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Noisy vestibular stimulation increases gait speed in normals and in bilateral vestibulopathy

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ABSTRACT

Background: Galvanic vestibular stimulation delivered as zero-mean current noise (noisy GVS) has been shown to improve static and dynamic postural stability probably by enhancing vestibular information.
Objective: /Hypothesis: To examine the effect of an imperceptible level of noisy GVS on dynamic locomotion in normal subjects as well as in patients with bilateral vestibulopathy.
Methods: Walking performance of 19 healthy subjects and 12 patients with bilateral vestibulopathy at their preferred speed was examined during application of noisy GVS with an amplitude ranging from 0 to 1000 μA. The gait velocity, stride length and stride time were analyzed.
Results: Noisy GVS had significant effects on gait velocity, stride length and stride time in healthy subjects as well as in patients with bilateral vestibulopathy ($p < 0.05$). The optimal amplitude of noisy GVS improved gait velocity by 10.9 ± 1.2%, stride length by 5.7 ± 1.2% and stride time by 4.6 ± 7% ($p < 0.0001$) compared to the control session in healthy subjects. The optimal stimulus improved gait velocity by 12.8 ± 1.3%, stride length by 8.3 ± 1.1% and stride time by 3.7 ± 7% ($p < 0.0001$) in patients with bilateral vestibulopathy. The improved values of these parameters of locomotion by noisy GVS in the patients were not significantly different from those in healthy subjects in the control condition ($p > 0.4$).
Conclusion: Noisy GVS is effective in improving gait performance in healthy subjects as well as in patients with bilateral vestibulopathy.

Introduction

The peripheral vestibular endorgans provide continuous input to the brain about angular and linear accelerations of the head, contributing to gaze stability and body balance during head movements through the vestibulo-ocular and vestibulo-spinal reflexes [1]. Bilateral vestibular dysfunction, the prevalence of which is estimated to be 28 per 100,000 adult in the United States [2], causes persistent imbalance and oscillopsia during the head movements as well as while walking, leading to a higher risk of falls and the subsequent substantial economic burden [3]. However, the treatment of this condition has been limited mainly to physical therapy so far.

Galvanic vestibular stimulation (GVS) delivers electrical current subcutaneously through electrodes placed over the mastoids, thereby modulating the activity of vestibular hair cells and their afferents [4,5]. GVS delivered as zero-mean current noise (noisy GVS) of an imperceptible magnitude has been reported to improve various functions, such as autonomic and motor functions in patients with neurodegenerative diseases [6,7]. The proposed explanation behind these ameliorating effects of noisy GVS is stochastic resonance (SR), where the response of a nonlinear system to a weak periodic input signal is optimized by the presence of an appropriate level of noise [8–10].

Previously, we have shown that noisy GVS can improve static postural stability in healthy subjects as well as in patients with bilateral vestibular dysfunction [11,12], and enhances the function of the vestibulo-ocular reflex [13]. The effects of noisy GVS on dynamic locomotion in healthy subjects and in patients with bilateral vestibulopathy have also been studied. It has been reported that noisy GVS decreases the variation in gait performance, especially at

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slower walking speeds [14,15]. However, in these previous studies, walking performance was measured using a treadmill at a constant walking speed. In the present study, we investigate the effects of noisy GVS on dynamic walking performance using a trunk-mounted triaxial acceleration sensor in healthy subjects as well as in patients with bilateral vestibulopathy, who walked at their preferred speed. We demonstrate that an appropriate intensity of noisy GVS can improve gait velocity, stride length and stride time in both groups. Notably, in patients these parameters were improved to the same levels as healthy subjects without noisy GVS, indicating the presence of a substantial functional recovery in dynamic walking performance.

Methods

Subjects

Nineteen healthy subjects (9 men, 10 women; mean age 45.5 ± 2 years; age range 33–60 years; Table 1) and 12 patients with bilateral vestibular dysfunction (9 men, 3 women: mean age 56.3 ± 4.3 years; age range 34–77 years; Table 2) participated in the study. There was no significant difference in ages between the healthy subjects and patients (Mann Whitney *U* test, $p = 0.056$). None of the healthy subjects reported any auditory, vestibular, neurological, cardiovascular, or orthopedic disorders. The etiologies of vestibular dysfunction in the patients are listed in Table 2. All the patients showed corrective saccades to horizontal head impulses bilaterally, and showed reduced or absent caloric responses to ice water irrigation of the external auditory canal bilaterally (maximum slow phase eye velocity < 10°/s) [16]. Cervical vestibular evoked myogenic potentials (cVEMPs) to air-conducted sound (500 Hz, 4 ms, 135dBSPL) and ocular evoked myogenic potentials (oVEMPs) to bone-conducted vibration (500 Hz, 128 dB re 1 μN, applied on the forehead in the midline) were used to assess otolith function [17]. All of the subjects and patients gave written informed consent. All procedures were in accordance with the Helsinki declaration and were approved by the University of Tokyo Human Ethics Committee (No. 3379) and registered in UMIN-CTR (UMIN00000829).

Table 1
Optimal stimulus intensity for noisy GVS and its effects on locomotion in normal subjects.

Patient	Age/Sex	Amplitude (μA)	Improvement (%)		
			Gait velocity	Stride length	Stride time
1	48/M	100	11.8	8.1	4.1
2	41/M	200	9	6	3.8
3	36/M	50	2.5	2.9	−1.9
4	40/M	500	25.9	19.4	3.8
5	59/F	200	11.7	7.8	4
6	53/F	500	7	6.2	1.8
7	41/M	700	10.1	9.7	1.8
8	57/M	500	12.9	0	9.8
9	60/F	200	13	5.7	6.5
10	49/F	50	4.5	0	4.3
11	42/F	500	6.1	−4.1	8.9
12	55/F	200	12.5	9.3	2
13	39/M	700	6.4	3.7	2.2
14	35/F	500	16.3	6.6	9.1
15	55/F	200	8.7	8.2	1.8
16	36/M	500	15	6	8
17	33/F	300	10.6	4.5	6.4
18	48/F	300	6.7	−1.5	6.5
19	37/M	300	15.3	9.6	3.9
Mean		342.1	10.9[a]	5.7[a]	4.6[a]
SEM		46.6	1.2	1.1	1.2

GVS: galvanic vestibular stimulation.
[a] $p < 0.0001$ compared with control ratio.

Galvanic vestibular stimulation

Noisy GVS was applied with electrodes on the right and left mastoids by a portable GVS stimulator (112 × 67 × 28 mm; 200 gm including dry cells) [7,12] with digital storage for GVS waveforms, which are digital-to-analog converted at 20 Hz (Fig. 1A). We used zero-mean white noise GVS, which ranged from 0.02 Hz to 10 Hz (Fig. 1B).

The peak amplitude of GVS was 0, 50, 100, 200, 300, 500 and 700 μA for healthy subjects and 0, 100, 200, 300, 500, 700 and 1000 μA for patients. These intensities, including 0 μA, were applied in a randomized order.

Procedures

We used a gait analysis system based on a trunk-mounted triaxial acceleration sensor and automatic gait detection algorithm (MG-M1110S, LSI Medience, Tokyo, Japan, size 80 mm × 60 mm x 20 mm, weight: 80 g) [18] to analyze walking performance. Data was collected at a sampling frequency of 100 Hz. Subjects were instructed to walk with their eyes open at their preferred walking speed for a distance of 15 m with various intensities of noisy GVS. The walking performance was analyzed in the middle 10 m of the 15 m walk. Between each recording session, the subject sat on a chair near the platform for at least 3 min. White noisy GVS with an amplitude ranging from 0 to 1000 μA was applied by a portable GVS stimulator during walking (Fig. 1).

After each session, subjects were asked whether they felt the stimulation and whether they felt an improvement or deterioration in their body balance during the stimulation.

Data analysis

The following parameters were analyzed: the gait velocity, stride length, stride time, lateral movement distance, vertical movement distance, and the coefficient of variations (CVs) of the stride time, lateral movement distance, vertical movement distance. The ratio of each parameter with noisy GVS to that without noisy GVS was calculated (normalized ratio: NR). The optimal stimulus was defined as the one at which the gait velocity measured during the stimulus was the largest except for the control stimulus (0 μA). Data are expressed as mean ± SEM. Data for the parameters of dynamic locomotion measured during the control and optimal stimulation trials were compared using a repeated measures analysis of variance on ranks (RM ANOVA) followed by the Bonferroni post-hoc test. The parameters in control (0 μA) and optimal conditions were compared using the Wilcoxon signed rank test. The parameters in healthy subjects and patients were compared using the Mann Whitney *U* test. The threshold of sensation and the optimal amplitude of the stimulus were compared using a *t*-test. A difference was considered significant at $p < 0.05$.

Results

Effects of noisy GVS on locomotion in healthy subjects

In a representative subject, white noise GVS at an intensity of 300 μA increased the gait velocity by approximately 15% compared with the control session (0 μA), while a further increase in the intensity of the stimulus resulted in a decrease in the improvement of the gait velocity, suggesting the presence of an SR-like