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Predictive factors of vertigo following cochlear implantation in adults

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Abstract

Objectives The occurrence of vertigo after cochlear implantation surgery is one of the most common complications, and often transient. The purpose of this study was to evaluate the occurrence of vertigo after unilateral or bilateral cochlear implantation as well as to identify potential predictive factors.

Materials and methods Patients who have undergone cochlear implantation and vestibular assessment pre- and postoperatively were included retrospectively. The presence of vertigo before and after surgery was noted. Postoperative vertigo duration was divided into 3 categories: immediate postoperative (less than 2 months), transient postoperative (between 2 months and 1 year), and persistent postoperative (greater than 1 year). Pre- and postoperative vestibular assessment results (caloric irrigation and VEMP tests) as well as patients' age, operated side, surgical technique for round window access, and characteristics of the electrode array were all analyzed as potential predictive factors of postoperative vertigo.

Results A total of 166 cochlear implants (137 patients) were included in the study, with a mean age of 57.5 ± 16.4 years. Of these, 36% developed postoperative vertigo, of which 19.3% was immediately postoperative. At 1 year postoperatively, 6 cases (3.6%) had persistent disabling vertigo, with 2 cases (1.2%) having no history of vertigo prior to cochlear implantation. Regarding caloric irrigation, 21% of the patients had a vestibular deficiency before surgery, and the same percentage had decreased vestibular responses. At 2 months after cochlear implantation, 31% of the patients exhibited an alteration in their vestibular test results, and 23.5% had experienced immediate postoperative vertigo. None of the factors studied (age, operated side, surgical technique, electrode array characteristics, and vestibular test alteration) correlated with the occurrence of short-term or long-term postoperative vertigo.

Conclusion The occurrence of vertigo after cochlear implantation is difficult to predict by the healthcare team and may develop into an invalidating condition. Each vestibular examination performed routinely only evaluates a specific vestibular organ dysfunction. Therefore, combining several vestibular assessments tests before and after cochlear implantation can increase their sensitivity of predicting the occurrence and eventual persistence of this symptom.

Keywords Cochlear implant · Vertigo · Postoperative · Complication

Introduction

Cochlear implant devices are considered one of the most marked innovations in hearing rehabilitation ever since its first experience conducted by Eyries and Djourno in 1957 [1]. Cochlear implantation is a safe and standardized surgery procedure with a low rate of major and minor postoperative complications such as facial palsy, infection, dysgueusia, and skin alterations [2]. During the surgery, it is necessary to open the cochlea for insertion of the electrode array and thus damage to the cochlear and vestibular function can occur. Vertigo is one of the most common minor complications in adults after cochlear implant surgery and is usually transient [2–4]. The incidence of this symptom after cochlear implantation varies between 32 and 74% [5–10]. Multiple factors have been attributed as possible causes, most notably the labyrinthine status prior to cochlear implant surgery or concurrent inner ear disease [11]. Factors related to the surgical intervention have also been described such as mechanical trauma to the saccule or the horizontal semicircular canal

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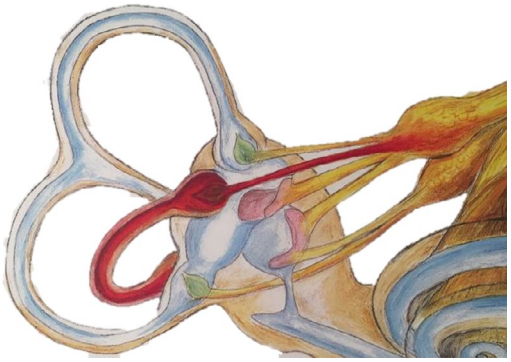
induced after insertion of the electrode array into the tympanic ramp [10, 12].

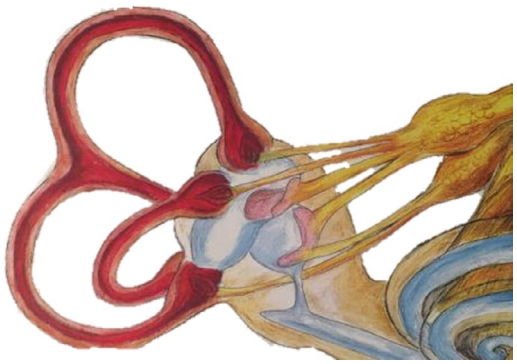
Vestibular function is systematically evaluated in clinics prior to cochlear implantation as it can influence the choice of the side of implantation in cases of symmetrical hearing loss. Vestibular function tests are organ specific and can't asses the global function of the entire vestibular system (Table 1). They typically include caloric irrigation and cervical Vestibular Evoked Myogenic Potential (cVEMP) tests. After cochlear implantation, tests can be repeated and an alteration or change of the examination results can sometimes be observed [13].

The objective of this study was to evaluate the occurrence of vertigo or balance disorder in patients during the

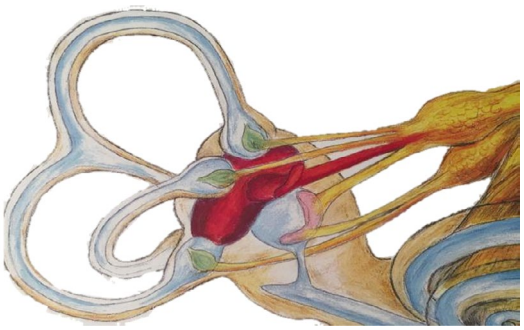
Table 1 Vestibular assessment test and related anatomical structure of the labyrinth



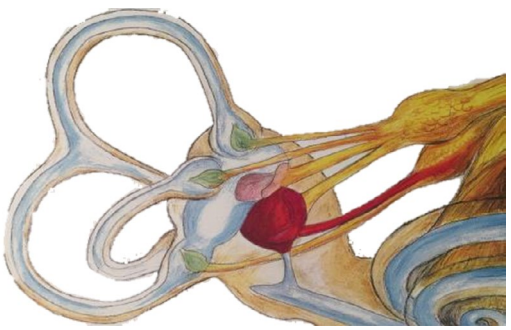
Caloric irrigation	- Horizontal semi-circular canal (low frequencies) - Superior vestibular nerve (ampullary branch)
Rotary Chair Test	- Horizontal semi-circular canal (high and low frequencies)
Head Impulse Test (HIT)	- Horizontal semi-circular canal



Video Head Impulse Test (vHIT)	- Horizontal, lateral, posterior semi-circular canals



Cervical Vestibular Evoked Myogenic Potentials (cVEMP)	- Saccule - Inferior vestibular nerve



Ocular Vestibular Evoked Myogenic Potentials (oVEMP)	- Utricle - Superior vestibular nerve (utricular branch)
Subjective Visual Vertical (SVV)	- Utricle

postoperative period following cochlear implantation, and to correlate it with the results of pre- and postoperative vestibular examinations. Other factors (cochlear implant side, age of the patient, surgical technique, and characteristics of the electrode array) were also analyzed.

Material and methods

Ethical considerations

Patients were informed and approved their personal data to be analyzed according to the Public Health Code (CNIL n° 20200529121727).

Study population

This single-center study was performed as part of the usual follow-up of adult patients with cochlear implants.

Patients that underwent cochlear implantation between 1999 and 2018 were included retrospectively. All patients met the criteria of the Haute Autorité de Santé (HAS) for cochlear implantation and were operated on by the same experienced surgeon. The HAS in France determines the indications for cochlear implantation in adults as bilateral post-lingual sensorineural hearing loss showing absence of benefits from hearing aids with less than 50% disyllabic speech intelligibility (Fournier lists) at 60 dB HL in a quiet setting and in the best hearing aided conditions [14]. Bilateral cochlear implants are indicated for adults with a unilateral cochlear implant and loss of hearing benefit on the opposite side causing socio-professional consequences or loss of autonomy, as well as in cases of bacterial meningitis or temporal bone fractures with risk of cochlear ossification [14].

Exclusion criteria were the absence of a pre- or postoperative caloric irrigation test results, history of congenital nystagmus, intraoperative middle ear obliteration (making vestibular assessment impossible), cases of explantation with re-implantation, and cases with intraoperative injury to the lateral semicircular canal.

Each cochlear implant case was considered separately, meaning the same patient can count twice in sequential bilateral cochlear implantation. Patients that underwent simultaneous bilateral cochlear implantation were considered as a single case because of the difficulty in discriminating the causative side in cases of vertigo.

Outcome measures

Demographic data for each patient were correlated with postoperative vertigo (Table 2). Vertigo is the sensation of self-motion when no self-motion is occurring or the sensation of distorted self-motion during an otherwise normal head movement. This "internal" vestibular sensation is distinguished from the "external" visual sense of motion. We included all forms of vertigo and noted their different characteristics (intensity, duration, mode of onset, triggering factors, spinning or non-spinning vertigo) [15]. Age was further subdivided into 10 year age groups, as performed by Hansel et al. in their meta-analysis [16]. Surgical parameters were reported and also analyzed: cochlear implantation side, electrode array characteristics (diameter at basal and apical ends as well as length of electrode array, and approach of the tympanic ramp by cochleostomy vs. round window insertion.

The patient's history investigated the onset and characteristics of the vertigo or balance disorder and the clinical examination assessed the patient's vestibular function prior to surgery and during the postoperative follow-up (2 months). Postoperative follow-up included medical consultations at 7 days, 2 months, then annually following surgery. The duration of postoperative vertigo was divided into 3 categories: immediate postoperative (< 2 months), transient postoperative (between 2 months and 1 year) and permanent postoperative (> 1 year). Vertigo intensity was subjectively assessed by the clinician as "instability", "mild" vertigo or "debilitating" vertigo.

Caloric irrigation and cervical Vestibular Evoked Myogenic Potential (cVEMP) tests were performed routinely in patients who have undergone cochlear implantation to assess vestibular function pre- and postoperatively. Caloric irrigation using air stimulation and cVEMP using short tone bursts were practiced according to the usual methods. The results of the vestibular examinations before and 2 months after cochlear implantation, as well as any alteration of the caloric irrigation test results, were investigated as potential factors predicting the occurrence of postoperative vertigo.

The diagnosis of decreased vestibular response was retained when the difference in caloric stimulation between the two labyrinths was greater than 20%. The diagnosis of vestibular deficiency was retained in cases of absence of a response, which corresponded to a difference of 100% between the two labyrinths [17]. Table 1 summarizes the different vestibular explorations and the structures involved.

Statistical analysis

Qualitative data were compared using a Chi-squared test when the number of subjects was ≥ 5 and using a Fisher's Exact test in the other cases. The criterion for statistical significance was set at p value = 0.05.

Table 2 Demographic characteristics and occurrence of postoperative vertigo in cochlear implant cases ($n=166$)

	Population *n* (%)	Cases with postoperative vertigo *n* (%)	Cases without postoperative vertigo *n* (%)
Number of cases			
Gender	166 (100)	60 (36.1)	106 (63.9)
Female	102 (614)	38 (372)	64 (62.7)
Male	64 (386)	22 (34.4)	42 (65.6)
Preoperative vertigo	60 (36)	28 (17)	32 (19)
Etiology of Preoperative Vertigo			
Undetermined	38	12	28
Assumed endolymphatic hydrops	10	10	–
BPPV	4	–	4
Perilymphatic fistula	3	3	–
Labyrinthine Malformation	2	1	1
Otosclerosis	1	1	–
Cholesteatoma	1	1	–
Contralateral Acoustic Neuroma	1	–	1
Side of cochlear implant			
Right	75 (45.2)	25 (33.3)	50 (66.6)
Of which sequential contralateral	19	8	11
Left	86 (51.8)	32 (37.2)	54 (62.8)
Of which sequential contralateral	15	4	11
Simultaneous Bilateral	5 (3)	3 (60)	2 (40)
Surgical approach			
Cochleostomy	24 (14.5)	11 (24)	13 (54.2)
Round Window	142 (85.5)	49 (34.5)	93 (65.5)
CI Brand			
Cochlear[†]	74 (44.6)	22 (29.7)	52 (70.3)
MED-EL[¶]	47 (28.3)	23 (48.9)	24 (51.1)
Advanced Bionics†	42 (25.3)	13 (31)	29 (69)
Oticon††	3 (1.8)	2 (66.7)	1 (33.3)

[†]Cochlear, Lane Cove, Australia

[¶]Med-El, Innsbruck, Austria

†Advanced Bionics, Stäfa, Switzerland

††Oticon Medical, Vallauris, France

Results

A total of 166 cochlear implant cases in 137 patients were included. Among them, 98 cases underwent unilateral cochlear implantation, 5 cases underwent bilateral cochlear implantation simultaneously and 34 patients (63 cases) underwent sequential implantation (Table 2). The etiologies of vertigo found in patients with preoperative vertigo were diverse: assumed endolymphatic hydrops, benign paroxysmal positional vertigo, peri-lymphatic fistula, labyrinthine malformation, otosclerosis, cholesteatoma and contralateral neuroma. Thirty-eight cases had an undetermined etiology. After cochlear implantation, 36% ($n=60$) of cases experienced postoperative vertigo, of which 43% already had a history of vertigo preoperatively. Of the five patients that underwent bilateral simultaneous cochlear implantation, 3 patients experienced postoperative vertigo. Two of those patients had a history of preoperative vertigo. Of those that underwent bilateral sequential cochlear implantation, data was analyzed for 29 patients as information on the first surgery was not available for 5 patients, showing that 41.4% experienced postoperative vertigo after first implantation, and 34.5% after the second implantation. A new-onset vertigo was developed postoperatively in 17.2% and 13.8% after first and second surgery, respectively. At 1 year after surgery, among bilateral cochlear implanted patients, 17.2% of cases had preoperative vertigo that persisted after both cochlear implantations, and one patient with no history of vertigo developed persistent vertigo after first and second cochlear implantation.

Thus overall, 32 cases had postoperative vertigo directly attributable to surgery, 26 cases after unilateral implantation, and 6 after sequential or bilateral implantation. Furthermore, 7.2% of cases with preoperative vertigo encountered disappearance of this symptom postoperatively.

Regarding the duration of postoperative vertigo in the 60 patients that experienced this symptom, 30% of cases reported vertigo only in the immediate postoperative period, 16.7% presented transient vertigo, and 53.3% of cases had permanent vertigo.

Regarding vertigo intensity, 5% of postoperative vertigo was characterized as instability, 76.7% as mild and 18.3% as disabling. One year after cochlear implantation, 2.4% of cases had instability, 13.2% had mild vertigo, and 3.6% of cases had disabling vertigo. Four cases with permanent disabling vertigo already had a history of preoperative vertigo.

Caloric vestibular examination and postoperative vertigo

Before cochlear implantation, 59% of cases had normal caloric responses, 19.9% of cases had decreased vestibular responses and 21% had vestibular deficiency. After cochlear implantation, an alteration of the caloric irrigation test results was seen in 26.5% of cases, on the implanted side. No correlation between the occurrence of postoperative vertigo and the alteration of caloric irrigation tests results was found (Chi 2 test; $p=0.61$; Fig. 1).

Among the 60 cases (36.1%) with postoperative vertigo, an alteration of caloric irrigation tests results was observed in 28.3%, and 71.7% had similar caloric responses preoperatively. 18.3% already had vestibular deficiency before surgery. Regarding the 106 cases with no postoperative vertigo (63.9%), 67.9% had similar caloric responses before and after cochlear implantation, 32% showed an alteration of their caloric irrigation test results, and 23.5% showed vestibular deficiency before cochlear implantation.

Of the cases that underwent bilateral simultaneous cochlear implantation ($n=5$), 1 case showed an alteration of their caloric irrigation test results while also experiencing postoperative vertigo, 2 cases experienced isolated postoperative vertigo with no caloric irrigation tests results, and 1case suffered from vestibular deficiency before cochlear implantation. Regarding the 29 cases analyzed that underwent bilateral sequential cochlear implantation, 27.6% showed an alteration of their caloric irrigation test results after first surgery vs. 20.7% after second surgery. Following first surgery, 13.8% of cases that experienced postoperative vertigo showed an alteration of their caloric irrigation test results vs. 3.4% after second surgery. Preoperatively, 17.2% suffered from vestibular deficiency before the first surgery vs. 20.7% before second surgery. Postoperatively, 24.1% showed vestibular deficiency after first surgery vs. 20.7% after second surgery.

Cervical VEMP and postoperative vertigo

CVEMPs were performed in 103 cases pre- and postoperatively. They were evoked in 21.4% of cases and absent in 78.6% of cases. Among the 60 cases with postoperative vertigo, preoperatively, cVEMP data was analyzed for 52 cases as 8 cases did not undergo postoperative testing. CVEMPs were evoked in 53.3% and absent in 33.3%. Postoperatively, cVEMP data was analyzed for 36 cases as 22 had not undergone postoperative testing. CVEMPs were evoked in 15.8% and absent in 84.2% of cases.

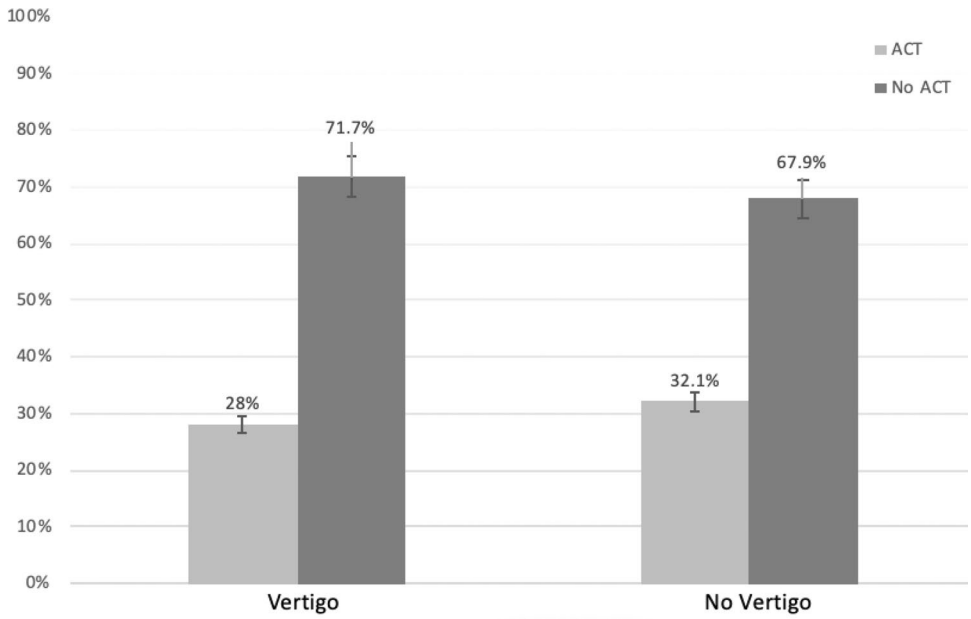


Fig. 1 Occurrence of postoperative vertigo and the alteration of caloric irrigation tests results. No correlation was found (Chi 2 test; $p=0.61$)

In total, 36 cases of postoperative vertigo could be analyzed with cVEMP results available pre- and postoperatively. Of those cases 38.9% showed an alteration in cVEMP results and 61.1% showed no change in cVEMP results after cochlear implantation.

Vestibular assessment and postoperative vertigo

By combining the vestibular examinations (caloric responses and cVEMP) in patients with postoperative vertigo, 8.3% of cases had an alteration of caloric irrigation tests results with an alteration of cVEMP as well, 5% only had an alteration of caloric irrigation tests results, and 15% cases only had an alteration of cVEMP results. Nineteen cases (31.7%) showed no changes in any of the vestibular tests (22 cases had no cVEMPs performed). No correlation was found between alteration of caloric irrigation tests results coupled with alteration of cVEMP and the occurrence of vertigo after cochlear implantation (Fisher's test = 0.69, Table 3).

Age and postoperative vertigo

The mean age at the time of cochlear implantation was 57.5 ± 16.4 years, range (21–87) (Table 4). There was no significant difference in age between cases of postoperative vertigo and those free from this symptom postoperatively (57.2 ± 16.2 years vs. 57.6 ± 16.4 years; Fisher test; $p = 0.71$. No statistical difference was found between the analyzed subgroups (20–29 years, 30–39 years, 40–49 years…).

Side of cochlear implantation and postoperative vertigo

Eighty-six cochlear implants were placed on the left side (unilateral or sequential bilateral) and 75 on the right side. Five cases were implanted bilaterally simultaneously (Table 2). The side of cochlear implantation had no influence on the incidence of postoperative vertigo (Chi 2 test, $p = 0.52$, Fig. 2a). The side of the second cochlear implant in sequential implantation being the right side ($n = 9$) or the left side ($n = 14$) had no influence on the occurrence of postoperative vertigo (Fisher test; $p = 0.48$); the same is true with bilateral simultaneous implantation (Fisher test; $p = 0.36$).

Table 4 Age of cases with postoperative vertigo ($n = 60$) (no correlation was found between age group and occurrence of postoperative vertigo (Fisher test $p = 0.71$)

Age at Time of Surgery (years)	Proportion of cases presenting with postoperative vertigo (%; *n*)	
10–19	0	0/2
20–29	25	3/12
30–39	46.2	6/13
40–49	47.4	9/19
50–59	45.5	15/33
60–69	36.4	13/44
70–79	36.1	13/36
80–89	14.3	1/7

Surgical approach and postoperative vertigo

The insertion of the electrode array into the cochlea was carried out via cochleostomy or via the round window. Cochleostomy was the first route historically described and was performed in 24 cases [18]. From 2011, a modification of the surgical practice led to favor the approach of the tympanic ramp via the round window (142 cases), when possible, in accordance with soft surgery technique recommendations [9]. Postoperative vertigo occurred in 45.8% of the cases of cochleostomy and 34.5% of the cases of round window approach, with no significant difference between these two groups (Chi2 test; $p = 0.29$) (Fig. 2b).

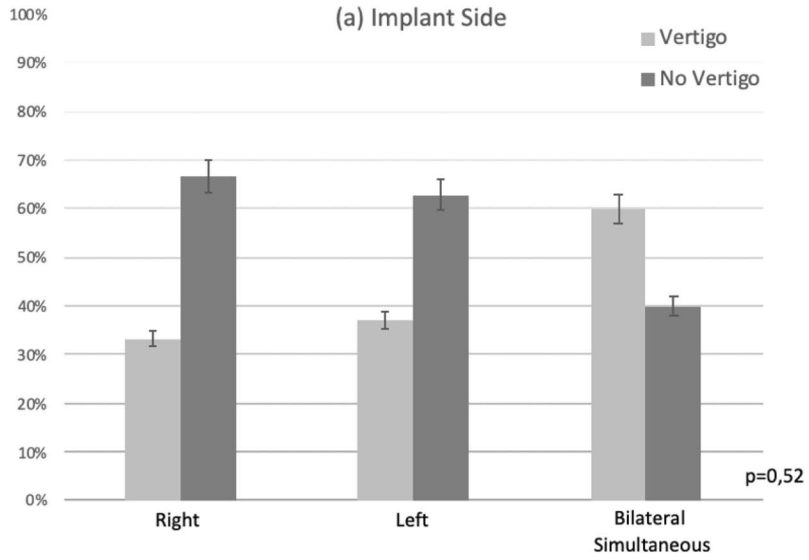
Electrode array characteristics and postoperative vertigo

The characteristics of the electrode array: length, diameter at the apex, diameter at the base, and the use of an insertion stylet were analyzed for the four brands of cochlear implants

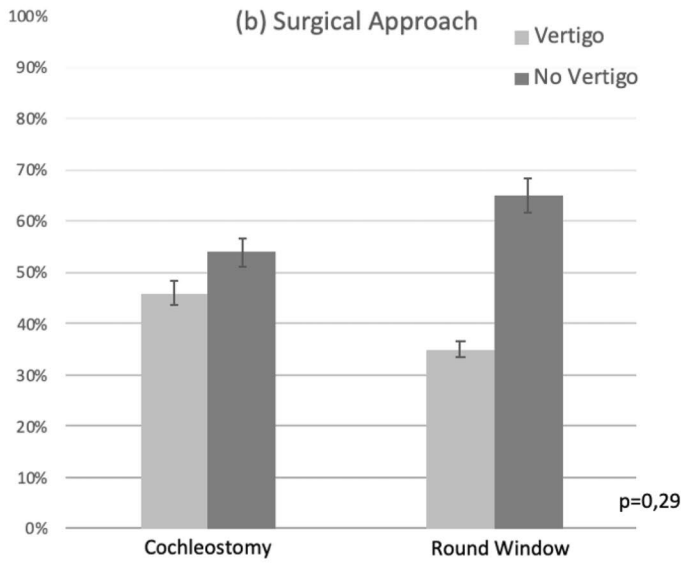
Table 3 Occurrence of vertigo and alteration of caloric irrigation tests results (ACIT) coupled with variations in cVEMP after cochlear implantation

	ACIT			No ACIT		
	cVEMP Alteration	No cVEMP Alteration	cVEMP Unknown	cVEMP Alteration	No cVEMP Alteration	cVEMP Unknown
Vertigo *n* (%)	4 (6.7)	5 (8.3)	8 (13.3)	19 (15)	8 (31.7)	15 (25)
No vertigo *n* (%)	4 (3.8)	11 (10.4)	9 (8.5)	9 (8.5)	38 (35.8)	25 (23.6)

No correlation between the ACIT coupled with variations in cVEMP and the occurrence of vertigo after postoperative cochlear implantation was highlighted (Fisher's test, $p = 0.69$)



Vertigo n ; (%)	25 ; (33.3)	34 ; (37.2)	3 ; (60)
No Vertige n ; (%)	50 ; (66.6)	52 ; (62.8)	2 ; (40)



Vertigo n ; (%)	11 (46)	49 (35)
No Vertige n ; (%)	13 (54)	93 (65)

Fig. 2 Postoperative vertigo in correlation with side of implant (**a**) and surgical approach of the round window (**b**). No correlation between implant side and occurrence of postoperative vertigo was found (test de Chi 2, $p=0.52$). No correlation between surgical approach and occurrence of postoperative vertigo was found (test Chi2; $p=0.29$)

available (Cochlear, MED-EL, Advanced Bionics, and Oticon) (Table 5). No significant difference was found for any of these characteristics with regard to the occurrence of postoperative vertigo.

Discussion

The occurrence of balance disorder or vertigo after cochlear implant surgery varies from 32 to 74% depending on the

Table 5 Characteristics of the electrode arrays

A. Length			B. Diameter of the apex			C. Diameter of the base		
Length (mm)	Vertigo (*n*)	No Vertigo (*n*)	Diameter (mm)	Vertigo (*n*)	No Vertigo (*n*)	Diameter (mm)	Vertigo (*n*)	No Vertigo (*n*)
16	0	1	0.25	1	5	0.40	0	1
18.5	4	8	0.30	25	37	0.60	15	34
19	7	15	0.40	16	31	0.70	5	12
23	1	4	0.50	18	29	0.80	32	48
24	10	3				1.07	2	1
25	23	49				1.30	6	6
26	2	1						
28	7	15						
31.5	6	6						

Length (A), diameter of the apex (B) and diameter of the base (C). (no correlation was highlighted between the length (Fisher test, $p=0.89$), the diameter of the apex (Fisher test, $p=0.71$), the diameter of the base (test of Fisher, $p=0.52$) and the occurrence of postoperative vertigo)

study [5–10]. The same is true for the alteration of vestibular function when assessed using caloric irrigation or cVEMP after cochlear implantation, which varies from 23 to 100% [13, 19, 20].

The present study demonstrated an occurrence of postoperative vertigo in 36% of cases after cochlear implantation, with only 11% occurring in the immediate postoperative period. This prevalence is higher than in other series, notably in comparison to the meta-analysis published by Hänsel et al. which involved 116 clinical studies (14,349 patients), and estimated the occurrence of postoperative vertigo at 9,3% in accordance with the criteria included in our study [21]. Due to close and standardized follow-up with systematic inquiry for postoperative vertigo, the estimate of patients reporting these symptoms seems as reliable as possible with a minimum number of patients lost to follow-up. However, vestibular follow-up examinations were carried out 2 months after surgery and some patients without vertigo did not want to repeat the caloric irrigation at that time, given the inconvenience of this examination, and thus were excluded.

Analysis on the effect of bilateral simultaneous or sequential cochlear implantation on vestibular function has not been well described in the literature. Wagner et al. evaluated the incidence of vestibular disorders after each surgery in patients undergoing bilateral sequential cochlear implantation showing a significant increase in subjective vertigo after the second surgery [20]. They concluded this to be due to possible bilateral impairment of vestibular receptors even when this was not always clearly reflected in vestibular examination results, because only one patient experienced an alteration in caloric responses after first surgery (vestibular deficiency), and no patients showed alteration of caloric responses after second surgery [20]. In the present study, 14 cases showed an alteration in caloric responses after surgery during bilateral cochlear implantation and indeed, much more patients experienced postoperative vertigo (41.4% and 34.5% after the first and second implantation, respectively). However, at 1 year after cochlear implantation, 24.1% had persistent vertigo and only one case experienced new-onset persistent vertigo, which is less than the overall proportion including bilateral and unilateral cochlear implantation.

In the present study, a low percentage of pathologic objective postoperative vestibular test results was found. However, none of the factors studied (age, operated side, surgical technique, electrode array characteristics, and vestibular test alteration) correlated with the occurrence of short-term or long-term postoperative vertigo.

No correlation was found between the occurrence of postoperative vertigo and the alteration of caloric irrigation test results. Interestingly, among patients with vestibular deficiency before cochlear implantation, 22% of them presented with postoperative vertigo. Vertigo presentation postoperatively could be surprising in this population as caloric responses were already altered prior to surgery. This suggests that caloric irrigation, which evaluates the horizontal semicircular canal, does not correctly or solely reflect vestibular function, which can be impaired after cochlear implant surgery, where damage to other vestibular structures can occur as well. As previously mentioned, caloric irrigation remains the most frequently performed test with various reporting regarding its relationship with the presence of vertigo after cochlear implantation, largely showing no correlation [5, 22, 23].

Thereafter, cVEMP can be affected by potential mechanical damage or electrical stimulation to the vestibular system caused by cochlear implantation, although an alteration in saccular function has not been found unanimously [1, 2, 24]. Tien et al. raised the possibility that the insertion of electrodes into the cochlea during cochlear implantation could cause morphological damage in the labyrinth [25].

The saccule remains the most frequently damaged, followed by the utricle and the semicircular canals [12]. Indeed, anatomically, the saccule is 1.5 mm from the round window and, therefore, closer to it than the utricle and the semicircular canals [26]. No correlation was found between alteration of cVEMP and the occurrence of postoperative vertigo in our study. Furthermore, when cVEMP was associated with caloric irrigation results, no correlation was found between alterations of cVEMP, caloric irrigation, and the occurrence of vertigo after cochlear implantation. However, this otolith function test was not performed systematically in the postoperative period for all patients. Although, Abouzayd et al. compared three vestibular function exams (caloric irrigation, cVEMP and Head Impulse tests), without finding any correlation between each test and the occurrence of vertigo after cochlear implantation. Consequently, to better identify the cause of vertigo after cochlear implantation, they suggested the systematic performance of two of these tests, such as caloric irrigation testing and cVEMP, to provide a more global assessment of the vestibular system, or choosing only video Head Impulse Test (vHIT) to assesses the 3 semicircular canals [22]. The vHIT is becoming more widely used as an initial test for patients with suspected vestibular disorders as it provides an objective and more appropriate evaluation of each of the semi-circular canals individually. Paired with caloric irrigation, it could provide a more comprehensive assessment of vestibular organ function. In our study the more recently implanted patients did undergo vHIT but data was insufficient between the pre- and post-operative period to be included in this study.

Theories other than mechanical damages to the vestibular structures have also been discussed. To explain postoperative vertigo, Krause et al., speak of an acute serous labyrinthitis due to cochleostomy or labyrinthitis as a reaction to a foreign body [27]. The effect of electrical vestibular stimulation by the implant on the labyrinth has also been considered [28]. The electrode array type or design had no influence on vestibular outcomes. Krause et al. also found no correlation between the brand of cochlear implant and vestibular changes following cochlear implantation after comparing 2 brands of cochlear implants: Med-El and Cochlear [10]. This was also reflected in the present study.

Therefore, many theories have been suggested as the cause of vestibular impairment following cochlear implantation leading to the understanding that vertigo possibly occurs due to multiple factors. Intrinsic factors are also considered such as patient's age or cause of deafness. After carrying out a comparable analysis to Hänsel et al. and subdividing the population by age group [21], no correlation was found between the age of the patients, the occurrence of vertigo and the alteration of caloric irrigation. It is likely, however, that the present study lacks a sufficient number of patients per age group. In the meta-analysis published by Hänsel et al., advanced age was a significant predictor of postoperative vertigo after cochlear implantation [21]. Certainly, older patients would be less able to compensate for vestibular dysfunctions.

Benign paroxysmal positional vertigo can occur prior implantation. In the present study, this represented 2.4% of cases preoperatively; however, no cases were identified postoperatively. It is important to identify the etiology of vertigo preoperatively to give the best possible information to patients benefiting from a cochlear implantation regarding the persistence of their balance disorder afterwards. Certain pathologies such as assumed endolymphatic hydrops (including Meniere's disease) and perilymphatic fistulas can also be responsible for vertigo in the pre and postoperative period, without cochlear implantation modifying their natural evolution [29]. In this study, patients with fistulas and assumed endolymphatic hydrops of the inner ear had persistent postoperative vertigo, which was present preoperatively, even with plugging of the oval and round window during surgery.

Limitations of this study mainly concerned the testing methods available in our center. The use of air caloric stimulation can produce weaker reactions in comparison to water caloric stimulation. The type of cVEMP stimulus can influence the responses evoked with the literature suggesting short tone bursts, used in this study, to be superior to click stimuli [30]. Ocular VEMP (oVEMP) tests the utricle and the superior vestibular nerve and can be significantly influenced after cochlear implantation (Table 1) [13]. OVEMP was not included in our routine cochlear implantation protocol as the material was not available in our institution.

Regarding the assessment of vertigo, the use of a standardized questionnaire, such as the Dizziness Handicap Inventory (DHI), can provide a more standard evaluation of dizziness and vertigo which can be difficult to evaluate [31]. However, classifying postoperative vertigo according to its duration is useful as immediate and transitional vertigo are not well assessed by standardized questionnaires. The DHI could be practically applied 1 year after surgery to better assess and characterize long term vertigo.

In our future practice adding more extensive vestibular testing including video Head Impulse Tests (vHIT), Subjective Visual Vertical (SVV), or ocular Vestibular Evoked Myogenic Potential (oVEMP) tests to routine pre- and postoperative follow-up could complete our findings and provide more information on the causes of postoperative vertigo following cochlear implantation.

Additionally, a study carried out on selected patients without vertiginous symptoms preoperatively could provide a better understanding of the mechanisms triggering vertigo postoperatively, allowing a more precise analysis with extensive vestibular assessment before and after cochlear

implantation (caloric irrigation, vHIT, SVV, saccular and utricular function testing using cVEMP and oVEMP)."

Conclusion

Postoperative vertigo occurred in 36% of cases and among them one third only during the postoperative period. Half of the patients with postoperative vertigo were directly attributable to cochlear implant surgery. No predictive factors for the occurrence of postoperative vertigo were found. A more global study of the vestibular apparatus before and after cochlear implant surgery (including the Subjective Visual Vertical, vHIT, or cervical and ocular VEMP) would improve the understanding of the pathophysiology of vertigo following cochlear implantation.

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Compliance with ethical standards

Conflict of interest The authors report no conflicts of interest.

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