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REVIEW ARTICLE

Vestibular function and cochlear implant

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Abstract Vestibular lesions are found after cochlear implantation in 23–100 % of cases. The objectives of this study were to evaluate the vestibular function before and after implantation while focusing its feasibility. This prospective study included 35 patients, mean age 49 years. Each patient enjoyed a vestibular balance before and after implantation in a median period of 5 months compared to surgery. Vestibular evaluations were performed using vestibular-evoked myogenic potentials (VEMP) and videonystagmography. Before implantation, the VEMPs were bilateral in 73 % of cases. They are modified after implantation for 13 patients, including 12 missing or reduced potentials on implanted side ($p = 0.0015$). Caloric tests found themselves a significant decrease in the reflectivity of the ear implanted ($p < 0.0001$). Vestibular symptoms were independent of changes on vestibular tests. No relation was found between the occurrence of post-operative vestibular symptoms and the results of the vestibular investigations. However, the achievement of these exams is not easy especially for children and only part of the vestibule is tested. In conclusion, the vestibular assessments help to choose the side of implantation, assess the pre-operative vestibular condition and assess and locate vestibular lesions induced. Further tests should enable a complete vestibular assessment.

Keywords Cochlear implantation · Caloric test · VEMPs · Vestibular symptoms

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Introduction

For over 30 years in adults and 20 in children, the objective of cochlear implantation has been to initiate or restore hearing function in patients with severe to profound bilateral sensorineural hearing loss, pre- or post-lingual, and not improved by conventional hearing aids. These forms of hearing loss, in the absence of a cochlear implant, give rise to a definitive disability and impaired quality of life [1]. In children, implantation should be as early as possible [2]. In adults, there is no age limit for implantation provided individual psycho-cognitive assessment is performed first [3].

Fitting cochlear implants (CI) is not without risk in respect of contiguous organs, particularly the vestibule. In fact, according to the literature, vestibular function is impaired in 23–100 % of cases following implantation [4]. One of the hypotheses for vestibular lesions is damage to the vestibular receptors on surgical insertion of the electrode into the cochlea [5, 6]. The saccule is the most commonly affected receptor [6]. To study these vestibular lesions, functional investigations have been developed. Aqueduct function is evaluated quantitatively using caloric tests. In the literature, ductal lesions following cochlear implantation are reported in 19–93 % of cases [7, 8]. Otolith function is evaluated in everyday practice by means of vestibular-evoked myogenic potentials (VEMP). They explore the saccular otolith system qualitatively by comparing the response obtained in each ear. A deterioration of saccular function is found in 21–100 % of cases [7, 9]. Increasing importance is placed on this vestibular function by dint of the recent increased scope of indications for bilateral implantation.

The main objective of this research was to evaluate vestibular function before and after implantation in candidates

Table 1 Population characteristics

Mean age at implantation	49 ± 25 (range 1–86)
Sex	
Male	12 (34 %)
Female	23 (66 %)
Hearing loss evolution	
Progressive	25
Fast	8
Brutale	4
Hearing loss origin	
Unknown	12 (34 %)
Genetic	11 (30 %)
Connexin 26 mutation	2
Aquired	14 (38 %)
Postmeningitic	2
Toxic	3
Chronic otologic disease	4
Post traumatic	5
CTscan, MRI	
Normal	32 (91 %)
Vestibular malformation	3 (9 %)
Defect of posterior semi-circular canal	2
Defect of lateral semi-circular canal	1

for cochlear implant. This investigation enables the pre-implantation vestibular status to be assessed and helps to select the side to receive the implant. It also enables the impact of surgery on vestibular function to be assessed while examining the feasibility of vestibular investigations in a hospital centre.

Materials and methods

Patients

This prospective study was based on 38 patients receiving an implant between February 2010 and June 2012 who had undergone prior vestibular testing. Of these 38 patients, 3 were excluded from the study because they did not attend for the post-implantation vestibular assessment. In sum, 35 patients were enrolled, 23 women and 12 men. Their mean age at the time of implantation was 49. Five of them were <18 years old when the CI was inserted. Some patients had hearing loss in either ear of different cause and development. The mean duration of hearing loss prior to formal expression of the indication for cochlear implantation was 29 years (0.4–83 years) (Table 1 Population characteristics).

Pre- and post-implantation

Before fitting the CI, patients underwent a work-up comprising a clinical exam, an orthophonic evaluation, consultation with a psychologist, tonal and vocal audiometry and/or auditory-evoked potentials, various types of imaging, vestibular tests and an anaesthetics consultation. Children in particular were offered a genetics consultation. All patients had audiometric criteria for cochlear implant insertion. All implantations were carried out by the same experienced medical team. The surgical technique was standardised with insertion of the electrode via the round window without cochleostomy (Fig. 1 Peroperatives photography, surgery on the left ear: Fig. 1a Posterior tympanotomy; Fig. 1b Electrode through the round window).

We encountered an intra-operative problem in one patient who had a very posterior round window. The mean time between the indication for implantation and the actual date of operation was 1 year (SD 104 days, range: 41 days to more than 9 years). Twenty patients received an implant on the right, 13 on the left and 2 patients bilaterally. A single hybrid implant was inserted. All the devices implanted were produced by Cochlear™ (Lane Cove, Australia). Three different types of implant were used: the Nucleus® Freedom™ electrode contour advance CI 24 RE, the Nucleus® Hybrid™ CI 24 REH and the Nucleus® CI 422 for the last three patients receiving an implant.

Vestibular investigations were always performed by a consultant specialising in vestibular disorders. The mean time between performing pre-implantation assessment and the actual date of operative was 156 days, i.e. a little more than 5 months (SD 104 days, from 19 days to 17 months). The mean time between the operation and post-implantation assessment was 154 days, i.e. 5 months (SD 74 days). They comprised, firstly, a clinical exam with targeted questioning before and after implantation including age on first walking and presence of vestibular signs (repeated falls, vertigo symptoms such as dizziness and/or other disturbances of balance). Two additional investigations were performed: VEMP and caloric tests.

VEMP

These were conducted using CENTOR USB software. A resistance of <3 kΩ was required for each EMG surface electrode. Stimulations were provided in log-on mode for 6.65 ms at a frequency of 750 Hz, by air and/or bone conduction. Cochlear processors were removed for the post-implantation assessment. Stimulations were repeated until at least three reproducible stimulations had been obtained

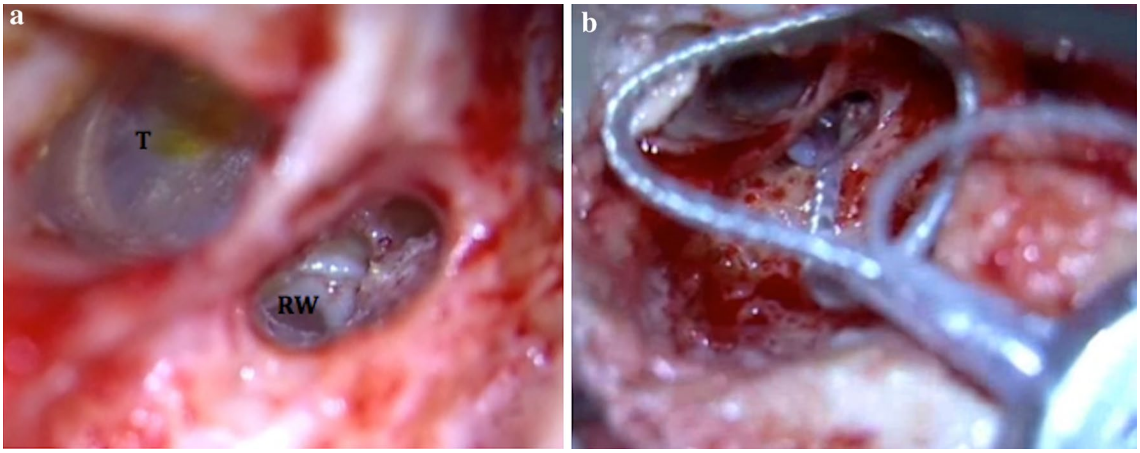

Fig. 1 **a** Posterior tympanotomy. **b** Electrode through the round window. *T* tympanic membrane, *RW* round window

for each ear. Curves obtained were biphasic with an early positive P13 wave followed by a negative wave (N23) [10]. One patient was unable to undergo pre-implantation VEMP on account of a technical problem.

Caloric tests

Caloric tests enabled low-frequency duct function to be studied by videonystagmography (VNG), on the right and left horizontal semi-circular canals alternately. They were performed using Fitzgerald and Hallpike's technique with VNG Ulmer software, and displayed on a Freyss diagram [11]. Several kinds of data were gathered: the reflectivity of each ear and the vestibular deficit of one ear versus the other. Reflectivity was the parameter which was most representative of ductal function, with a very high degree of interindividual variability (from 6 to 80°/sec). The vestibular deficit was defined as the difference in reflectivity between both ears and expressed as a percentage. It was defined as significant by our team when it was higher than 15 %.

In our study, four patients were unable to undergo pre- and post-implantation caloric tests on account of contraindications or difficulties in carrying out the test linked to the patient's age (child). In sum, 31 complete pre-implant and 30 complete post-implant tests were performed.

Statistical analyses

Statistical study initially consisted of a descriptive analysis of data (qualitative variables expressed as percentages and quantitative variables as means, medians and standard deviation). Variables were compared using the following statistical tests: Wilcoxon's and McNemar's tests. The level of significance chosen for these tests was $p \leq 0.05$. Analyses were made using the R software, version 2.1.1, by the biostatistics and clinical research team.

Results

Thirty-five patients who met the criteria for cochlear implantation were enrolled. Twenty received an implant on the right side including one hybrid, 13 on the left and two received bilateral implants. Data from the medical history were collated for the 35 patients before and after implantation.

Clinical evaluation

Age of first walking could be established for 18 patients (27.7 %) with a median of 13.5 months (11–24 months). Of these 18 patients, 7 had a hearing loss present since the age of 2. Of these 7 patients, the median was 15 months (from 12 to 24 months). For the 11 other patients, the median age on first walking was 12 months (from 11 to 18 months).

Regarding vestibular symptoms, a single patient had repeated falls before CI. This patient was a child. Following insertion of the implant, he stopped falling. Before implantation, 11 patients experienced vertigo symptoms, including 2 of the 4 patients with abnormal imaging. After implantation, 12 patients had vertigo symptoms. Several patients described immediate post-operative vertigo which was not recorded in the data report and no longer persisted at the post-implantation assessment. In sum, a stable vestibular status was observed in 26 cases with improved symptoms in 4 cases and a worsening in 5 cases. Patients of <18 years of age did not present either vertigo or other balance problems before or after implantation (Table 2 Vestibular symptoms before and after implantation).

On comparing the group of patients with vertigo symptoms and those without symptom before implantation, there was no significant correlation with implantation age, patient sex or implant side. However, the median implantation age for patients without symptom

Table 2 Vestibular symptoms before and after implantation

$n = 35$	Before implantation	After implantation	No change after implantation	New symptoms after implantation	Symptoms disappearance after implantation
Vestibular symptoms	11 (31 %)	12 (34 %)	7	–	4
No vestibular symptoms	24 (69 %)	23 (66 %)	19	5	–
Total	35	35	26 (74 %)	5 (14 %)	4 (12 %)

was 46, whereas for patients with vertigo symptoms it was 64 ($p = 0.24$). Furthermore, after implantation, the median age of patients presenting vertigo symptoms was 64, whereas it was 48 for those who did not present vertigo ($p = 0.39$).

VEMP

Of the 34 patients who underwent pre-operative assessment, four VEMP evaluations were performed using bone conduction (BC) only. They were present bilaterally. These patients showed no change in their post-operative evaluation. VEMP was performed using air conduction (AC) for 30 of the 34 patients. They were bilateral in 22 cases (73 %), unilateral in 6 cases (20 %) and absent in 2 cases. After implantation, VEMP using AC was performed in 32 patients. Potentials were absent in 2 cases, bilateral in 18 cases (56 %) and unilaterally right or left in 12 cases (37 %).

Of the 22 patients who had symmetrical bilateral VEMP before implantation, 13 (59 %) were changed after implantation. Twelve patients had a decrease or disappearance of the VEMP on the implant side ($p = 0.0015$). In one case, VEMP disappeared on the right although the implant had been fitted on the left. The two patients in whom VEMP had been absent before implantation did not show any change after the implant had been fitted. Of the six patients who had unilateral pre-implantation VEMP, only one changed after implantation with the onset of bilateral VEMP. In this case, the implant had been fitted on the left. Regarding vertigo symptoms, they appeared in 2 of the 13 patients who exhibited VEMP modifications and they disappeared in another 2 of these patients.

Caloric tests

Thirty-one pre-CI and 30 post-CI tests were carried out.

The median pre-implantation vestibular deficit in the 31 patients was 11 % (from 1 to 88 %) between both tested ears. After implantation, the median deficit in the 30 tested patients was 23 % (from 0 to 88 %) ($p = 0.058$) (Fig. 2 Vestibular deficit an caloric tests before and after implantation). Considering only deficits categorised as significant (i.e. >15 %), 13 out of 31 cases before implantation, i.e. 42 %, and 21 out of 30 cases after implantation, i.e. 70 %, were affected. Considering patients who received an implant on a single side and who were tested before and after implantation, i.e. 29 patients, 17 received the implant on the same side as their pre-operative deficit. Thirteen (76 %) experienced an ipsilateral deficit increase on implantation, nine of whom went from a deficit of <15 % to more than 15 %. The remaining four showed a decrease in their deficit. Twelve patients received the implant on the opposite side to their deficit. Four retained a contralateral deficit on implantation but to a lesser degree. The deficit side changed in eight patients with deficit onset on the implant side. This post-implantation deficit was >15 % in five of these patients. In sum, there was either onset or increase in the vestibular deficit on the implant insertion side in 21 out of 29 patients (72.4 %). When the pre-operative deficit was contralateral to the implant side, four patients showed a reduction in this deficit which, in spite of the intervention, remained contralateral. A reduced vestibular activity was therefore found on the implant insertion side in 25 out of 29 cases (86 %).

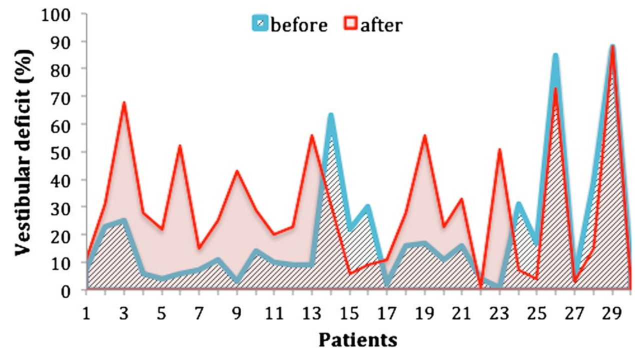

Fig. 2 Vestibular deficit an caloric tests before and after implantation

Of these 25 patients, 2 experienced a disappearance of pre-existing vertigo symptoms and 3 (12 %) experienced the onset of vertigo symptoms. For patients who received bilateral implants, the deficit remained on the same side and showed very little modification in falling from 9 to 5 %. Very little change was observed for the five patients aged <18 ($p = 1$).

Median pre-implantation reflectivity for the ear about to undergo implantation was 36.8°/sec (from 2.2 to 112). It was 17.5°/sec after implantation (from 1.2 to 109.3)

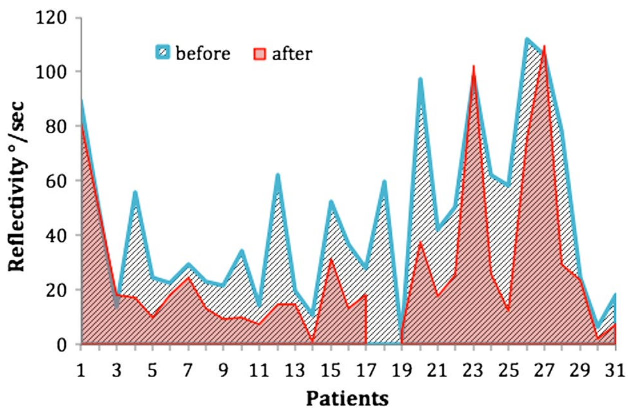

Fig. 3 Reflectivity for the implanted ear before and after implantation

($p < 0.0001$) (Fig. 3 Reflectivity for the implanted ear before and after implantation). This significant difference was not replicated in the group of five patients aged <18 ($p = 0.25$). Regarding the non-implant ear, median pre-implantation reflectivity was 42.2°/sec (from 5.5 to 102), i.e. better than the ear about to undergo implantation. After implantation, it fell to 33.6°/sec (from 2.9 to 104.8) ($p = 0.72$). For patients who were tested and had bilateral implants, reflectivity in both ears fell: from 62.3 to 25.9°/sec for the first ear and 52.5 to 23.4°/sec for the second ear.

Specific implants

Concerning the hybrid implant, the only vestibular change after implantation was the disappearance of the VEMP on BC on the side of the implant, without increase in the vestibular deficit. Concerning the three new-generation implants with electrodes, an increase in the vestibular deficit was found on the implant side in two patients. The third showed the onset of VEMP on the contralateral side to the implant. None of these patients presented pre- or post-implantation symptoms.

For the two patients who had bilateral implants fitted, one had vestibular symptoms after implantation without modification in VEMP or the caloric tests. In the second patient, there was no onset of vertigo symptoms but unilateral right VEMP before implantation became bilateral after implantation. Caloric tests were not carried out since they were too difficult to perform in this child.

Discussion

In this study, we evaluated the clinical and paraclinical impact of implantation on the vestibular system. Our patient cohort was heterogeneous, consisting of both children and adults with an age range of 18 months to 86 years, suffering from various causes of hearing loss and comparable to those in the literature [4, 12–14]. Implant patients may have vertigo symptoms which pre-exist insertion of the implant: there were 13 such patients in our series [15]. In our study, 8 patients had modified pre-implantation VEMP and 13 with a deficit ≥15 % on pre-implantation caloric tests regardless of the aetiology of their hearing loss. Katsiari et al. [16] found that 70 % of pre-operative vestibular investigations were abnormal.

Cochlear implantation is not without danger for the vestibular system. In fact, analysis of VEMP and caloric tests revealed vestibular lesions linked to insertion of the cochlear implant, both in the saccule and the lateral semicircular canals. In the literature, impairment of vestibular function has been documented in 23–100 % of implant patients [4]. The study conducted in 2009 by the team led by Jacot and Wiener-Vacher [17] found a level of 40 % vestibular modification in children after implantation. Histopathological studies based on temporal bone specimens show that cochlear implantation may give rise to morphological lesions in the peripheral vestibular apparatus, affecting in particular the bony spiral lamina, basilar membrane and vestibular receptors [6, 18]. Among these receptors, the saccule is the most commonly affected, followed by the utricle and semi-circular canals [6]. The electrode insertion technique has been incriminated in the vestibular lesions. Todt et al. [5] compared two insertion techniques and showed that the surgical technique influenced the rate of vestibular adverse effects. In patients who received direct insertion via the cochlear window, deterioration of otolith and semi-circular canal function as well as the onset of vertigo symptoms were significantly less common than after insertion with cochleostomy. The outcome of surgical and above all technological improvements, especially new electrodes, is that the risk of cochleo-vestibular damage is constantly being minimised. It is therefore now possible to preserve residual hearing with the insertion of hybrid implants which are reputedly less traumatic [19].

Regarding saccular function, different studies suggest a deterioration in 21 [5] to 100 % [9] of cases. In our study, 59 % of VEMP which were symmetrically present before implantation underwent modification. These modifications occurred significantly more often on the implanted side. Jin et al. [9] examined saccular function in a group of 12 children before and after fitting of a cochlear implant. Pre-operatively, 6 children exhibited bilateral VEMP. Post-operatively, VEMP were absent in 11 children; a single child exhibited measurable VEMP although of diminished amplitude. Krause et al. [12, 20] also found a significant decrease in saccular function when analysing VEMP.

Regarding the aqueducts, our study found a significant difference in reflectivity on the implant side after fitting of the implant. Contralateral reflectivity was, by contrast, preserved. We also detected deficit onset or increase on the same side as the implant in 72.4 % of cases. Reflectivity is not a parameter which has been greatly studied in the literature, although it allows a more exact analysis of horizontal semi-circular canal function and enables pre- and post-implantation comparisons to be made for the same ear. Buchman et al. [4] analysed 22 publications for vestibular function before and after cochlear implantation between 1995 and 2004 and found a modification in the caloric test response in 71 out of 186 patients (38 %). In the literature, duct impairment after cochlear implantation varies from 19 % [5] to 93 % [8]. Differences observed may be secondary to several factors (number and population-type of patients enrolled, implant type, surgical technique). Similarly, the recording technique, standards applied and interpretations of vestibular tests are not always identical. The table above recapitulates some of the studies performed on this topic (Table 3 Overview of clinical studies on the function of peripheral vestibular receptors of the implant ear before and after cochlear implantation [12].

In the literature, the incidence of vertigo symptoms after insertion of a cochlear implant varies from 0.33 to 75 % of cases [4, 13, 14, 21–23]. Vertigo symptoms after implantation may be secondary to direct injury [24], intra-operative loss of perilymph [25], post-cochleostomy labyrinthitis, endolymphatic hydrops [13], implant-linked electrical stimulation [26] or foreign-body-induced labyrinthitis [23]. Evaluation of the quality of life by questionnaire has been proposed, in particular using the Dizziness Handicap Inventory questionnaire [27]. In our study, vertigo symptoms appeared in 5 out of 22 patients (22.7 %). We did not find any correlation between the disappearance of VEMP and/or reduced reflectivity in the implanted ear and the onset of symptoms. These results are consistent with those in the literature [16, 21, 28]. Kubo et al. [23], in their series of 84 patients, found early-onset vestibular symptoms (63 % at 1 month) which, however, did not persist (<2 % at 6 months). Advanced age has been found to be a factor predictive of the onset of these post-operative vestibular symptoms [12]. This correlation has not always been reproducible [14, 16, 29]. Other studies failed to find any correlation between post-operative vestibular symptoms and sex, implant side [16, 29] or results of pre-operative caloric tests [14]. Jacot et al. [17] failed to find any correlation with the aetiology of hearing loss, age, implant type or surgical technique in a cohort consisting solely of children.

Regarding bilateral implantations, the indications have been broadened and continue to develop. Some studies have shown a benefit linked to the fitting of a bilateral implant, whether in terms of hearing level, sound localisation or even sound discrimination, notably in children [30]. Pre-operative evaluation of vestibular function is as important as for unilateral implants since bilateral areflexia also produces disturbances of balance as well as oscillopsia [31].

Table 3 Overview of clinical studies on the function of peripheral vestibular receptors of the implant ear before and after cochlear implantation [12]

Reference	Patients	Measurable functional impairment of		Method
	n	hSCC (%)	Sacculus (%)	
Basta et al. [7]	18		100	VEMP
Jin et al. [9]	12		100	VEMP
Todt et al. [5]	35/28	19	21	ENG_{cal}, VEMP
Krause et al. [12]	30	50	86	VNG_{cal}, VEMP
Katsiari et al. [16]	20	60	60	ENG_{cal}, VEMP
Brey et al. [30]	17	40–43		$ENG_{cal+rot}$
Fina et al. [13]	66	56		$ENG_{cal+rot}$
Enticott et al. [14]	86	32		ENG/VNG_{cal}
Filipo et al. [8]	14	93		VNG_{cal}
Huygen et al. [31]	13	31		ENG_{cal}
Ito [32]	24	38		ENG_{cal}
Mangham [33]	9	44		ENG_{rot}
Szirmai et al. [34]	60	23		ENG_{cal}
Our study	35	72.4	59	VNG_{cal}, VEMP

VEMP vestibular-evoked myogenic potentials, *ENG* electronystagmography, *VNG* videonystagmography, *cal* caloric testing, *rot* rotatory chair testing, *hSCC* horizontal semi-circular canal

The post-implantation work-up was performed 5 months after the implants were inserted. There is no consensus about exactly when these investigations should be performed. Katsiari et al. [16] compared assessments carried out 1 month and 6 months after implantation. In a cohort of 20 patients, he found no modification between these two assessments for the VEMP and only one modification in the caloric tests.

These vestibular investigations require medical and paramedical personnel who are qualified and able to devote time to the procedures. Complete vestibular work-ups tend to last about an hour and often longer for children. Effective parental co-operation is absolutely essential. VEMP can be recorded even in very young children as soon as an adequate contraction of the sternocleidomastoid muscle can be obtained [32, 33]. Interpretation is straightforward and the test not unduly restrictive for patients. On the other hand, difficulties may be encountered when performing caloric tests (vertigo, nausea, length of the test, need to make the surroundings and equipment child-friendly, etc.). Licameli et al. [34] were able to carry out caloric tests in only 3 of the 42 children enrolled in their study on account of the difficulty they experienced in complying with the test. Jacot et al. [17], however, managed to perform caloric tests in 87 out of 89 children enrolled. Investigations were conducted by a highly trained team and using techniques specially adapted for children.

Conclusion

For more than 30 years, the objective of cochlear implantation has been to initiate or restore hearing function in patients with severe to profound bilateral sensorineural hearing loss. Indications continue to expand and the population potentially able to benefit from this technology is becoming ever larger. Accordingly, otologists and physiologists have been interested for some years now in the consequences, particularly vestibular, of inserting a cochlear implant. Our study, like other reports in the literature, found vestibular lesions after implantation, affecting both the saccule and aqueducts.

One of the causes highlighted to account for these vestibular lesions is the surgical technique, essentially insertion of the electrode. Technological advances offer electrodes which are increasingly less traumatic, shorter and of finer bore, and which no longer require an insertion mandrel.

Cochlear pre-implantation work-ups are carried out by a multidisciplinary team. Vestibular assessments require time and experience. VEMP are straightforward to perform irrespective of the age, and while caloric tests provide quantitative results which are easy to interpret; they may be awkward to perform in small children.

The consequences of destruction or partial lesion of the vestibular system do not appear to be correlated with vertigo symptoms experienced by patients. However, cochlear implanted candidates should be informed for the possibility of post-operative symptoms.

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