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Original Article

Vestibular Co-stimulation in Adults with a Cochlear Implant

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BACKGROUND: Vestibular co-stimulation is a side effect of cochlear implant stimulation. The electrical currents delivered by the cochlear implant can spread toward the vestibular system and thus stimulate it. The aim of the study is to evaluate whether it is feasible to functionally restore the balance by modifying the vestibular co-stimulation.

METHODS: Four adult patients, who had received a commercially available cochlear implant previously, were enrolled. Counterbalanced biphasic pulses were presented as bursts or as an amplitude-modulated biphasic pulse train (modulation frequencies ranging from 1 to 500 Hz) at the participant's upper comfortable level for electrical stimulation. Subjective sensations and vestibular-mediated eye movements were used for evaluating the possible effects of vestibular co-stimulation.

RESULTS: One participant experienced a cyclic tilting of his head in response to an amplitude-modulated biphasic pulse train with a modulation frequency of 2 and 400 Hz. However, during a follow-up visit, the sensation could not be replicated.

CONCLUSION: Subjective vestibular sensations or vestibular-mediated eye movements could not be electrically evoked with a commercially available cochlear implant in 4 adult patients with almost normal vestibular function. Therefore, customized design of the hard-, firm-, and/or software of the commercially available cochlear implant might be necessary in order to electrically restore vestibular performance.

KEYWORDS: Cochlear implants, electrical vestibular stimulation, spread of excitation

INTRODUCTION

Bilateral vestibulopathy (BVP) is a chronic vestibular syndrome that can have a serious impact on the quality of life. Patients with BVP are at increased risk of falling, which can result in several detrimental and sometimes even fatal consequences (e.g., (hip) fractures, hospital admissions, death).[1,2] Because these patients continuously and consciously have to correct their balance, the cognitive load is often increased as well.[3,4] Participation in social and professional activities may thus become complicated with social isolation as a result.[5,6] There are a couple of treatment options for patients with vestibular loss like vestibular rehabilitation or sensory substitution devices.[7-10] However, these treatment options rely on multisensory integration rather than actual restoration of the vestibular reflexes. Therefore, electrical vestibular stimulation (EVS) has been suggested as an alternative approach for artificially restoring the vestibular input. One example of EVS is vestibular co-stimulation with a commercially available cochlear implant (CI). The underlying mechanism of vestibular co-stimulation is based on the theory of spread of excitation, which implies that the currents delivered by the CI can spread toward the surrounding neural structures and tissues. Multiple reports of vestibular co-stimulation have been made throughout the years. In 1982, Eisenberg et al[11] wanted to investigate the possibly detrimental influence of a single-electrode CI on the vestibular system, but instead, they had to conclude that using a CI can actually improve postural stability. Later, Bance et al[12] were able to evoke a nystagmus beating toward the side of implantation with a multichannel CI, albeit in 1 case only. More recently, Nassif et al[13] concluded that the gain of the video head impulse test (vHIT) increased during CI stimulation in comparison to the gain measured without the CI activated in the same patients. Several other researchers observed improvements in postural stability and gait,[14-17] and

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perception of verticality.[18] Furthermore, cervical and ocular vestibular-evoked myogenic potentials (c- and oVEMPs, respectively) have been shown to be electrically evocable through CI stimulation.[17,19] The results of the abovementioned studies suggest that the CI is capable of simultaneously stimulating the auditory and vestibular system without requiring additional modifications of the device and/or the surgical technique.

In this study, the otolith system is targeted as it is mainly responsible for the prevention of falls and their detrimental consequences.[20] The goal of this study was to evaluate whether it was possible to electrically elicit otolith-mediated motion percepts (e.g., head tilt or translations) or otolith-mediated reflexes (translational vestibulo-ocular (tVOR) reflex or ocular counter-rolling) in adult CI patients.

MATERIALS AND METHODS

Participants

Four adult CI recipients (2 males and 2 females) were enrolled at least 6 months after the initial activation of their CI. The subjects were implanted at the European Institute for ORL-HNS (Sint-Augustinus, GZA Hospital, Antwerp, Belgium). In order to be able to subjectively perceive the effect of vestibular co-stimulation, it was decided to include only patients with residual or normal vestibular function. The likelihood of detecting a perturbation was expected to be higher in patients without total deprivation of the vestibular afferents.

Subject 1 (S1) and subject 4 (S4) were unilaterally implanted with a Nucleus® CI532 (Cochlear™, Sydney, Australia), while S2 and S3 received a Nucleus® CI512 (Cochlear™, Sydney, Australia) (Table 1). All participants had progressively developed bilateral profound sensorineural or combined hearing loss (Table 1). No anatomical anomalies were detected on computed tomography or magnetic resonance imaging at the time of implantation.

Vestibular Function Tests

The vestibular performance was evaluated before and after implantation. Postoperative vestibular testing was performed without CI. The vestibular test battery included the sinusoidal harmonic acceleration (SHA) test, the caloric irrigation test, the horizontal vHIT, the cVEMP test, and the oVEMP test.

The SHA test (Minitorque, Difra Instrumentation SA, Eupen, Belgium) was performed at a rotation frequency of 0.05 Hz with a maximum velocity of 50°/s. A gain above 0.29 was considered normal (Table 2). Subsequently, caloric irrigations were performed with cold (30°C) and warm (44°C) water (Aquastar, Difra Instrumentation SA, Eupen, Belgium). The caloric response was considered normal when the caloric sum of all irrigations was >48.8°/s and the unilateral weakness parameter was <17.4% (Table 2). Subject 1 did not receive caloric testing after the implantation due to a blind sac closure (Table 2).

For the horizontal vHIT (Headstar, Difra Instrumentation SA, Eupen, Belgium), only head impulses with a velocity of approximately 200°/s were accepted. The gain was calculated according to the regression slope of the eye velocity (°/s) in relation to the head velocity (°/s). Gains higher than or equal to 0.61 were considered normal (Table 2). Subject 4 had a normal gain in combination with overt correction saccades in the unimplanted ear (left). None of the other subjects had overt or covert correction saccades.

The cVEMP test was performed with air- or bone-conducted 500-Hz tone bursts of alternating polarity (2-2-2 ms rise/fall and plateau time; repetition rate = 5.1 Hz) (Neurosoft®, NeurAudio®, Ivanovo, Russia). The air-conducted cVEMP was evoked with insert earphones (Tone 3A Insert Earphones, E-A-R Auditory Systems®, Indianapolis, Ind, USA) at a maximum sound level of 135 decibel sound pressure level (dB SPL). The implanted ear of S1 required a blind sac closure due to chronic middle ear disorders. Therefore, bone-conduction cVEMP was performed for assessing the saccular function after the cochlear implantation. A B71 bone vibrator (B71 Bone Transducer Headset, RadioEar®, Middelfart, Denmark) attached to an additional amplifier with a gain of 15 dB (Neurosoft®, NeurAudio®, Ivanovo, Russia) was used for stimulation at the mastoids. The output was 117 dB force level (dB FL).

Table 1. Patient Demographics

	Subject 1		Subject 2		Subject 3		Subject 4	
Age at implantation (years)	70		37		70		69	
Age at time of the study (years)	71		40		72		69*	
PTA (dB HL)	Right	Left	Right	Left	Right	Left	Right	Left
	65	deaf	93	92	85	85	68	73
Implant side	Left		Right		Right		Right	
Implant type	CI532		CI512		CI512		CI532	
Contralateral ear	Hearing aid		Hearing aid		Hearing aid		Unaided	
Diagnosis	Chronic middle ear disorders (progressive, permanent hearing loss)		Idiopathic SNHL with onset at 4 years old (unidentified hereditary component)		Idiopathic SNHL (probably due to streptomycin treatment during childhood)		Iatrogenic SNHL (streptomycin treatment during childhood)	

SNHL, sensorineural hearing loss; CI, cochlear implant; PTA, pure tone audiometry (average of hearing thresholds at 500 Hz, 1000 Hz, and 2000 Hz) before implantation; dB HL, decibel hearing level.
*Six months after initial cochlear implant activation.

Table 2. Semicircular Canal Function After Cochlear Implantation

	Implanted Ear		Unimplanted Ear		Caloric Test	
	SHAT: Gain	vHIT: Gain	SHAT: Gain	vHIT: Gain	Caloric Sum (°/s)	Unilateral Weakness (%)
S1	0.38	1.17	0.64	1.06	Blind sac closure	Blind sac closure
S2	0.28	0.73	0.19	0.98	52°/s	6% contralateral
S3	0.55	0.77	0.64	0.95	140°/s	8% ipsilateral
S4	0.40	0.72	0.36	0.81	57°/s	17% contralateral

S, subject; ipsilateral/contralateral, ipsi- or contralateral with regard to the implanted ear; SHAT, sinusoidal harmonic acceleration test; vHIT, video head impulse test.

Only cVEMP traces with an average muscle contraction level higher than 100 µV were accepted.[21] The cVEMP was interpreted as normal when the left–right threshold difference was ≤10 dB and when the left–right difference in corrected amplitude was ≤1.7 (Table 3).

A hand-held bone-conduction vibrator (Mini Shaker type 4810, amplifier model 2718, Brüel & Kjaer®, Nærum, Denmark) was placed at Fz, that is, the midline of the forehead near the hairline, for evoking the oVEMP (Neurosoft®, NeurAudio®, Ivanovo, Russia) (Table 3). The Mini Shaker delivered 500-Hz square wave jerks with an alternating polarity at a 5-Hz stimulation rate. The stimuli were presented at 121 dB FL. The recording surface electrodes were placed as close as possible underneath the inferior orbital rim. The reference electrodes were placed 2 cm below the recording electrodes and the ground electrode was placed on the sternum. The oVEMP was interpreted as normal when bilaterally present at 121 dB FL with a maximal left–right amplitude difference of 12 µV (Table 3).

Electrical Stimulation and Response Recordings

The eye movements were monitored and recorded through videonystagmography (Headstar, Difra Instrumentation SA, Eupen, Belgium). Visual suppression of eye movements was prevented by covering the second eye and by dimming the light in the examination room. The subjects were instructed to report any kind of (non-) vestibular sensation and were seated on a stable chair. In order to facilitate communication, contralateral hearing aids were kept activated during the session.

A baseline measurement without electrical stimulation was performed first, in order to detect the presence of a spontaneous nystagmus. Subsequently, the stimuli were programmed through the Nucleus Implant Communicator (NIC) software (Cochlear™, Sydney, Australia) and presented by an L34 research processor (Cochlear™, Sydney, Australia). Finally, the already implanted intracochlear electrode array delivered the stimuli to the inner ear.

The stimulation patterns were presented for 60 seconds and consisted of counterbalanced biphasic pulses (phase width = 100 µs, interphase gap = 7 µs) presented as bursts or as an amplitude-modulated biphasic pulse train (Figure 1). For the latter, modulation frequencies between 1 and 500 Hz were used.

For each subject, the stimuli were different and dependent on the subject's reports and the observed results (Tables 4 and 5). An individual dynamic range (i.e., the range between the sound detection threshold and the upper comfortable level (UCL)) was defined for each stimulus in order to avoid overstimulation. Increments of 5 current levels (CL) were used to define the UCL. Once the UCL was determined for a specific stimulus, the stimulation was presented for 60 seconds at that intensity. None of the participants reported pain or discomfort during this study. Before and after every 60 seconds of stimulation, the eye movements were recorded for 30 seconds so that any changes upon activation or deactivation of the stimulation could be detected.

Monopolar (MP) stimulation was used in all 4 cases. In general, the reference electrode configuration was set as a combination of the ball (MP1) and plate electrode (MP2) but when the conditions allowed for it (based on time, tiredness of subject, …), the effects of MP1 and MP2 were examined separately as well. The stimuli were delivered through a basal (E3) electrode contact of the intracochlear electrode array. One middle electrode contact (E12) and one apical electrode contact (E22) were used for additional measurements (Tables 4 and 5).

Statistics

Statistical analyses could not be performed due to the small sample size (n = 4). This prospective open study was conducted according

Table 3. Otolith Function After Cochlear Implantation

	Implanted Ear			Unimplanted Ear		
	cVEMP		oVEMP	cVEMP		oVEMP
	Threshold (dB SPL)	Corrected Amplitude*	Amplitude (µV)	Threshold (dB SPL)	Corrected Amplitude*	Amplitude (µV)
S1	Absent	Absent	Absent	130	1.0	Absent
S2	115	1.2	21.0	120	1.7	17.3
S3	Absent	Absent	14.8	Absent	Absent	13.3
S4	135	0.4	9.7	125	1.4	5.7

S, subject; c/oVEMP, cervical/ocular vestibular-evoked myogenic potential; dB SPL, decibel sound pressure level.
*Measured at the highest level of stimulation.

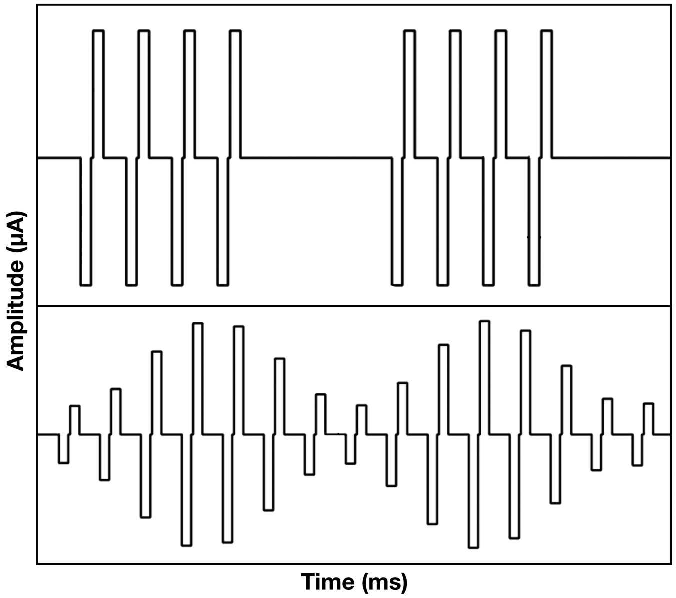

Figure 1. The upper waveform represents a pulse train of biphasic pulses that were presented in bursts. The lower waveform is the amplitude-modulated biphasic pulse train.

to the principles of the Declaration of Helsinki, and institutional ethical approval was obtained from the local ethics committee (GZA Hospital, Antwerp; study number: 181111ACADEM). All participants provided written informed consent.

RESULTS

Subject 1

The first subject (S1) had a discrete spontaneous nystagmus to the right. The spontaneous nystagmus was present throughout the entire session and did not change direction or velocity. Regardless of which stimulation configuration was used (Table 4), the subject only perceived auditory percepts (e.g., buzzing, ticking, chirping sound). Electrically evoked eye movements were also absent. At the end of the session, one measurement was performed with electrical stimulation at E12 and one at E22, but besides a change in the auditory percept (i.e., more low-frequent sound percepts with the more apical electrode contacts), no changes in subjective or objective vestibular outcomes were observed.

Subject 2

Subject 2 had a rightward beating spontaneous nystagmus with a discrete downbeat component during his first session. Electrical stimulation with bursts did not evoke vestibular sensations or additional eye movements (Table 4). Stimulation with amplitude-modulated biphasic pulse trains (Table 5) with a modulation frequency of 2 Hz at E3 induced a perception of the head tilting to the left (i.e., away from the stimulation site). The same sensation was evoked with a 400-Hz modulation frequency but not with modulation frequencies 10 Hz, 20 Hz, and 100 Hz. A reduction in the stimulation rate from 4673 pulses per second (pps) to 2336 pps diminished the strength of the tilt sensation. A further reduction of the stimulation rate to 1168 pps led to a stronger perception of the head tilt, as it allowed for higher stimulus intensity. There were no changes observed in the eye movements, regardless of the stimulus used.

Due to the obtained results, S2 was invited for a second session. During the baseline measurement, a spontaneous nystagmus to the right with a discrete upbeat component was observed (in contrast to the initial discrete downbeat nystagmus). The characteristics of the spontaneous nystagmus did not change during the experiment. The stimuli that were presented were those that evoked the head tilt during the first session. However, 2 additional modulation frequencies (1 Hz and 5 Hz) were added. Unfortunately, none of the results from the first session could be replicated and the subject clearly indicated that he only experienced auditory percepts (e.g., chirping) during the second session. Changing the reference or stimulation electrode did not change the outcome.

Subject 3

During the baseline measurement of S3, a discrete spontaneous nystagmus to the left was visible with additional sporadic horizontal and vertical flutter-like eye movements. A head tremor with horizontal and vertical components was observed as well. It is unclear whether the flutter-like eye movements were the VOR in response to the head tremor or rather an additional symptom. Imaging did not reveal abnormalities and the patient did not report any symptoms. Both stimulation patterns (amplitude-modulated biphasic pulse trains and bursts) (Table 5) presented at E3 did not evoke vestibular sensations or changes in the eye movements.

Subject 4

The baseline eye recordings of subject 4 showed a leftward beating spontaneous nystagmus. No changes of the eye movements were observed during electrical stimulation, regardless of which type of stimulus (bursts or amplitude-modulated pulse trains) was presented (Tables 4 and 5). The subject did not report any vestibular percepts either. There was no detectable effect of modulation frequency (2 Hz, 10 Hz, 100 Hz, and 400 Hz), stimulation electrode contact (E3 or E22), or reference electrode (MP1 or MP1+2).

DISCUSSION

The goal of this study was to evaluate the feasibility of indirectly stimulating the vestibular nerve by means of the current spreading from a CI. The results show that it is difficult to evoke objective or subjective vestibular responses with the described approach. One of the participants (S2) perceived a head tilt during stimulation but this percept could not be replicated. Moreover, there were no electrically mediated eye movements that coincided with the alleged vestibular sensation. In a recent study, a higher activation threshold was observed for electrically evoked vestibular percepts in comparison to electrically evoked VOR or cVEMPs.[22] Thus, a coexisting eye movement could have been expected during the tilt sensation; however, this was not the case. It is therefore unlikely that the perceived head tilt was electrically mediated. It seems that S2 was biased by the vestibular nature of the study and that he perceived the envelope of the amplitude-modulated pulse train as a wave-like motion or head tilt. Elimination of the auditory component could have prevented this, though it seems difficult to accomplish due to the location of the stimulating electrode inside the cochlea. Furthermore, vestibular co-stimulation is a form of far-field stimulation and is dependent on the total amount of electrical energy delivered by the intracochlear array. Lowering the total amount of energy to avoid the audibility of the signal probably would have reduced the likelihood of evoking a vestibular reflex or percept even further.

Table 4. Individual Stimulation Parameters: Biphasic Pulses Presented as Bursts

Intra-Burst Pulse Rate (pps)	f_{burst} (Hz)	Electrode Contact	Reference Electrode	Current Level	Current (μA)	N_p/Burst
Subject 1						
4673	100	E3	MP1 + MP2	150	263	1
4673	20	E3	MP1 + MP2	170	377	1
4673	300	E3	MP1 + MP2	130	183	1
4673	10	E3	MP1 + MP2	175	413	1
4673	300	E3	MP1 + MP2	130	183	2
4673	100	E3	MP1 + MP2	120	153	4
2336	300	E3	MP1 + MP2	125	167	4
1558	100	E3	MP1 + MP2	140	219	8
4673	300	E3	MP1 + MP2	120	153	8
4673	20	E3	MP1 + MP2	150	263	16
4673	100	E3	MP1 + MP2	120	153	24
1168	20	E3	MP1 + MP2	145	240	24
4673	10	E3	MP1 + MP2	140	219	48
4673	20	E3	MP1 + MP2	130	183	96
4673	10	E12	MP1 + MP2	165	345	1
4673	10	E22	MP1 + MP2	140	219	1
Subject 2 (First Visit)						
Intra-Burst Pulse Rate (pps)	**f_{burst} (Hz)**	**Electrode Contact**	**Reference Electrode**	**Current Level**	**Current (μA)**	**N_p/burst**
4673	2	E3	MP1 + MP2	95	97	584
4673	2	E3	MP1 + MP2	100	107	292
4673	2	E3	MP1 + MP2	135	200	1
Subject 3						
Intra-Burst Pulse Rate (pps)	**f_{burst} (Hz)**	**Electrode Contact**	**Reference Electrode**	**Current Level**	**Current (μA)**	**N_p/Burst**
4673	2	E3	MP1 + MP2	120	153	1
4673	400	E3	MP1 + MP2	140	219	1
4673	100	E3	MP1 + MP2	145	240	1
4673	2	E3	MP1 + MP2	110	128	584
4673	400	E3	MP1 + MP2	130	183	3
4673	100	E3	MP1 + MP2	120	153	12
4673	100	E3	MP1 + MP2	125	167	12
4673	200	E3	MP1 + MP2	130	183	6
4673	10	E3	MP1 + MP2	130	183	117
4673	400	E3	MP1 + MP2	140	219	3
Subject 4						
Intra-Burst Pulse Rate (pps)	**f_{burst} (Hz)**	**Electrode Contact**	**Reference Electrode**	**Current Level**	**Current (μA)**	**N_p/Burst**
4673	2	E3	MP1 + MP2	160	315	1
4673	2	E3	MP1 + MP2	160	315	1
4673	400	E3	MP1 + MP2	130	183	1
4673	100	E3	MP1 + MP2	140	219	1
4673	2	E3	MP1 + MP2	110	128	584
4673	400	E3	MP1 + MP2	125	167	3
4673	100	E3	MP1 + MP2	115	140	12

pps, pulses per second; f_{burst} (Hz), burst frequency (Hertz); E3/12/22, basal/middle/apical electrode contact; MP1, ball reference electrode; MP2, fixed location on the implant; N_p/burst, number of biphasic pulses in 1 burst.

Table 5. Individual Stimulation Parameters: Amplitude-Modulated Pulse Train

Pulse Rate (pps)	Modulation Frequency (Hz)	Electrode Contact	Reference Electrode	Current Level	Current (µA)
Subject 2 (First Visit)					
4673	2	E3	MP1 + MP2	105	117
4673	400	E3	MP1 + MP2	110	128
4673	100	E3	MP1 + MP2	105	117
4673	20	E3	MP1 + MP2	105	117
4673	10	E3	MP1 + MP2	105	117
4673	2	E3	MP1 + MP2	105	117
4673	2	E3	MP1 + MP2	105	117
2336	2	E3	MP1 + MP2	105	117
1168	2	E3	MP1 + MP2	115	140
4673	2	E12	MP1 + MP2	115	140
4673	2	E22	MP1 + MP2	90	89
2336	2	E22	MP1 + MP2	90	89
Subject 2 (Second Visit)					
Pulse Rate (pps)	**Modulation Frequency (Hz)**	**Electrode Contact**	**Reference Electrode**	**Current Level**	**Current (µA)**
4673	20	E3	MP1 + MP2	105	117
4673	400	E3	MP1 + MP2	100	128
4673	2	E3	MP1 + MP2	105	117
4673	1	E3	MP1 + MP2	105	117
4673	5	E3	MP1 + MP2	105	117
4673	2	E12	MP1 + MP2	110	117
4673	2	E22	MP1 + MP2	100	117
4673	1	E22	MP1 + MP2	105	117
4673	2	E22	MP1	105	117
4673	2	E22	MP2	110	117
4673	1	E3	MP2	105	117
Subject 3					
Pulse Rate (pps)	**Modulation Frequency (Hz)**	**Electrode Contact**	**Reference Electrode**	**Current Level**	**Current (µA)**
4673	2	E3	MP1 + MP2	90	89
4673	400	E3	MP1 + MP2	130	183
4673	100	E3	MP1 + MP2	115	140
4673	200	E3	MP1 + MP2	130	183
4673	10	E3	MP1 + MP2	125	167
Subject 4					
Pulse Rate (pps)	**Modulation Frequency (Hz)**	**Electrode Contact**	**Reference Electrode**	**Current Level**	**Current (µA)**
4673	2	E3	MP1 + MP2	110	128
4673	400	E3	MP1 + MP2	120	153
4673	100	E3	MP1 + MP2	120	153
4673	2	E22	MP1 + MP2	115	140
4673	400	E22	MP1 + MP2	120	153
4673	100	E22	MP1 + MP2	115	140
4673	2	E3	MP1	125	167
4673	100	E3	MP1	115	140
4673	10	E3	MP1	115	140

pps, pulses per second; MP1, ball reference electrode; MP2, fixed location on the implant; E3/12/22, basal/middle/apical electrode contact.

Most studies that succeeded in evoking or improving vestibular reflexes in CI recipients used audible stimulation at UCL,[11,15,18,19] which is similar to the present study. A possible explanation for the discrepancy in obtained results may be the number of stimulating electrode contacts. In most studies, the participant's standard CI settings were used, which implies that multiple electrode contacts were activated during stimulation, especially when background noise or music was presented.[11,15] Therefore, the total amount of electrical energy delivered to the inner ear may have been higher than in the present study (as only 1 electrode contact was activated during each measurement). Nonetheless, Gnanasegaram et al[18] and Parkes et al[19] used just 1 electrode contact and they successfully elicited cVEMPs and improved the perception of verticality. The waveforms of the stimuli that were used (i.e., single biphasic pulses or biphasic pulse trains) were quite similar to those used in the present study, but the parameters of the biphasic pulses were slightly different. In their studies, the phase width of the biphasic pulse was much shorter (25 µs with a 7-µs interphase gap) which may explain the higher UCLs that were used. The lowest UCL in the studies of Gnanasegaram and colleagues[18,19] was comparable to the highest UCL in the present study. The phase width was fixed in the present study at 100 µs, but systematic comparison of different phase widths may help to understand the observed discrepancy.

In previous studies, the electrically restored auditory (directional) cues have been suggested to contribute to the improved balance,[23] especially when background noise or music is provided.[12,15,17,24] In the present study, the possible beneficial effects of the electrically restored auditory cues were not investigated. The subjects did perceive electrically evoked sounds, but these were artificially mediated by the NIC software (Cochlear™, Sydney, Australia) and were not the environmental sounds contributing to spatial orientation.

At the moment, the unwanted audibility of the signal and the absence of reproducible signs of effective vestibular stimulation limit the functional implementation of the described stimulation paradigm as an efficient treatment method. This conclusion is however based on a very small sample size (n = 4) and should be further explored. As the likelihood of detecting a perturbation was expected to be higher in patients without deprived vestibular afferents, only patients with almost normal vestibular function were included. However, such patients may not be the ideal study population as the high amount of residual vestibular function may impede the possible effects of stochastic resonance, even though the oVEMPs and cVEMPs were absent in some of them. Stochastic resonance (SR) is a physiological mechanism that improves the performance of a non-linear system (like the vestibular system) with subthreshold residual function when noise is provided.[25] In case of too much residual function or too much noise (e.g., the electrical stimulus), SR fails to improve the overall performance.

Moreover, the long-term goal is to use vestibular co-stimulation as a treatment option for patients with BVP. Even though patients with afferent deprivation should be avoided, future studies should focus on patients with more abnormal vestibular function.

As all patients received their CI prior to the study, manipulation of the position of the reference electrode was limited to MP1, MP2, or MP1+MP2. Intra-operative manipulation of the ball electrode (e.g., positioning in the vicinity of the vestibular structures) may revoke this limitation. As a result, the current pathway can be directed toward the vestibular structures, which may increase the likelihood of successful vestibular co-stimulation.

The applied changes to the stimulation parameters were also limited, as the goal was to not drastically change the hard-, firm-, or software of the commercially available CI. The present results however suggest that modifications to the design of the CI are warranted.

CONCLUSION

Subjective vestibular sensations or otolith-mediated eye movements could not be evoked through vestibular co-stimulation with a commercially available CI in 4 adult patients with almost normal vestibular function. Therefore, customized design of the hard-, firm-, and/or software of the commercially available cochlear implant might be necessary in order to electrically restore vestibular performance.

Ethics Committee Approval: Ethical committee approval was received from GZA Hospital, Antwerp (181111ACADEM).

Informed Consent: Written informed consent was obtained from all participants.

Peer-review: Externally peer-reviewed.

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