REVIEW

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CURRENT OPINION

Milestones in the development of a vestibular implant

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Purpose of review

Bilateral vestibular deficits exist and their prevalence is more important than believed by the medical community. Their severe impact has inspired several teams to develop technical solutions in an attempt to rehabilitate patients. A particularly promising pathway is the vestibular implant. This article describes the main milestones in this field, mainly focusing on work conducted in human patients.

Recent findings

There have been substantial research efforts, first in animals and more recently in humans, toward the development of vestibular implants. Humans have demonstrated surprising adaptation capabilities to the artificial vestibular signal. Today, the possibility of restoring vestibular reflexes, particularly the vestibulo-ocular reflex, and even achieving useful function in close-to-reality tasks (i.e. improving visual abilities while walking) have been demonstrated in humans.

Summary

The vestibular implant opens new perspectives, not only as an effective therapeutic tool, but also pushes us to go beyond current knowledge and well-established clinical concepts.

Keywords

balance, neuroprosthesis, plasticity, vestibular function, vestibulopathy

INTRODUCTION

Deafness and blindness are widely recognized handicaps. In contrast, only a few people are aware that one can be born without vestibular function or that it can be lost later in life. However, it is estimated that approximately 500 000 patients suffer from a complete bilateral vestibular deficit (BVD) in Europe and the United States [1]. Dandy [2] already gave a first rough description of this condition based on reports of patients who underwent bilateral surgical section of the vestibular nerves for Menière's disease in 1941. Yet, most medical specialists seem to ignore the existence of BVD as suggested by the large number of doctors that patients have to consult before diagnosis is made [3]. In particular, diagnosis is missed when there is no known classical cause (e.g. ototoxic or traumatic) and when hearing is preserved [4]. This is dramatic in regard to the consequences of the disorder on physical, emotional and social functioning [5].

No medical treatment to restore lost vestibular function exists and physical therapy is only mildly effective in BVD patients [6]. These facts justify the efforts toward the development of technical aids, for example sensory substitution devices that provide acoustic or tactile information according to body movement direction and amplitude [7–10]. Another novel and promising field is that of noisy (i.e. subthreshold) galvanic vestibular stimulation. Indeed, recent studies have demonstrated the possibility of enhancing vestibular reflexes and even improving postural stability both in healthy volunteers and in patients with BVD using this technique [11–16]. Interestingly, these positive effects seem to persist even hours after stimulation is stopped [17]. The mechanism underlying the observed improvements

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KEY POINTS

- BVDs exist, are more common than generally believed and have severe impact.
- Vestibular implants appear as a promising means of rehabilitation for patients suffering from severe BVDs.
- Animal experiments paved the way to human research and initial technical developments. However, the surprising adaptation capacities to the 'artificial' vestibular signal observed in humans, much more efficient than in animal models, simplified the development pathway and at the same time challenge established clinical concepts.
- Vestibular implants are effective tools to restore vestibular function.
- Vestibular implants offer unprecedented possibilities to evaluate balance in general and central adaptation capacities.

still remains poorly understood, but the most popular hypothesis is that of stochastic resonance enhancing residual vestibular function (see, e.g. [18,19]).

Another particularly promising and recent technical alternative is the vestibular implant. This device was conceived following the same concept than that of the cochlear implant used to rehabilitate deaf patients. The vestibular implant consists of motion sensors rigidly fixed to the patient's head and of electronic components (processor and stimulator) that translate the received motion information into electrical signals transmitted to the brain via electrodes implanted in the vicinity of vestibular nerve endings. Today, the project is limited to restoring semicircular canal function, none of the teams involved in this development are working on restoring otolith function.

The purpose of this article is to retrace the major milestones in the development of vestibular implants, and to highlight an unexpected observation in humans that challenges well-established clinical concepts.

ANIMAL STUDIES

The first milestone in the development of vestibular implants must be attributed to Cohen and Suzuki [20–23]. They systematically studied eye movements and postural changes induced by electrical stimulation of semicircular canal nerves in various animal models during the 60s. They demonstrated that 'eye movements in any spatial plane can be induced by summing the eye movements induced by the stimulation of several canal nerves'.

On the basis of this pioneering work and on the knowledge subsequently acquired in vestibular physiology [24–26], Gong and Merfeld [27] at Harvard University (Boston, USA) were the first to imagine restoring lost vestibular function using a vestibular implant. This group fulfilled important milestones in the field. In 2000, they described a first prototype that was tested in guinea pigs. They showed that a rotational cue could be delivered to the nervous system using a piezo-electric gyroscope that modulated, according to head movements, the frequency of constant-amplitude electrical pulsatile signals ('baseline electrical activity') delivered to both ears. This is the first report of an artificially generated vestibulo-ocular reflex. They also showed that after long-term stimulation, even at stronger electrical intensities, animals could maintain righting and vestibulo-ocular reflexes. This demonstrated that their chronic electrical stimulation profile preserved the stimulated nerve in the long term.

In order to limit the risks of hearing deficit related to surgery, the bilateral vestibular implant concept evolved to a unilateral device. Restoring vestibular reflexes by implanting a single ear required the development of specific stimulation methods allowing to encode bidirectional movements. This could be achieved by re-establishing a 'baseline electrical activity' which could be increased or decreased to encode movements in both directions. In 2002, Gong and Merfeld [28] reported that sudden unilateral restoration of this 'baseline electrical activity' resulted in important vestibular symptoms, such as nystagmus similar to that observed in human patients following a sudden unilateral vestibular loss, but in the opposite direction. The nystagmus subsided after approximately 1 day of continuous electrical stimulation, after which the 'baseline electrical activity' could be modulated to generate the artificial vestibulo-ocular reflex. The nystagmus reappeared when the electrical stimulus was suddenly stopped, but in reversed direction and with shorter duration. This confirmed that the animal could adapt to the artificial 'baseline electrical activity' and validated the stimulation paradigm.

After these fundamental demonstrations of feasibility, Merfeld's team focused on investigating the ability of the central nervous system to adjust responses to chronic stimulation conditions. For example, in a set of experiments, electrodes implanted on the posterior ampullary nerve were driven by a motion sensor kept parallel to the axis of the lateral canals. Over 1 week, the axis of the ocular response shifted from their original vertical alignment to the horizontal head rotation [29]. Another important observation of this group was that successive 'on-off' cycles of continuous electrical stimulation resulted in progressively shorter periods of nystagmic responses at the onset and offset of stimulation [30]. Finally, they also demonstrated that the modulation of the 'baseline electrical activity' still elicited vestibulo-ocular reflexes even after months of chronic stimulation [31].

These results of animal experiments, showing rapid adaptation to the restoration of electrical activity in the vestibular system and demonstrating the ability to generate artificial reflexes even after months of continuous stimulation, set the basis for starting experimental work in human patients.

HUMAN STUDIES

The first step in the research conducted in humans was to determine suitable implantation sites to selectively stimulate the structures of the vestibular system. An extralybyrinthic approach was developed to place the electrodes close to the posterior [32] and lateral ampullary nerves [33] without opening the labyrinth. An intralabyrinthic approach allowing positioning an electrode in the ampulla of each of the three semicircular canals was also developed [34].

The second step was to explore the responses of the human vestibular system to electrical stimulation, similar to the experiments by Cohen and Suzuki [20–22]. Acute trials of electrical stimulation of the vestibular nerve branches were performed in patients undergoing surgery for cochlear implantation or suffering from intractable definite unilateral Meniere's disease eligible for a surgical labyrinthectomy. The posterior [35,36] and the lateral [37] ampullary nerves were surgically exposed under local anesthesia via the external auditory canal and electrically stimulated for periods of 20–60 s. Eye movements were recorded using a two-dimensional video-oculography system. These experiments confirmed that nystagmic responses aligned with the plane of the stimulated canal could be evoked in human patients. The amplitude of the response correlated with the frequency and with the amplitude of the electrical stimulus. Interestingly, a noticeable decrease in response amplitude was observed after only a few seconds of stimulation. This was followed by a reversed nystagmus at the cessation of the stimulus, providing the first indications of rapid adaptation to the artificial vestibular signal.

The next step was to demonstrate the possibility of restoring a 'baseline electrical activity' in the vestibular apparatus that could be modulated according to head movements, to mimic the physiology of the system. For these experiments, Guyot *et al.*'s [38] group in collaboration with Med El (Innsbruck, Austria) developed a first vestibular implant prototype based on a modified cochlear

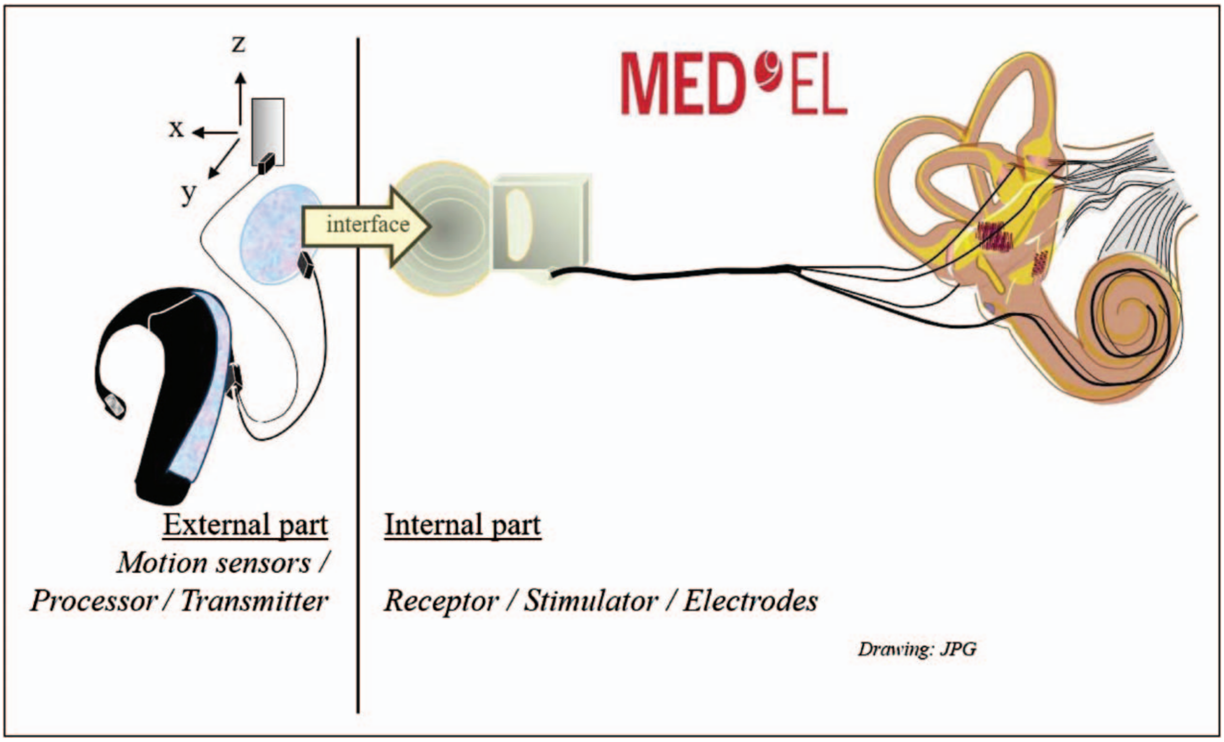


FIGURE 1. Cochleo-vestibular implant prototype. Scheme of the vestibulo-cochlear prototype developed by the Geneva – Maastricht group in collaboration with Med El (Innsbruck, Austria). One to three electrodes are removed from the cochlear array and placed in the vicinity of the vestibular nerve branches innervating the semicircular canals.

Table 1. Criteria of bilateral vestibular deficit

Caloric (30° and 44°)	Slow phase average peak velocity ≤ 5°/s
Pendular (0.05–0.1 Hz, ω_{max} 60°/s)	Gain ≤ 0.2
Video head impulsion test	Pathological for six semicircular canals
cVEMPS and oVEMPS*	Absent on both sides

VEMPS, vestibular evoked myogenic potentials.
Criteria of bilateral vestibular loss used by the Geneva – Maastricht group.

implant. Some electrodes were removed from the cochlear array and implanted in the proximity of the vestibular nerve branches innervating the semicircular canals (Fig. 1) in patients suffering from BVD chosen according to strict criteria (Table 1). For safety reasons, only patients with at least one deaf ear were eligible for vestibular implantation.

The first implantation was performed in 2007. The device had only one vestibular electrode that was placed on the posterior ampullary nerve. When the electrode was activated for the first time, a strong nystagmic response was observed. Surprisingly, the nystagmic response subsided very rapidly, in only 27 min. When the stimulation was stopped, a nystagmus of opposite direction was observed, lasting only approximately 3 min, further confirming that the patient had adapted to the continuous electrical stimulation. Moreover, successive 'on-off' periods of continuous stimulation resulted in progressively shorter adaptation periods. Finally, after adaptation it was possible to generate bidirectional, smooth eye movements by up modulating and down modulating the 'baseline electrical activity' [38,39]. Amplitude modulation produced oscillatory eye movements of larger amplitude than frequency modulation.

The ability of humans to adapt rapidly to the 'baseline electrical stimulation' without major discomfort and the possibility to generate controlled eye movements with a unilateral prosthesis fulfilled the first fundamental prerequisites for the development of a vestibular implant in humans.

Today, 13 patients have been instrumented with prototype cochleo-vestibular implants by the Geneva-Maastricht group. A special interface coupling a motion sensor to the system was developed [40] to capture the signals from a three-axis gyroscope (LYPR540AH; ST Microelectronics; Geneva, Switzerland) and modulate the 'baseline electrical activity' (Fig. 1). This allowed the group to focus on the evaluation of the clinical prospects of the vestibular implant. In 2014, the group achieved the first demonstration of restoration of an artificial vestibulo-ocular reflex in three patients [41]. This artificial vestibulo-ocular reflex was almost absent in the low frequencies of rotation and started to grow at 0.5 Hz reaching its maximum at rotation frequencies of 1 and 2 Hz, similar to the natural reflex [42,43] (Fig. 2) [41]. However, it is essential that

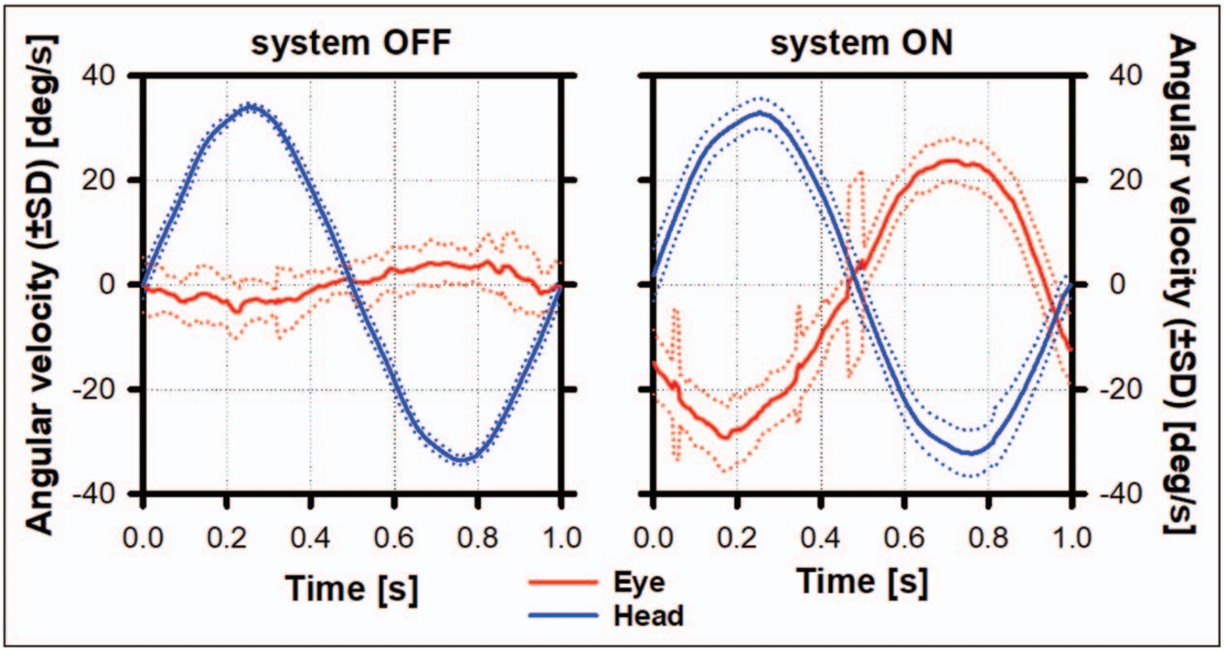


FIGURE 2. Restoration of the vestibulo-ocular reflex with a vestibular implant [32]. Patients suffering from a BVD and equipped of a vestibular implant were submitted to horizontal whole-body rotations. The vestibulo-ocular reflex is absent with the device turned OFF (left) and normalized when the device was turned ON (right). From [41].

the vestibular system responds to higher frequency angular accelerations that occur frequently during natural activities. Guinand *et al.* [44▪▪] were able to reproduce such high-frequency vestibulo-ocular reflexes with gains increasing proportional to stimulation strength from 0.4 to supranormal values above 1 (Fig. 3) [35,44▪▪]. They also showed that the gain for excitatory movements was superior to that for inhibitory head impulses, consistent with the observations in patients with unilateral vestibular loss.

The last milestone required to demonstrate the feasibility of the vestibular implant was to show that the artificially restored vestibular reflexes were sufficient to lessen patient complaints, notably oscillopsia, a frequent BVD symptom. In 2016, Guinand *et al.* [47▪▪] measured the visual acuity of six implanted patients using Sloan letters displayed on a computer screen and compared it in static (at rest) and dynamic (while walking on a treadmill at controlled velocity) conditions. Without the vestibular implant, their visual acuity was impaired in dynamic conditions, consistent with findings in BVD patients [45,46]. However, it normalized when the vestibular implant was turned ON (Fig. 4) [47▪▪].

All these studies in humans focused on the vestibulo-ocular reflex, the parameter most frequently used to evaluate peripheral vestibular function. As this reflex is successfully evoked by the vestibular implant, it is also possible that other vestibular functions can also be restored [48▪]. For example, further

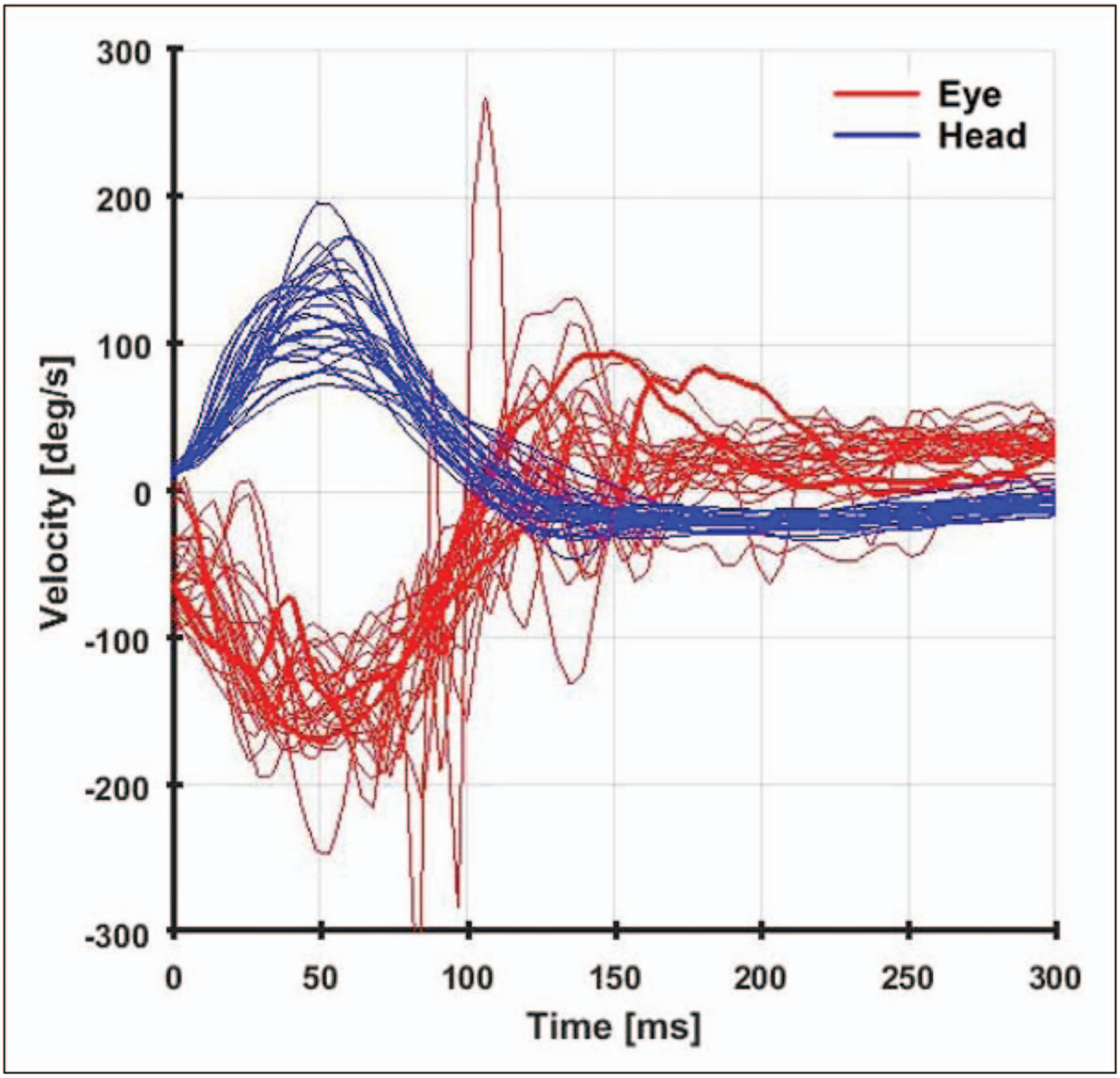


FIGURE 3. Vestibulo-ocular response to the head impulse test in a patient equipped with a vestibular implant [35]. In this case, the response replicates the normal behavior of the normal reflex. From [44▪▪].

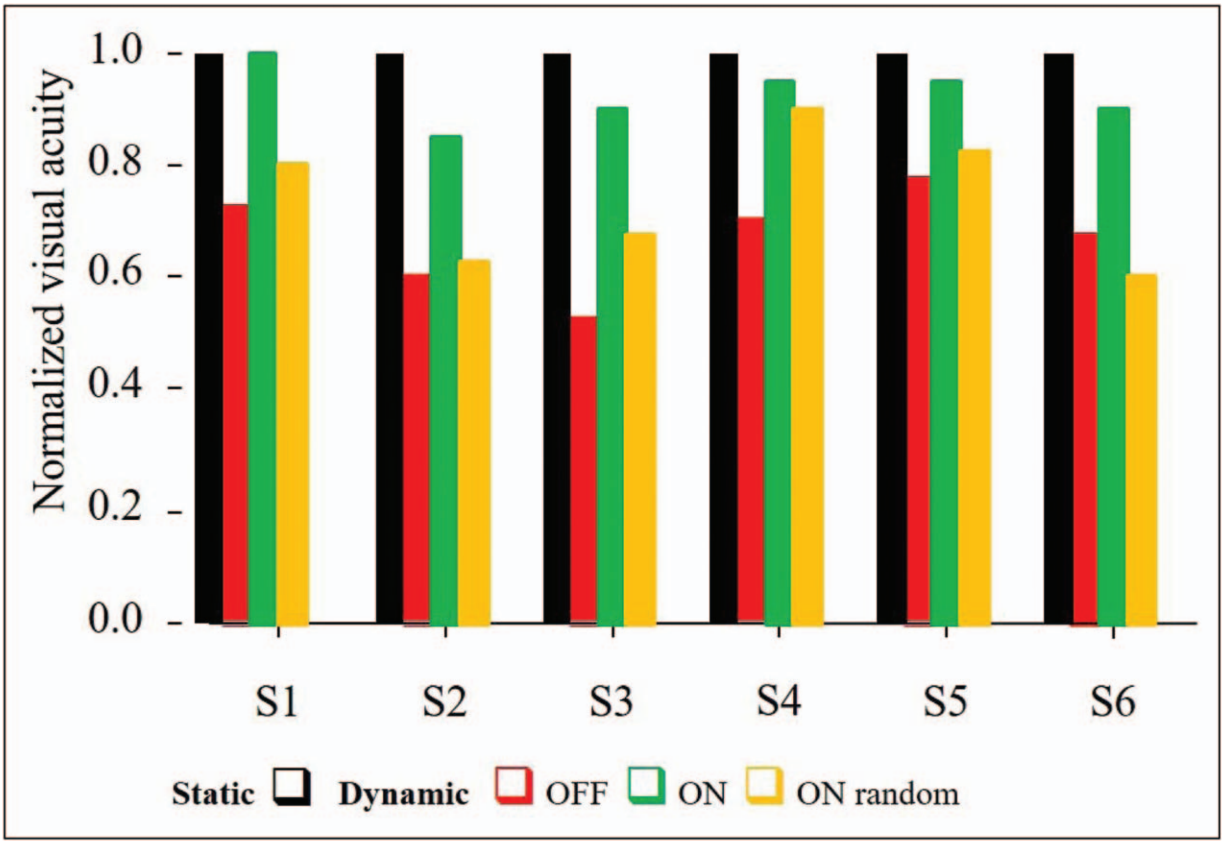


FIGURE 4. Comparison of visual acuity scores measured in six BVD patients equipped with the vestibular implant [38]. The visual acuity was measured using Sloan letters displayed on a computer screen in static (at rest) and dynamic (while walking at controlled velocity) conditions. Values were normalized to those obtained in static conditions. The visual acuity decreased in dynamic condition and normalized when the vestibular implant was turned ON. This finding was reinforced by the fact that visual acuity decreased again when the prosthesis provided random information instead of motion information, ruling out a 'placebo' effect. Modified from [47▪▪].

evaluations are underway to evaluate postural balance in BVD patients equipped with a vestibular implant.

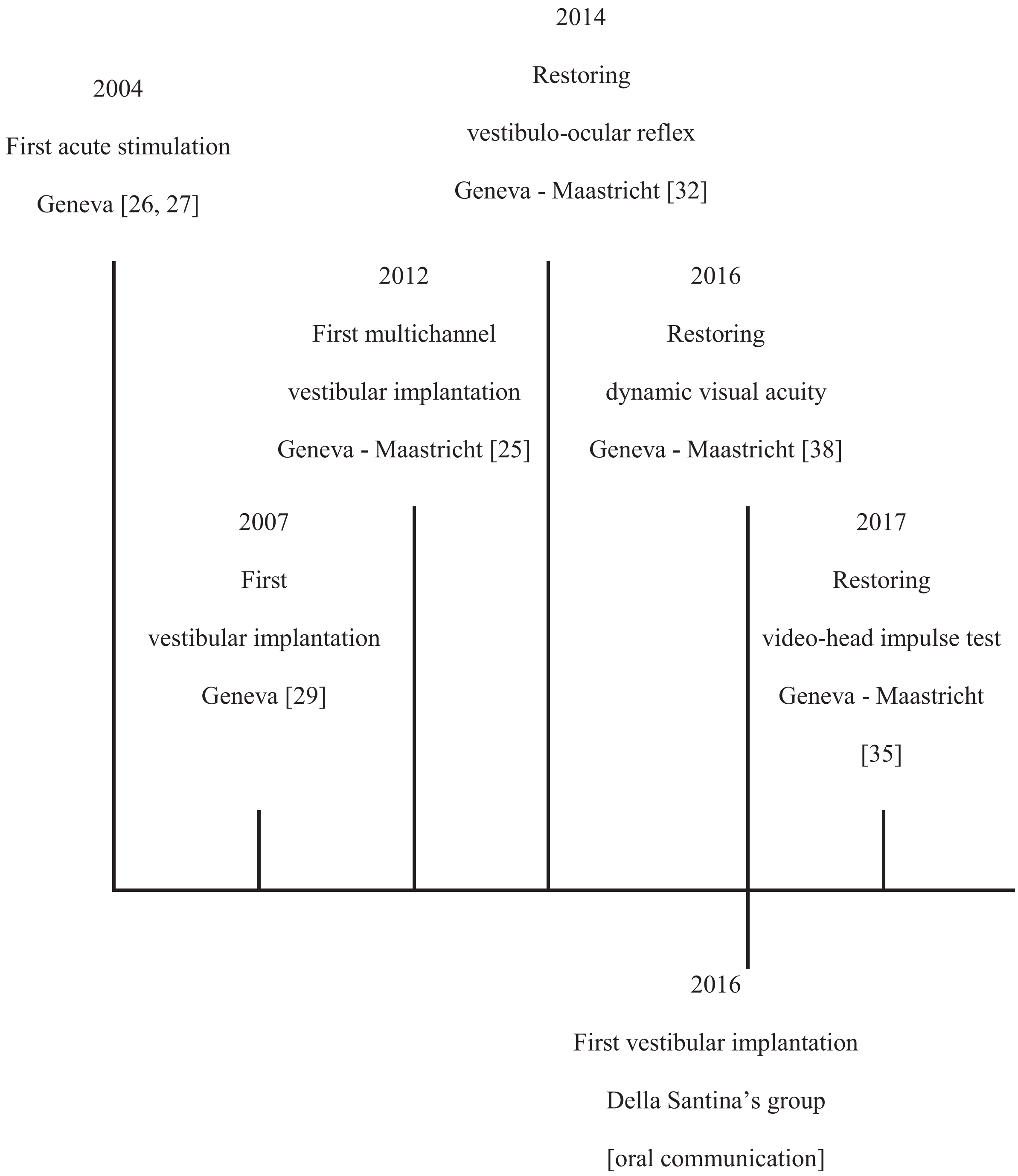
Additional work in the field

Table 2 summarizes the chronology of experiments in humans aiming at restoring vestibular function in case of BVD. In addition to the Geneva-Maastricht team, another two groups are working on the development of vestibular implants.

The group led by Della Santina (Vestibular NeuroEngineering Laboratory – Johns Hopkins Medicine) has undertaken a meticulous development pathway involving animal experiments, technical developments and physiological models [49–52]. Their idea is to develop a standalone vestibular implant, not combined with a cochlear implant, and able to function continuously (24 h a day, 7 days a week) in order to avoid episodes of vertigo when the device is turned ON or OFF. This imposes that the prosthesis be water proof and that the battery be changed without interrupting stimulation. However, the observation by Guyot *et al.* that adaptation time to OFF – ON and ON – OFF stimulations was much shorter in humans than in animals [38,39] should simplify the technical development of the device. Furthermore, having a device that is frequently turned ON and OFF can have other advantages. This feature should allow patients to keep their ability to adapt quickly to the 'ON' and 'OFF' conditions, therefore limiting the risk of important vertigo in case of device failure. It will also result in less discomfort than a device that has to be worn continuously, regardless of its dimensions. To the best of our knowledge, Della Santina's group has not published any results of experiments in humans yet.

Finally the team led by Jay T. Rubinstein (Vestibular Implant Development Team – University of Washington) initially investigated a concept fundamentally different from those mentioned before. They developed a device designed to function as a 'vestibular pacemaker' to treat Menière's disease attacks: it was supposed to be switched ON only

Table 2. Chronology of experiments in humans toward the development of a vestibular implant for patients suffering from a total bilateral vestibular deficit



when symptoms appeared or during periods of frequent attacks [53]. Unfortunately, although the vestibular stimulator successfully encoded vestibular information in Menière's patients, it also led to loss of hearing and vestibular function in the implanted ear, forcing them to temporarily stop the project [54].

GENERAL COMMENTS

Some of the observations made in the context of the development of vestibular implants question some well-established clinical notions. For example, it is generally accepted that a vestibular disorder must be associated with a nystagmus whose characteristics primarily serve (among other things) to differentiate a peripheral or central origin [55]. However, when the ‘baseline electrical activity’ was delivered progressively to implanted patients they reported perceiving ‘something’ at intensities of stimulation 10-fold lower than those required to trigger nystagmus. This supports the idea that vertigo of peripheral vestibular origin may exist without detectable nystagmus. Another interesting observation was the fast adaptation to the restoration of a ‘baseline electrical activity’ in the vestibular system. This raises intriguing questions about why patients remain dizzy for several days after sudden unilateral vestibular deficits regardless of their origin.

CONCLUSION

All teams involved in the development of a vestibular implant primarily aim at helping patients suffering from severe disease. In view of the encouraging results obtained so far in humans and the now important involvement of cochlear implant manufacturers, we can reasonably expect the first, worldwide and multicentric clinical trials of vestibular implants to begin within 5 years. All these efforts should lead to a clinical application in the near future.

It should also be mentioned that the vestibular implant opens new possibilities for exploring several fundamental issues: balance function, the adaptive capacities of the brain, the processes of temporal integration of sensory information necessary for equilibrium [56,57] and probably for better understanding vestibular physiology and vestibular disorders.

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Conflicts of interest

There are no conflicts of interest.

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