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Original Article

Analysis of Eye Movements Using 3–Dimensional Video–oculography in Response to Galvanic Vestibular Stimulation

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BACKGROUND: Quantitative assessment of vestibular nerve activity has been difficult with conventional electrophysiological techniques. This study aimed to develop a novel method combining galvanic vestibular stimulation (GVS) with 3-dimensional video-oculography (3D-VOG) to evaluate vestibular function noninvasively.

METHODS: Eye movements were recorded from healthy individuals using a high-resolution infrared VOG system (yVOG, Yamaguchi University). Bipolar GVS was applied bilaterally over the mastoid processes with various current intensities (0.5-2.0 mA) and polarities. Horizontal, vertical, and torsional eye-movement components were extracted and analyzed in relation to stimulus parameters.

RESULTS: Torsional nystagmus amplitude and slow-phase velocity increased proportionally with stimulus intensity and reversed with polarity. Healthy participants exhibited symmetric responses. The induced eye-movement responses showed reproducible polarity- and intensity-dependent characteristics.

CONCLUSION: This study demonstrates that GVS-VOG provides a direct, reproducible, and noninvasive means of evaluating vestibular nerve function through eye movement analysis. The method may complement existing vestibular function tests in future clinical applications. Galvanic vestibular stimulation-video-oculography also offers utility in both research and clinical settings by linking physiological mechanisms with observable oculomotor responses. This approach holds promise as a diagnostic tool for vestibular disorders, especially when conventional tests yield inconclusive results.

KEYWORDS: Three-dimensional video-oculography, galvanic vestibular stimulation, torsional eye movement, vestibular function testing

INTRODUCTION

Galvanic vestibular stimulation (GVS) induces galvanic body sway and nystagmus by directly activating the vestibular nerve afferents.[1-7] It has long been used in physiological and clinical research as a method to probe vestibular function. Recent studies have further shown that noisy GVS (nGVS) can reduce postural sway and improve dynamic gait stability in both healthy individuals and patients with bilateral vestibular dysfunction, suggesting its potential value as a novel vestibular rehabilitation tool.[8]

However, the detailed characteristics of GVS-induced nystagmus remain incompletely understood, mainly because the electrical current used for stimulation contaminates electronystagmographic recordings with artifacts.[9] With the recent advancement of 3-dimensional video-oculography (3D-VOG), it has become possible to quantify horizontal, vertical, and torsional eye movements precisely without electrical interference.[10,11] This technique enables artifact-free investigation of eye-movement responses induced by GVS.[12] Video-based techniques capable of tracking torsional eye movements have also been developed in other contexts, such as gaze-controlled camera systems using real-time eye tracking.[13] In recent years, video-oculography has become widely used in clinical vestibular testing. However, most previous studies analyzing GVS-induced eye movements relied on specialized experimental setups, and quantitative evaluation using clinically available VOG systems has not been fully explored.

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Previous studies using VOG to evaluate galvanic nystagmus have examined normal participants and patients with peripheral vestibular dysfunction.[2,14-18] Early physiological work described the linearity and polarity-dependent features of eye-movement responses to GVS.[19] Subsequently, it has been clarified that GVS activates both semicircular canal and otolithic afferents, indicating that the induced eye movements reflect a composite vestibular input rather than a single end-organ response.[20] More recently, the thresholds for vestibular perception and oculomotor responses to GVS have been examined, and measurable vertical and torsional components have been demonstrated.[21]

Despite these findings, most previous reports have focused mainly on the horizontal component or investigated a limited range of stimulus conditions. Therefore, a systematic 3-dimensional quantitative evaluation of horizontal, vertical, and torsional eye-movement components under controlled current polarity and intensity remains lacking.

In the present study, the vestibular system was stimulated using GVS, and the resulting nystagmus was analyzed 3-dimensionally with a high-resolution VOG system. The aim was to quantitatively characterize GVS-induced eye-movement components and clarify their physiological significance, thereby establishing a noninvasive and reproducible method for assessing vestibular nerve activity.

METHODS

Participants

Fifteen normal individuals (10 men, 5 women; mean age = 38.3 years, median age = 30 years, range = 22-79 years) underwent testing with GVS after providing informed consent. The study protocol was approved by the Institutional Review Board of Yamaguchi University Hospital (Approval No.: H2019-15, H30-077; Date: 07.11.2019). Participants were healthy adult volunteers with no history of vestibular, neurological, or otological disorders. Participants reporting symptoms such as vertigo, dizziness, hearing loss, or imbalance were excluded based on medical history and interview.

Galvanic Vestibular Stimulation

Galvanic stimulation was delivered via surface electrodes measuring 2500 mm^2 (DAIICHI MEDICAL CO., LTD. Tokyo, Japan) that were placed over each mastoid process of the participant. The participants underwent bilateral electrostimulation (cathode applied to one mastoid process and the anode to the other) with an electrical stimulation device (Electrical Stimulation Device FDS 2017, DAIICHI MEDICAL CO., LTD. Tokyo, Japan) with adjustable current intensity, duration, and polarity. These participants underwent stimulation for 10 seconds with current intensity of 0.5, 1.0, and 2.0 mA (square wave, direct current). The interval between each stimulation was 10 seconds (Figure 1A).

Recording System for Eye Movements

Eye movements were recorded using the VOG system (yVOG, software version 1.80-RC6; DAIICHI MEDICAL CO., LTD., Tokyo, Japan) connected to goggles (yVOG-Glass, DAIICHI MEDICAL CO., LTD., Tokyo, Japan) worn by the participants. The yVOG-Glass system is a certified medical device for eye-movement examination in Japan (JMDN code 70093000). The system uses a single infrared complementary metal-oxide-semiconductor (CMOS) image sensor for monocular eye-movement recording and is capable of recording horizontal, vertical, and torsional eye movements. The imaging system is based on a 1/1.8-inch CMOS image sensor with a resolution of 1.3 megapixels, while eye movements were analyzed at a spatial resolution of 640 × 480 pixels and a sampling rate of 60 frames per second. According to the manufacturer's specifications, the error of eye-position detection is within ±2°. Eye-position signals were calibrated before each recording session. Technical specifications of the eye-tracking system and data-processing procedures are reported in accordance with recent recommendations for eye-tracking research reporting.[22] Participants were instructed to keep their eyes open during the recordings while seated in a stable position. Eye movement signals were processed by the yVOG software to calculate horizontal, vertical, and torsional eye velocities.

Statistical Analysis of Eye Movements

The frequency of nystagmus, average slow-phase velocity, and eye velocity were calculated immediately after stimulation from the eye movements recorded on yVOG. All records were statistically processed using the statistical processing software R version 3.1.0 [R Core Team (2014)]. To minimize the influence of noise, segments affected by blinking or recording artifacts were excluded from the analysis. Eye-position signals were calibrated before each recording session. Slow-phase velocity was calculated from clearly identifiable nystagmus beats selected from the VOG recordings. Despite the relatively small slow-phase velocities observed in the present study, reproducible horizontal and torsional eye-movement responses were consistently detected across stimulus conditions.

Frequency of Nystagmus

The nystagmus during electrical stimulation (10 seconds) was defined as an eye movement composed of fast- and slow-phases. The nystagmus frequency was defined as the number of nystagmus per 10 seconds counted by an otolaryngologist in this study.

Average Slow-Phase Velocity

Three definite instances of nystagmus during electrostimulation were selected from VOG, and the average slow-phase velocity was calculated. The horizontal, vertical, and torsional components of the slow-phase velocity were analyzed in all subjects.

RESULTS

Frequency of Nystagmus

Horizontal-torsional nystagmus toward the left was observed during stimulation (left cathode/right anode) in the normal participants.

MAIN POINTS

- The combination of galvanic vestibular stimulation (GVS) and 3-dimensional video-oculography (3D-VOG) allows direct, noninvasive assessment of vestibular nerve function.
- Torsional eye movements induced by GVS correlate with stimulus intensity and polarity, reflecting vestibular nerve excitability.
- Quantitative parameters from GVS-VOG are consistent with conventional vestibular function tests.
- This novel GVS-VOG method bridges the gap between experimental vestibular physiology and clinical diagnostics.

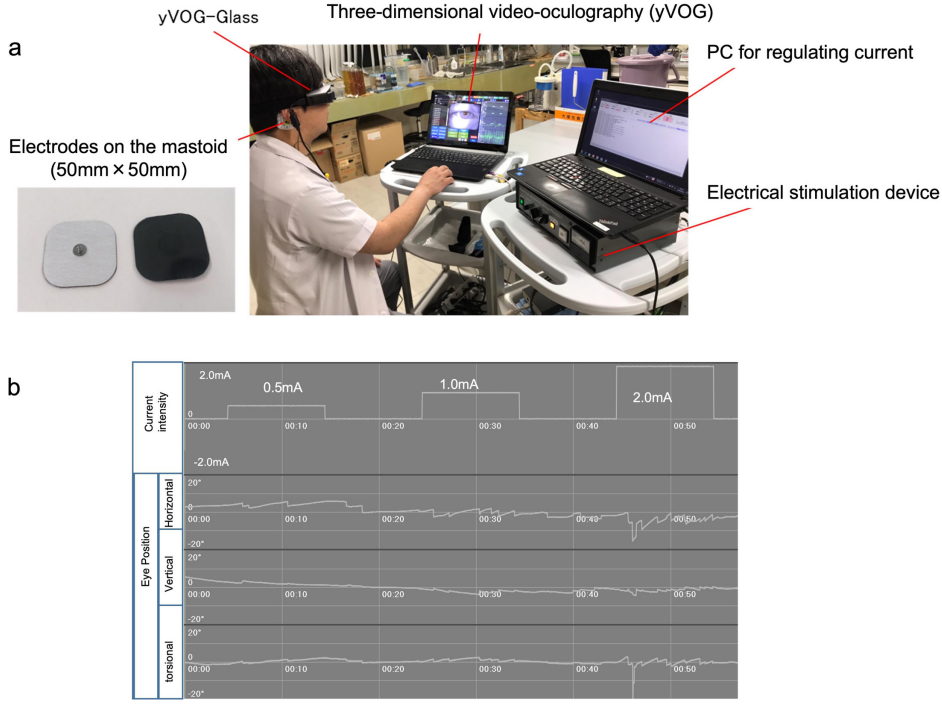


Figure 1 (A): Galvanic vestibular stimulation (GVS) and recording system for eye movements. Galvanic stimulation was delivered via surface electrodes of 2500 mm^2 that were placed over each mastoid process in normal participants. The participants received bilateral electrostimulation with an electrical stimulation device with adjustable current intensity, duration, and polarity. Eye movements were recorded using the 3-dimensional video-oculography system (3D-VOG) (yVOG) connected to goggles worn by the participants. (B): GVS and nystagmogram recorded on the 3D-VOG system. The normal participants underwent stimulation for 10 seconds with current intensities of 0.5, 1.0, and 2.0 mA (square wave, DC). The interval between each stimulation was 10 seconds. Horizontal-torsional nystagmus to the left was observed during stimulation (left cathode/right anode). The average frequency of nystagmus during 10 seconds of stimulation was higher for stronger current intensities.

An example of nystagmus recorded under these conditions is shown in Figure 1B. The average frequency of nystagmus increased with increasing current intensity (Figure 2). This increase was statistically significant (Friedman test, χ^2 (2) = 28.13, $P < .001$). Post hoc Steel–Dwass tests showed that the frequency at 2.0 mA was significantly higher than that at 0.5 mA.

On the other hand, horizontal-torsional nystagmus toward the right was observed during stimulation with the anode on the left side and cathode on the right side. A similar increase in nystagmus frequency with increasing current intensity was observed in the opposite polarity (Figure 2). This increase was also statistically significant (Friedman test, χ^2 (2) = 25.43, $P < .001$). Post hoc Steel–Dwass tests showed that the frequency at 2.0 mA was significantly higher than that at 0.5 mA.

Average Slow-Phase Velocity (Horizontal component)

The horizontal component of nystagmus was observed constantly toward the left during stimulation with the cathode on the left side and anode on the right side.

The horizontal component of the average slow-phase velocity increased with increasing current intensity (Figure 3). This increase was statistically significant (Friedman test, χ^2 (3) = 25.64, $P < .001$). Post hoc Steel–Dwass tests showed significant differences between control and 1.0 mA ($P = .003827$), control and 2.0 mA ($P < .001$), and between 0.5 mA and 2.0 mA ($P = .002065$).

On the other hand, the horizontal component of nystagmus was observed constantly toward the right during stimulation with the anode on the left side and cathode on the right side. The horizontal component of the average slow-phase velocity similarly increased with increasing current intensity (Figure 3). This increase was also statistically significant (Friedman test, χ^2 (3) = 31.88, $P < .001$). Post hoc Steel–Dwass tests showed significant differences between control and 0.5 mA ($P = .040278$), control and 1.0 mA ($P = .018133$), control and 2.0 mA ($P < .001$), between 0.5 mA and 2.0 mA ($P = .001422$), and between 1.0 mA and 2.0 mA ($P = .030343$).

Average Slow-Phase Velocity (Vertical Component)

The vertical component of nystagmus during stimulation with the cathode on the left side and anode on the right side showed small values, and did not show a constant direction. Moreover, the vertical component of the average slow-phase velocity did not show any significant difference with respect to the intensity of the current (Friedman test, χ^2 (3) = 1.80, $P = .615$). This tendency was observed even when the stimulus direction was reversed (χ^2 (3) = 2.10, $P = .551$) (Figure 4).

Average Slow-Phase Velocity (Torsional Component)

The torsional component of nystagmus was observed constantly in the clockwise direction during stimulation with the cathode on the left side and anode on the right side. The torsional component of the average slow-phase velocity increased with increasing current intensity (Figure 5). This increase was statistically significant (Friedman test, χ^2 (3) = 13.20, $P = .0042$). Post hoc Steel–Dwass tests showed significant differences between control and 2.0 mA ($P = .0093$) and between 0.5 mA and 2.0 mA ($P = .0125$).

On the other hand, the torsional component of nystagmus was observed constantly in the counterclockwise direction during

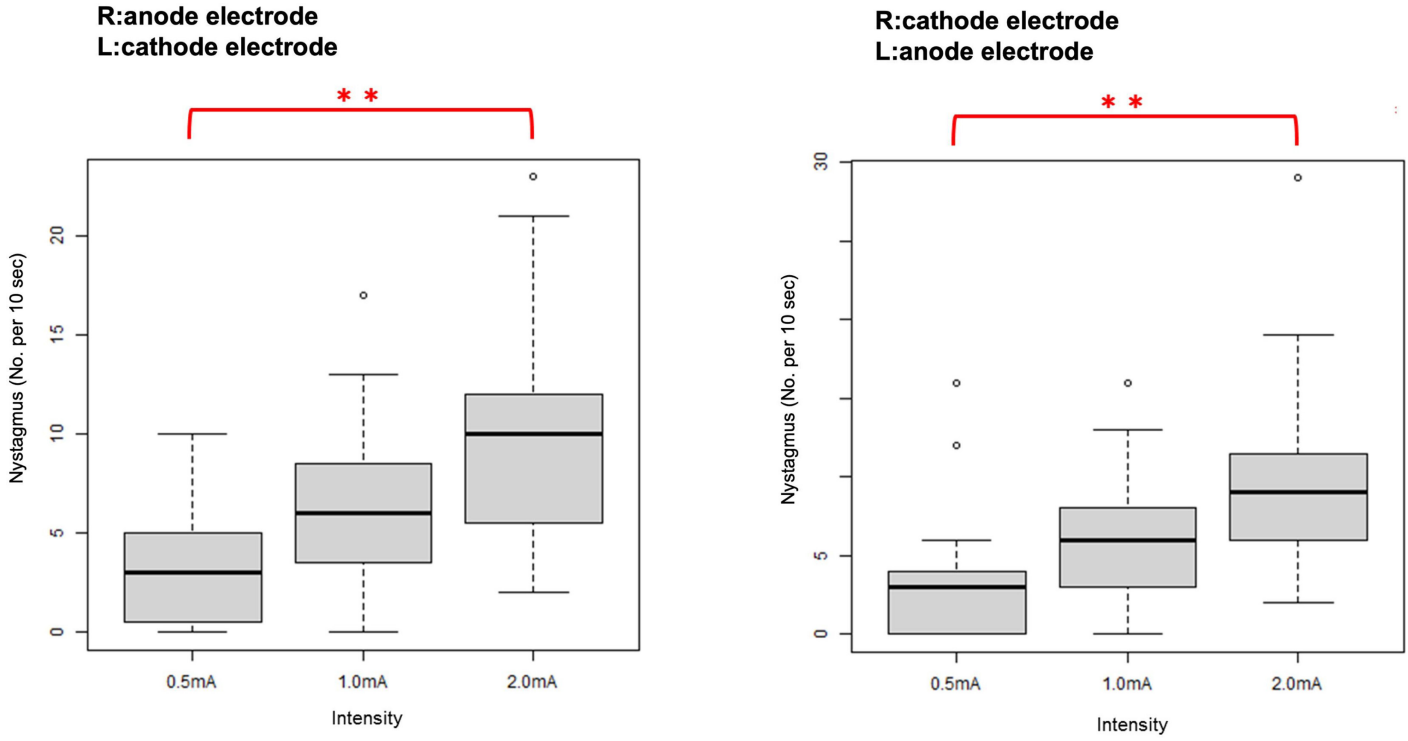


Figure 2. Frequency of nystagmus. The left panel represents stimulation with the right anode and left cathode (R anode / L cathode), and the right panel represents stimulation with the right cathode and left anode (R cathode / L anode). The frequency of nystagmus increased significantly with increasing stimulus intensity in both polarities (Friedman test). Post hoc Steel–Dwass tests revealed a significant difference between 0.5 mA and 2.0 mA in both conditions. ** indicates a significant difference between 0.5 mA and 2.0 mA.

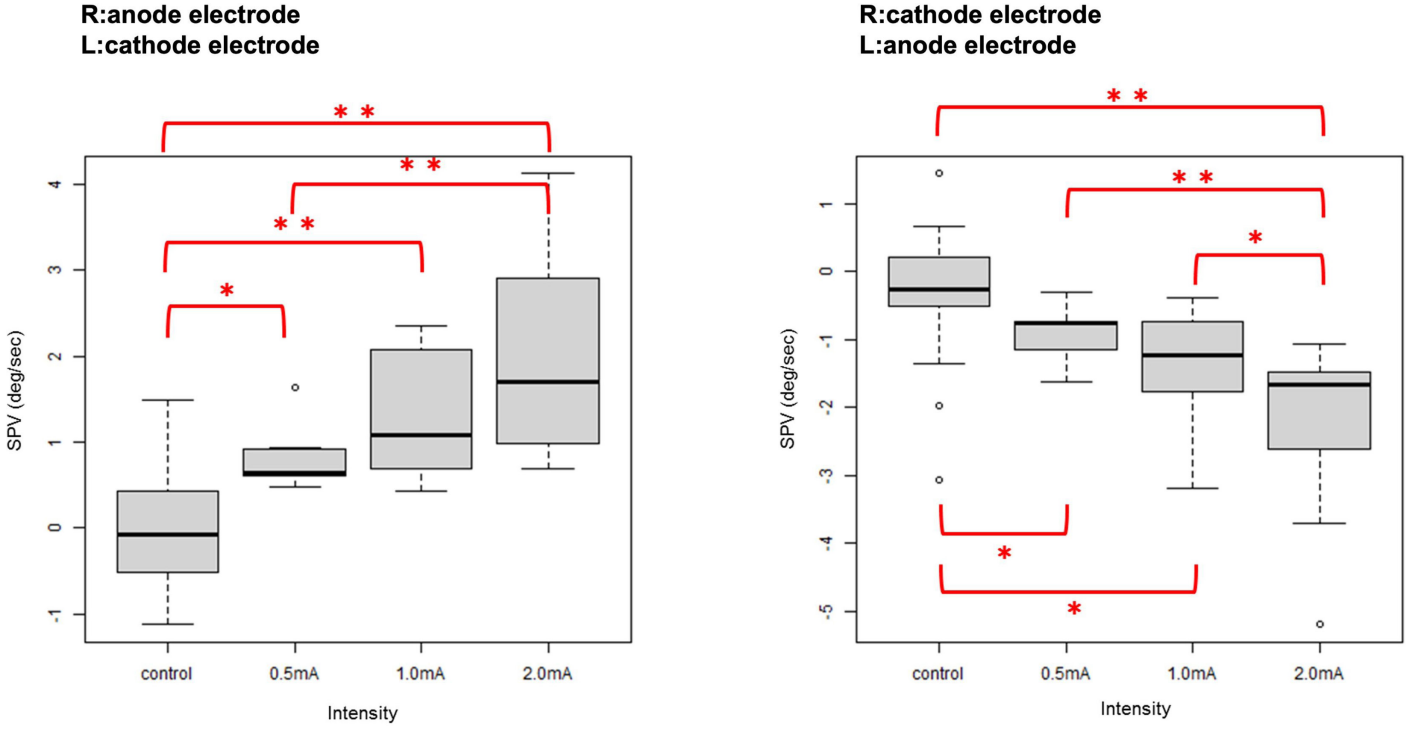


Figure 3. Average slow-phase velocity: horizontal component. The left panel represents stimulation with the right anode and left cathode (R anode / L cathode), and the right panel represents stimulation with the right cathode and left anode (R cathode / L anode). The horizontal component of the average slow-phase velocity increased significantly with increasing stimulus intensity in both polarities (Friedman test; left panel: χ^2 (3) = 25.64, $P < .001$; right panel: χ^2 (3) = 31.88, $P < .001$). Post hoc Steel–Dwass tests revealed significant differences between conditions as indicated in the figure. * indicates $P < .05$ and ** indicates $P < .01$.

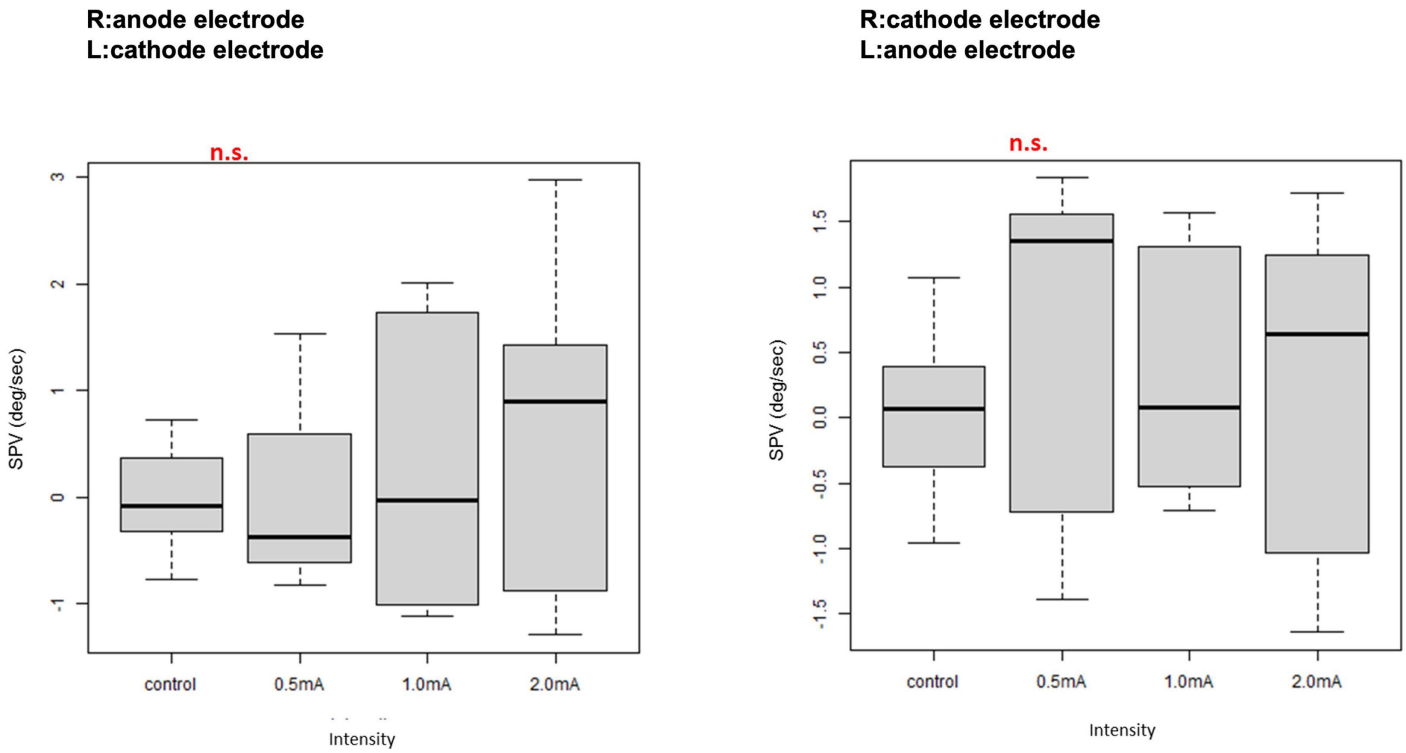


Figure 4. Average slow-phase velocity: vertical component. The vertical component of nystagmus during stimulation did not show a constant direction, i.e., it was neither upbeat nor downbeat in either polarity. The vertical component of the average slow-phase velocity did not show any significant difference with respect to the intensity of the current (Friedman test; left panel: χ^2 (3) = 1.80, P = .615; right panel: χ^2 (3) = 2.10, P = .551).

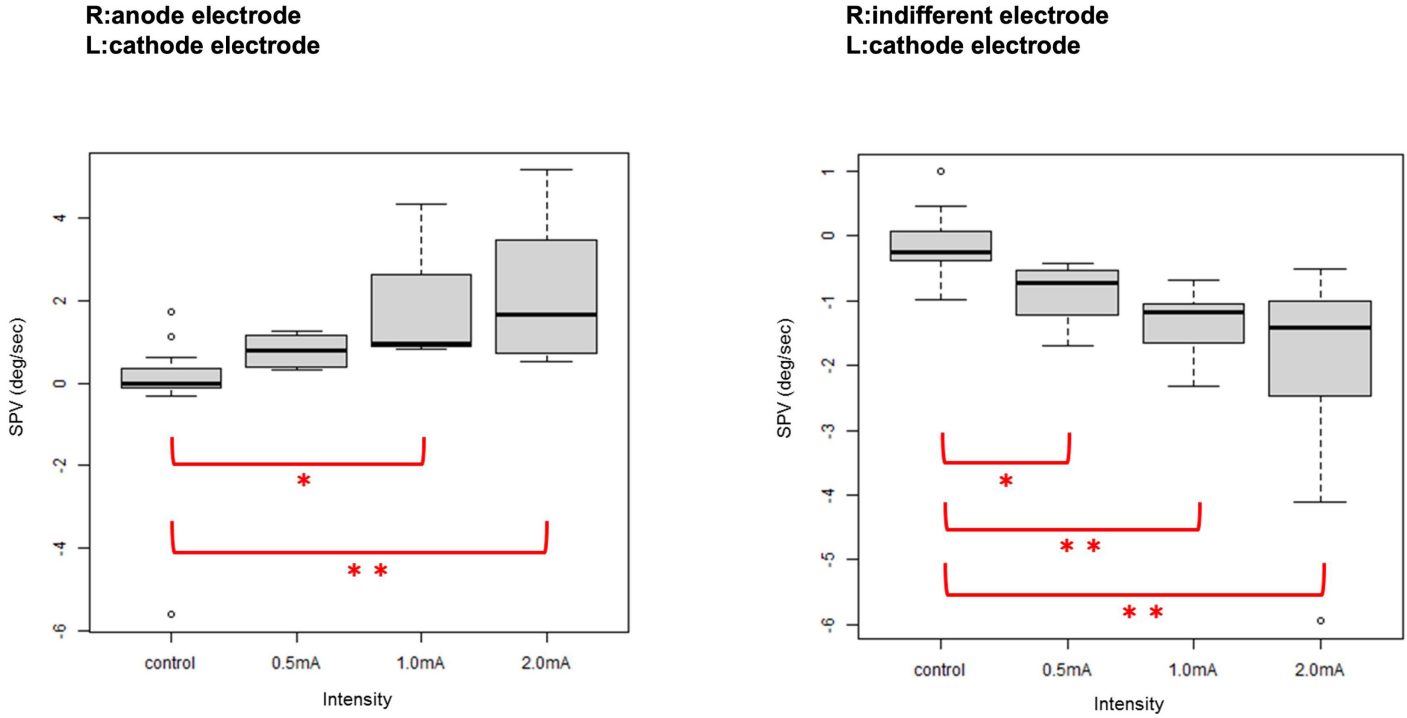


Figure 5. Average slow-phase velocity: torsional component. The left panel represents stimulation with the right anode and left cathode (R anode / L cathode), and the right panel represents stimulation with the right cathode and left anode (R cathode / L anode). The torsional component of the average slow-phase velocity increased significantly with increasing stimulus intensity in both polarities (Friedman test; left panel: χ^2 (3) = 13.20, P = .0042; right panel: χ^2 (3) = 15.80, P = .0012). Post hoc Steel–Dwass tests revealed significant differences between conditions as indicated in the figure. * indicates P < .05 and ** indicates P < .01.

stimulation with the anode on the left side and cathode on the right side. The torsional component of the average slow-phase velocity similarly increased with increasing current intensity (Figure 5). This increase was also statistically significant (Friedman test, χ^2 (3) = 15.80, P = .0012). Post hoc Steel–Dwass tests showed significant differences between control and 2.0 mA (P = .0056),

between 0.5 mA and 2.0 mA ($P = .0078$), and between 1.0 mA and 2.0 mA ($P = .0184$).

DISCUSSION

Animal studies with implanted stimulating electrodes have shown that GVS activates primary vestibular afferents, particularly those with irregular discharge patterns, from both the semicircular canals and otolithic organs.[17,23] It has also been demonstrated that GVS most likely stimulates these afferents in a composite manner that does not correspond to any natural rotational or translational mot ion.[1,7,17,23,24] Therefore, GVS can be used to evaluate the overall function of the peripheral vestibular system, unlike other established methods such as the caloric test, video head impulse test (vHIT), or vestibular evoked myogenic potentials (VEMPs), which each assess only specific receptor functions.

Recent studies have refined this concept. It has been clarified that canal and otolith afferents are simultaneously activated by GVS, resulting in a net vestibular signal that drives both horizontal and torsional eye movements.[20] It has been further shown that the 3-dimensional components of GVS-induced eye movements can be quantified using high-resolution VOG, emphasizing the importance of analyzing the torsional component.[19] More recently, vestibular perception and oculomotor thresholds to GVS have been examined, and measurable vertical and torsional components have been demonstrated even at low stimulus intensities, indicating that such responses are physiologically significant.[21]

In the present study, it was confirmed that GVS-induced horizontal–torsional nystagmus directed toward the cathodal side and that both the nystagmus frequency and slow-phase velocity increased with stronger current intensity. These findings are consistent with previous reports focusing mainly on horizontal eye movement,[2,14-16] but extend them by providing a quantitative description of the torsional component. The proportional increase in torsional velocity with stimulus intensity supports the view that torsional motion reflects a robust vestibular output mediated by simultaneous activation of multiple afferent groups.

Previous studies by the groups of Halmagyi, Curthoys, and Schneider have provided important insights into 3-dimensional eye movements induced by vestibular stimulation, including torsional components. Many of these studies used specialized laboratory techniques such as scleral search coil recordings to achieve high-precision measurements. In addition, video-based techniques capable of tracking torsional eye movements have also been developed in other contexts, such as gaze-controlled camera systems.[13] The present study shows that eye movements induced by galvanic vestibular stimulation can be analyzed 3-dimensionally using a clinically available video-oculography system. This approach suggests that quantitative evaluation of GVS-induced eye movements, including the torsional component, may be feasible in routine clinical vestibular testing.

However, the nystagmus induced by GVS is very faint. Therefore, participants are required to keep their eyes open during the recording when evaluating eye movements with VOG. Blinking, artifacts from the upper eyelid hanging over the pupil, and the inability to maintain steady fixation often make accurate recording difficult. Moreover, it has been reported that nystagmus induced by GVS is difficult to interpret precisely because of large interindividual variability in response patterns.[25-27]

On the other hand, it has been shown that eye movements immediately after the onset of stimulation exhibit little variability among individuals, since they are not affected by saccades, vision, or adaptation. In these studies, the vestibulo-ocular reflex (VOR) was recorded immediately after stimulation using a scleral search coil system, and the VOR was found to be highly repeatable across individuals.[26] This method provides highly objective results because it does not require manual selection of nystagmus events from continuous recordings.

In the study, only the slow-phase velocity of nystagmus was evaluated; however, additional analytic approaches—such as immediate post-stimulation eye velocity analysis—may further enhance objectivity and reproducibility.

The VOG system used in this study is less invasive than the scleral search coil and has already been widely adopted in clinical settings. The findings demonstrate that a clinically available VOG device can reliably capture oculomotor responses induced by GVS. This suggests that the GVS-VOG method may serve as a practical and noninvasive clinical tool for assessing vestibular dysfunction, including both inner ear and vestibular nerve disorders, complementing established diagnostic methods such as caloric testing, vHIT, and VEMP.

CONCLUSION

The evaluation of eye movements with 3-dimensional VOG enabled the analysis of the vertical and torsional components of the nystagmus induced by GVS. The present study was conducted using VOG that is a less invasive tool and has been adopted widely in clinical practice. In the future, this method would be a valuable tool for evaluating vestibular dysfunction, in addition to other established methods.

Data Availability Statement: The data that support the findings of this study are available on request from the corresponding author.

Ethics Committee Approval: Ethical committee approval was received from the Ethics Committee of the Institutional Review Board of Yamaguchi University Hospital (Approval No.: H2019-15, H30-077; Date: 07.11.2019).

Informed Consent: Written informed consent was obtained from the patients who agreed to take part in the study.

Peer-review: Externally peer-reviewed.

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Declaration of Interests: The authors have no conflicts of interest to declare.

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