12.2) ($p < 0.0001$). Vestibular end-organ dysfunction and its resulting balance impairment have been identified as important risk factors for CI failure in children.

Janky & Givens (2015) aimed the study on determining of age-related changes in peripheral vestibular tests occur; quantifying peripheral vestibular function in children with normal hearing and children with cochlear implantate; and determining if amount of vestibular loss predicts visual acuity and balance performance. Eleven children with cochlear implantation and 12 children with normal hearing completed the following tests of vestibular function: ocular and cervical vestibular evoked myogenic potential to assess utricle and saccule function, and the video head impulse test to assess semicircular canal function. The relationship between amount of vestibular loss and the following balance and visual acuity outcomes was assessed (dynamic gait index, single leg stance, the sensory organization test, and tests of visual acuity, including dynamic visual acuity and the gaze stabilization test). There were no significant age-related changes in peripheral vestibular testing with the exception of the cervical vestibular evoked myogenic potential latency, which was moderately correlated with age. Children with cochlear implantation had significantly higher rates of vestibular loss for each test of canal and otolith function. Amount of vestibular loss predicted performance on single leg stance, the dynamic gait index, some conditions of the sensory organization test, and the dynamic visual acuity test. Age was also a contributing factor for predicting the performance of almost all outcomes. Preliminarily, children with vestibular loss do not recover naturally to levels of their healthy

peers, particularly with activities that utilize vestibular input. They have poorer visual acuity and balance function.

Chen, Chen, Zhang et al., 2016 studied the influence of cochlear implantation on vestibular function in patients with severe and profound sensorineural hearing loss, and to analyze a possible correlation between the changes in vestibular testing and post-operative vestibular symptoms. Thirty-four patients were evaluated for vestibular function using the cervical and ocular vestibular-evoked myogenic potentials (cVEMP and oVEMP, respectively), and 29 patients underwent caloric tests pre-operatively and 4 weeks post-operatively. Before surgery, the cVEMPs were recorded bilaterally in 22 patients, unilaterally in eight patients, and absent bilaterally in four patients. The cervical and ocular vestibular-evoked myogenic potentials oVEMPs were recorded bilaterally in 19 patients, unilaterally in six patients, and absent bilaterally in nine patients. After implantation, the cVEMPs were absent in 10 patients and the oVEMPs were absent in seven patients on the implanted side. Caloric tests demonstrated canal paresis in 17 patients, and normal responses were recorded in 12 of the 29 patients pre-operatively. There was a significant decrease post-implantation in the ear implanted, with the exception of two patients. Two patients presented with vertigo and another two patients reported slight unsteadiness post-operatively, but all symptoms resolved within 7 days. The impaired vestibular function did not correlate with vestibular symptoms, age, or gender. Function on the contra-lateral side remained unaffected.

Oyewumi, Wolter, Heon et al. (2016) determined if bilateral vestibular dysfunction can be predicted by performance on standardized balance tasks in children with sensorineural hearing loss (SNHL) and cochlear implants. In study were pediatric patients (4.8–18.6 years) with profound SNHL using CIs. Vestibular end-organ (horizontal canal and otoliths), and balance were assessed. Comparison of balance skills, measured by the Bruininks Oseretsky Test of Motor Proficiency II (BOT-2), was performed between two groups of children with SNHL and CI: 1. total bilateral vestibular loss (TBVL) ($n = 45$), and 2. normal bilateral vestibular function ($n = 20$). Balance as measured by the BOT-2 balance subtest was significantly poorer in children with TBVL than those with normal vestibular function ($p < 0.0001$). “Eyes closed” tasks best identified children with TBVL having the highest sensitivity and specificity. One-foot standing eyes closed was found to have the best performance as a screening tool for TBVL using a timed cutoff of 4 seconds. A brief in-office screen of balance function using one of the BOT-2 balance subtest tasks, one-foot standing eyes closed, is able to identify children at risk of total bilateral vestibular loss with excellent sensitivity and specificity and should be used to screen for total bilateral vestibular loss in all children presenting with sensorineural hearing loss.

The study of Ebrahimi, Movallali, Jamshidi et al. (2016) compared the static and dynamic balance performance of deaf children with and without cochlear implants.

This is a cross-sectional study of 145 school children, aged between 7 and 12 years comprising 85 children with congenital or early acquired bilateral profound sensorineural hearing loss (the hearing loss group) and 60 normal hearing age-matched control counterparts were assessed using the balance subtest of Bruininks-Oseretsky test of Motor Proficiency (BOTMP). The hearing loss group, 50 without cochlear implants (the non-implant group) and 35 of them with unilateral cochlear implants (the implant group) were recruited from schools for the deaf and normal hearing children (the control group) randomly selected from two randomly selected elementary schools of Tehran city. The total score of deaf children especially the implant group were significantly lower than the control group ($P < 0.001$). The balance performance of the control group was better than the implant group in all of the items as well as the non-implant group except the fourth tested item (walking forward on a line) ($P < 0.05$). The balance score of the implant group was significantly lower than the non-implant group except for the third tested item (standing on the preferred leg on a balance beam with eyes closed). The findings suggested that deaf children, specifically those with cochlear implants are at risk for motor and balance deficits.

Nair, Gupta, Nilakantan et al. (2017) identified vestibular dysfunction in children after cochlear implant surgery and studied the utility of static posturography in evaluating vestibular function in children. A prospective study was carried out on 25 children between 2 and 7 years of age with sensorineural hearing loss with no overt vestibular dysfunction. All children underwent static posturography using a static platform with foam. The centre of pressure (COP) shift was recorded as statokinesiogram on the software and the mean vestibular, visual and somesthetic scores were obtained. Cochlear implantation surgery was done with insertion of Med-El Pulsar standard cochlear implant with 12 twin electrodes. Children were evaluated again after 4 weeks of CI surgery (2 weeks after switch on) with static posturography on the same SPS software. The vestibular system was at high risk of injury leading to vestibular dysfunction in children during CI.

Dagkiran, Tuncer, Surmelioglu et al. (2019) evaluate all five vestibular end-organ functions (lateral, anterior, posterior semicircular canal, utricle, and saccule) and investigate the relationship between Dizziness Handicap Inventory (DHI) and vestibular functions prior to cochlear implantation and at postoperative day 3 and month 3. A total of 42 patients (age 16–70 years) with normal vestibular functions preoperatively and undergoing unilateral cochlear implantation were included in this prospective descriptive study. Video head impulse test (vHIT) for three semicircular canal (SSC) functions, ocular vestibular-evoked myogenic potential (oVEMP) for utricle function, cervical vestibular-evoked myogenic potential (cVEMP) for saccule function and DHI for subjective vertigo symptoms were performed prior to CI and at postoperative day 3 and month 3. There was a significant impairment of vestibular function in 12 patients (28.5%) on the implantation side and significant DHI increase

was observed in 13 of 42 (30.9%) patients at postoperative day 3 after CI ($p < 0.05$). We found SSC dysfunction in 7 patients (16.6%) who underwent observation with vHIT, saccule dysfunction in 8 patients (19%) with cVEMP and utricle dysfunction in 5 patients (11.9%) with oVEMP on the operated side 3 days after surgery ($p < 0.05$). Posterior SSC functions (5 patients) were more affected than lateral SSC functions (3 patients). At postoperative month 3, six patients (14.2%) still had deteriorating results in the objective tests and significant DHI increase was continued in 4 (9.5%) patients ($p < 0.05$). The deterioration in vHIT continued in only 1 (2.3%) patient ($p > 0.05$). The deterioration in cVEMP continued in 5 (11.9%) patients ($p < 0.05$). The deterioration in oVEMP continued in 2 (4.7%) patients ($p > 0.05$). There was a significant correlation between DHI and objective vestibular tests both in the early and late postoperative period ($r = 0.795$; $p < 0.05$). This study showed that both canal and otolith functions can be damaged after cochlear implantation especially in the early postoperative period. Surprisingly, posterior SSC functions were more affected than lateral SSC.

2.2 Research surveys with reported improvements after cochlear implantation on the vestibular system and balance control

The pilot study of the Parietti-Winkler, Lion, Montaut-Verient et al. (2015) aimed to assess the effects of unilateral cochlear implantation on the modalities of balance control and sensorimotor strategies. Posturographic and vestibular evaluations were performed in 10 patients (55 ± 20 years) with profound hearing loss who were candidates to undergo unilateral multichannel cochlear implantation. The evaluation was carried out shortly before and one year after surgery. Posturographic tests were also performed in 10 age-matched healthy participants (63 ± 16 years). Vestibular compensation was observed within one year. In addition, postural performances of the patients increased within one year after cochlear implantation, especially in the more complex situations, in which sensory information is either unavailable or conflicting. Before surgery, postural performances were higher in the control group compared to the patients' group. One year after cochlear implantation, postural control was close to normalize. The improvement of postural performance could be explained by a mechanism of vestibular compensation.

Mazaheryazdi, Moossavi, Sarrafzadah et al. (2017) present study which aimed to evaluate the postural control perturbations by the center of pressure parameters in two main approaches, cochlear implant turned "on" and "off". They included 25 children aged 8–10 years with unilateral cochlear implants and bilateral vestibular hypofunction deficit. To evaluate the postural function, each children was asked to stand on the force plate under three different conditions and cochlear implant turned

“on” and “off”: Condition (A) double stance from open eyes to closed eyes; Condition (B) double stance with open eyes engaging in the dual task and Condition (C) From double leg stance to one leg stance with open eyes for assessment of dynamic postural control. Also to calculate the center of pressure parameters, they designed new software for the force plate. In condition A, although the results demonstrated an overall reduction in the mean of center of pressure parameters when the cochlear implant was “on”, only the significant differences were seen in mean and standard deviations for anterior-posterior displacement, mediolateral displacement, area and mean velocity in open eyes. In condition B, no significant difference was found between “on” and “off” cochlear implant in single or dual-task situations. In condition C, mean velocity variable demonstrated a significant difference in the cochlear implant “on” condition in double leg stance only. Also, anterior-posterior displacement demonstrated a significant difference, when the cochlear implant was turned “on” in one leg stance situation. The results of study show that auditory information can improve postural stability and reduce body sways in different situations as an underlying system for reinforcement of the postural control in children without complete normal balance subsystems.

Zur, Ben-Rubi Shimron, Leisman et al. (2017) described the effect of vestibular rehabilitation on anxiety, dizziness and poor balance that developed after cochlear implant surgery. A 54-year-old woman, with profound hearing loss since the age of 2 years, underwent right CI surgery 2 years previously. On implant activation, the patient immediately felt dizziness and imbalance, which affected the ability to perform activities of daily living and increased anxiety to where the patient considered the cochlear implant removal. Prior to vestibular rehabilitation the patient was evaluated with the Dizziness Handicap Inventory and the Visual Vertigo Dizziness Questionnaire and clinically with the Zur Balance Scale and Video Head Impulse Test. The patient underwent 14 VR sessions over 4 months that included compensation, adaptation and habituation exercises. After vestibular rehabilitation the patient was able to maintain good balance while using the CI. Dizziness and anxiety improved dramatically. This report increases awareness that a cochlear implant could compromise balance, which can be overcome with personalized vestibular rehabilitation.

The effect of audition on gait, a dynamic task also linked to fall risk, has not been fully examined in study of Weaver, Shayman, & Hullar (2017). Auditory input in people with hearing impairment will improve balance while walking. Several studies have found auditory cues to improve static balance measured on a sway platform. If a positive effect were shown between audition and balance, it would further indicate that improving hearing could also improve balance. In this study inertial sensors were quantified gait parameters of 13 bilateral hearing aid users and 12 bilateral cochlear implant users with their hearing devices on and off. Outcome measures included gait velocity, stride length variability, swing time variability, and double

support phase. Group analysis of each of the gait outcomes showed no significant differences between the aided and unaided conditions in both the hearing aid and cochlear implant groups. Gait velocity, an outcome most strongly linked to fall risk had 95% confidence interval differences of -2.16 to 1.52 and -1.45 to 4.17 cm/s in hearing aid and cochlear implant users, respectively (aided versus unaided condition). There was considerable variation among participants with some individuals improving in all four parameters. The overall findings were not statistically significant, however, a small subset of our population improved clinically across several outcomes. This demonstrates that audition may have a clinically beneficial effect on balance in some patients.

Buhl, Artemiev, Pfiffner et al. (2018) studied dynamic postural stability before and after cochlear implantation using a functional gait assessment (FGA). As a second, they evaluate the correlation between loss of residual hearing and changes in dynamic postural stability after cochlear implantation. Candidates for first-sided cochlear implantation were prospectively included. The FGAs and pure-tone audiograms were performed before and 4–6 weeks after cochlear implantation. Twenty-three subjects were included. Forty-eight percent ($n = 11$) showed FGA performance below the age-referenced norm before surgery. One subject had a clinically relevant decrease of the FGA score after cochlear implantation. No significant difference between the mean pre- and postoperative FGA scores was detectable ($p = 0.4$). Postoperative hearing loss showed no correlation with a change in FGA score after surgery ($r = 0.3$, $p = 0.3$, $n = 16$). Single-sided cochlear implantation does not adversely affect dynamic postural stability 5 weeks after surgery. Loss of functional residual hearing is correlated with a decrease in dynamic postural stability.

Wisnomsirskaa, Zdrodowskaa, Tacikowskab et al. (2019) studied standard cochlear implantation influence on postural stability in patients with hearing loss. The study included 21 adult individuals qualified to undergo cochlear implant due to severe or profound hearing loss. Participants were qualified for both groups by a physician based on an interview, an otoneurological examination and vestibular tests. The first group included patients without vestibular dysfunction, whereas the other group consisted of persons with vestibular dysfunction. The research methodology included medical examinations, anthropometric measurements and stabilometry on the Biodex Balance System SD (BBS) platform. The examinations were carried out twice, i. e. prior to and 3 months post implantation. The recorded data was compared between the first and the second examination. Study showed that 52.4% of the participants obtained results within the norm, while 47.6% scored below it. The comparison of stability indices of the examined individuals, with and without vestibular dysfunction, did not reveal statistically significant differences. The only difference was the anterior-posterior stability index assessed in static conditions. Three months after the implantation, no changes in the majority of indices were noted, with the exception

of anterior-posterior stability index, which improved following the implantation. Cochlear implant does not affect postural stability changes in the study participants.

2.3 Research surveys with reported featureless impact of the cochlear implantation on the vestibular system and balance control

Ajalloueyan, Saeedi, Sadeghi et al. (2017) realized a prospective cohort study, 27 children with bilateral profound hearing loss (all candidates for cochlear implantation) were evaluated for their vestibular function before and after cochlear implantation. Vestibular evaluations consisted of Vestibular Evoked Myogenic Potentials, caloric testing and the Head-Impulse Test. Mean age at the time of cochlear implantation was 27.19 months. Without considering vestibular evaluation results, one of the ears was selected for surgery. Vestibular tests after surgery were not indicative of any statistically significant change in vestibular system or balance. These limited data show that cochlear implantation did not impair the vestibular system of these patients. By the results of our study it is possible to conclude that round window implantation does not have any disturbing impact on vestibular function in children.

The objective of study of le Nobel, Hwang, Wu et al. (2016) was to conduct a pilot study assessing the effects of unilateral cochlear implantation on balance and the vestibular system in post-lingually deafened adults. Twelve patients were included in this pilot study and were assessed pre-operatively and at immediate, 1 week, and 1 month post-operative intervals. Assessments consisted of the dizziness handicap inventory (DHI), subjective visual vertical (SVV), and timed up-and-go testing (TUG). When applicable, testing was repeated with the cochlear implant on and off. Many patients were found to have deviated SVV at pre-operative and post-operative assessments. However, statistically significant changes were not seen when comparing pre-operative and post-operative SVV or when comparing SVV with the cochlear implant on and with the cochlear implant off. DHI was found to improve in five patients and worsen in two patients, however, no statistically significant change was found in DHI scores or with TUG testing. This current pilot study does not indicate that cochlear implant surgery or implant activity influence vestibular or balance function, however, this pilot study is underpowered and greater numbers of patients need assessment to confirm these findings.

The goal of the present study of Maheu, Pagé, Sharp et al. (2017) was to investigate the impact of unilateral cochlear implantation on postural control in relation to the vestibular status before cochlear implant surgery. They recruited 17 participants (four cochlear implant candidates and 13 hearing controls) and performed complete vestibular evaluation (cVEMP, oVEMP, vHIT) and postural evaluation using a force platform, prior and following unilateral cochlear implant surgery. Study suggests

that an increase in postural sway following cochlear implant was present only for the participants that received the implant in the ear with the better vestibular function. cVEMP and oVEMP measures in the implanted ear prior to unilateral cochlear implantation may help to predict postural control performance following surgery. A thorough evaluation of the vestibular function, as described in the present study, could not only be helpful to make a more accurate prognosis of the risks of fall following cochlear implantation, but also to provide proper vestibular rehabilitation for at-risk patients.

The aim of the meta-analysis of the Ibrahim, Daniela da Silva, Segal et al. (2017) is to quantify the effect of cochlear implant before and after surgery on the outcomes of vestibular tests, postural stability, and subjective perception of dizziness. They evaluate the effects of cochlear implant surgery on vestibular function in adult patients (≥ 18 years) with sensorineural hearing loss who underwent unilateral or bilateral implantation. Published studies of adult patients who received unilateral or bilateral cochlear implants and whose vestibular function or postural stability was assessed before and after surgery. From each study, test results before and after surgery were compared, for the following five tests: clinical head impulse test (HIT); bi-thermal caloric irrigation of the horizontal semicircular canal; vestibular evoked myogenic potential (VEMP); dizziness handicap inventory (DHI); and computerized dynamic posturography (CDP). Twenty-seven studies met all inclusion criteria. Most studies performed either bi-thermal caloric irrigation and/or VEMP, with fewer studies investigating changes in HIT, posturography or DHI. CI surgery significantly affected the results of caloric and VEMP testing. However, HIT results, posturography, and DHI, scores were not significantly affected after CI surgery. CI surgery has a significant negative effect on the results of caloric as well as VEMP tests. No significant effect of CI surgery was detected in HIT, posturography, or DHI scores. Overall, the clinical effect of CI surgery on the vestibular function was found to be insignificant.

The relation between well-controlled auditory stimulation through cochlear implant and the body balance has been sparsely investigated by Oikawa, Kobayashi, Hiraumi et al. (2018). The purpose of this study was to evaluate the body balance function of cochlear implant patient's with- and without-sound in anechoic sound-shielded room. They recorded 8 experienced CI recipients and 8 young normal-hearing volunteers. All subjects were assessed using posturography under 4 conditions: 1. eyes open with-sound, 2. eyes closed with sound, 3. eyes open without-sound, and 4. eyes closed without-sound. The total path length and the total area were significantly larger in the eyes closed condition than in the eyes open condition. In normal hearing subjects, the average displacement of center of pressure (COP) in the medio-lateral direction under with-sound condition was not different from that under without-sound condition. In CI recipients, the COP (Center of Pressure) significantly displaced to the cochlear implant side after the deprivation of visual

cues in without-sound condition. This shift was eliminated in with-sound condition (significant interaction among sound condition, eye condition, and between-group factor). In cochlear implant subjects, sound stimulation improves the abnormal displacement of COP in the medio-lateral direction. A posturographic study under an anechoic condition proved that sound stimulation improves body balance function in cochlear implant subjects.

Stieger, Siemens, Honegger et al. (2018) examined differences in stance and gait balance control before versus after cochlear implant surgery. Balance control of 30 cochlear implant patients (mean age 59, SD 15.4 years), receiving a first unilateral cochlear implant surgery, was measured preoperatively and postoperatively 1 month after the initial implant stimulation (2 months after surgery). Trunk sway was measured during 14 stance and gait tests using an angular-velocity system mounted at lumbar vertebrae L3. For pre- versus postoperative comparisons across all 30 patients, a nonsignificant worsening in balance control was observed. Significant changes were, however, found within subgroups. Patients younger than 60 years of age had a significant worsening of an overall balance control index (BCI) after cochlear implant surgery ($p = 0.008$), as did patients with a normal BCI preoperatively ($p = 0.005$). Gait task measures comprising the BCI followed a similar pattern, but stance control was unchanged. In contrast, patients over 60 years or with a pathological BCI preoperatively showed improved tandem walking postoperatively ($p = 0.0235$). Across all CI patients, cochlear implant surgery has a minor effect on balance control 2 months postoperatively. However, for patients younger than 60 years and those with normal balance control preoperatively, balance control worsened for gait indicating the need for preoperative counseling.

The aim of the study of Hänsel, Gauger, Bernhard et al. (2018) was to investigate both subjective complaints of vertigo before and after cochlear implantation and related vestibular diagnostic tests on cochlear implant candidates. They found 116 eligible studies investigating subjective complaints of vertigo after cochlear implantation and/or related vestibular diagnostic tests. They conducted three meta-analyses of 46 eligible studies with matched pre- and postoperative data to calculate the odds ratio of new vertigo onset, as well as the impairment of vestibular receptors measured by nystagmography and cervical vestibular evoked myogenic potentials (cVEMP). Postoperative vertigo was calculated from 95 studies and further subdivided by mean age with pooled data. They observed a significant increase in postoperative vertigo and significant impairment of nystagmography and cVEMP detection. Vertigo after cochlear implantation was reported in 9.3% of the patients with a continuous increase in patient age at surgery. In a subgroup of studies, new onset of vertigo was found in 17.4% of the patients. In addition, 7.2% of the patients had persisting vertigo complaints, whereas 11.6% described an altered vertigo quality and 7.7% had their preoperative complaints resolved. A comparison of round window approach

and cochleostomy revealed significantly increased vertigo after cochleostomy. Both insertion methods showed similar effects in nystagmography and cVEMP testing. Cochlear implantation has a significant impact on subjective vertigo and vestibular receptor function. This is affected by the patient's age at the time of surgery. The surgical technique (round window or cochleostomy) may influence the outcome, but this requires further investigation. Younger patients may compensate better following vestibular dysfunction. Peri-operative testing is required to correlate vestibular impairment and subjective complaints.

Kelly, Liu, Leonard et al. (2018) evaluated the vestibular function of children who had unilateral and bilateral cochlear implants compared with a control group of otherwise healthy children who had not been implanted. Posturography was carried out in the form of a Modified Clinical Test of Sensory Interaction on Balance using a Wii Balance Board and the Vestio App on an iPod Touch. Thirty children in total were tested, 10 children in each cohort. Results in the form of root mean square calculations were available for each child. Results showed a significant difference in the vestibular function of implanted children and the non-implanted control group ($P < 0.05$). As expected, children in all groups had more difficulty maintaining posture with their eyes closed on a compliant surface ($P < 0.05$). Thirty per cent of children with bilateral and 10% with unilateral cochlear implants were unable to complete testing. Our study demonstrates posturography as an inexpensive, easily operated tool that can be used to assess pediatric vestibular function. It showed a significant difference between the control group and the implanted groups. Further work prompted by this study will include interval post-operative testing to more accurately assess the effect that implantation has on vestibular function.

Berge, Nordahl, Aarstad et al. (2019) evaluate the association between hearing and postural balance. Patients examined for suspected vestibular disorder were included in this study. The outcome variable was postural sway measured by static posturography during quiet standing with eyes closed. The predictor variable was pure-tone average hearing threshold on the best hearing ear at 0.5, 1, 2, and 3 kHz. Covariates were age, sex, and vestibular disease or vestibular asymmetry assessed by bithermal caloric irrigation. In total, 1075 patients were included. Increased hearing threshold was a strong predictor of increased postural sway (path length) after correcting for age and sex. A 10-dB increase in hearing loss on the best hearing ear predicted a mean 6.0% increase in path length (confidence interval, 2.9–9.3%, $P < .001$). Of the covariates, increasing age ($P < .001$) and male sex ($P = .009$) were significant predictors of increased postural sway. The effect of increased hearing threshold was also significant after adjusting for vestibular disease. Increased hearing threshold was an independent predictor of increased postural instability, and this effect was strongest for the best hearing ear. Unilateral vestibular disease did not seem to explain this association

between hearing and postural balance. Reduced hearing is associated with impaired balance, and interventions to prevent falls should be considered for patients at risk.

Yong, Young, Lea et al., (2019) investigated the presence, magnitude, and clinical significance of vestibular dysfunction that occurs after pediatric cochlear implantation. Parameters that were assessed included number of patients, pre- and post-operative vestibular evoked myogenic potentials (VEMPs), head impulse testing (HIT), caloric's, and posturography, timing of pre- and postoperative testing, symptomatology, and other demographic data such as etiology of the hearing loss. Ten articles were included. Relative risk values evaluating the effect of cochlear implantation on vestibular function were calculated for VEMPs and caloric testing due to the availability of published data. I2 values were calculated and 95% confidence intervals were reported. Separate analyses were conducted for each individual study and a pooled analysis was conducted to yield an overall relative risk. Assessment on risk of bias in individual studies and overall was performed. Pediatric cochlear implantation is associated with a statistically significant decrease in VEMP responses post-operatively (RR 1.8, $p < 0.001$, I2 91.86, 95%CI 1.57–2.02). Similar results are not seen in caloric testing. Insufficient data is available for analysis of HIT and posturography. Further studies are necessary to determine the effect of cochlear implantation on objective vestibular measures post-operatively and whether any changes seen are clinically relevant in this population.

3 Conclusion

Further studies are necessary to determine the effect of cochlear implantation on vestibular functions. It is undisputed that in many cases, vestibular dysfunctions, motor and balance disabilities will occur after cochlear implantation. It is believed that the lower age of the patient may play an essential positive role in the lower occurrence of undesirable consequences of cochlear implantation, as well as in the better further development of the patient condition. In some cases, slight improvements are even possible after cochlear implantation. It is believed that this may be due to compensation, learning new movement and balance strategies (also in an effort to eliminate the possible fall risk).

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