Three-Dimensional Eye-Movement Responses to Surface Galvanic Vestibular Stimulation in Normal Subjects and in Patients

A Comparison

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KEYWORDS: galvanic vestibular stimulation (GVS); ocular torsion, labyrinth; eye movement

Vestibular stimulation produces characteristic eye movements or vestibular ocular reflexes (VORs). The spatial components of VORs have been attributed to activation of specific vestibular sensory regions: 1 stimulation of a semicircular canal (SCC) mainly produces nystagmus around an axis which is roughly perpendicular to the plane of that canal, whereas stimulation of the otoliths mainly produces changes in ocular torsional position (OTP). Galvanic vestibular stimulation (GVS) of human subjects by currents of 5mA delivered through large-surface-area electrodes on the mastoids is painless and produces a range of vestibular responses, 2, 3 including characteristic eye movements. By recording human eye movements using 3-D video during prolonged GVS, we have observed that normal subjects show eye-movement response patterns that could be expected from stimulation of a combination of vestibular sensory regions. Reliable characteristic patterns of these eye-movement components suggest that in humans surface GVS acts on otoliths and SCCs in an idiosyncratic fashion.

Similarities in the patterns of results between normal subjects provide the basis of a heuristic model that describes eye-movement responses to GVS as the weighted sum of inputs from all vestibular end-organs. In our work, the eye-movement response to GVS is modelled so that stimulation of the otoliths produces mainly OTP changes (upper poles of the eyes rotate toward the anode/away from the cathode). Stimulation of the horizontal canals mainly produces horizontal nystagmus with the slow phases directed towards the anode/away from the cathode. Stimulation of the anterior SCC produces downward eye movement, and stimulation of the posterior SCC produces upward eye movement, with a torsional velocity component. In nor-
mal healthy subjects, during GVS, the downward eye movement produced by the an-
terior SCC is opposed by upward eye movement produced by the posterior SCC, so
that the simultaneous stimulation of both vertical SCCs produces mainly torsional
nystagmus with almost no vertical components (FIG. 1A).

Using the foregoing principles, we have shown that individual characteristic eye-
movements to GVS can be modelled by varying the effective activation and inhibi-
tion of each vestibular sensory region. Such variability in the pattern of effective
stimulation may reflect the variability of inner-ear morphology and impedance
paths. This model also allows predictions about the eye-movement response charac-
teristics in patients with specific vestibular dysfunction. The present study investi-
gates whether the responses of patients with known vestibular dysfunction are
consistent with these predictions.

**BILATERAL VESTIBULAR LOSS**

The model predicts that a patient with non-surgical bilateral vestibular loss
should not show a substantial change in any eye-movement component in response
to GVS delivered to either side. We tested a patient with non-surgical bilateral ves-
tibular dysfunction (total loss on left, 80% paresis on right) as a result of sequential
neuritis. The subject’s data show small horizontal and vertical nystagmus, but other-
wise minimal oculomotor responses to GVS delivered to either side (FIG. 1B).

**UNILATERAL VESTIBULAR LOSS**

The model predicts that a patient with surgical unilateral vestibular loss should
show no response to GVS delivered to the affected side, whereas the eye-movement
response to GVS on the healthy side should be normal. We tested a patient who un-
derwent left unilateral vestibular neurectomy 15 years earlier. The subject has some
hearing preserved on the left, suggesting that some response to GVS might be pos-
sible on that side. The subject’s data show marked reduction in all oculomotor re-
sponses to GVS delivered on the affected side, compared to a relatively normal
response to GVS on the healthy side (FIG. 1C).

**INFERIOR VESTIBULAR NEURITIS**

The model predicts that a subject with inferior division neuritis (posterior SCC
and saccule affected) should show vertical nystagmus in response to GVS: with an-
odal current delivered to the affected side producing slow phases directed down as a
result of the imbalance in activity of the vertical canals. We tested a patient with pro-
found deafness, absent VEMP’s, and absent caloric responses on the left but pre-
served function on the right. The subject’s data show vertical nystagmus (slow
phases: down) in response to GVS delivered on the right side, compared to a rela-
tively normal response to GVS on the left side. There is no reduction in OTP re-
sponse to GVS on the right side compared to the left side, which is consistent with
dysfunction of the saccule but preserved function of the utricle (FIG. 1D).
FIGURE 1. Predicted range (grey bars) and observed magnitude (solid black trace) of OTP and horizontal, vertical and torsional slow-phase velocity (SPV) responses to GVS for five subjects. Row A shows the results of a subject without diagnosed vestibular dysfunction (normal); row B shows a subject with non-surgical bilateral vestibular loss; row C shows a subject with surgical (left) unilateral vestibular loss; row D shows a subject whose response is consistent with (right) inferior vestibular neuritis; and row E shows a subject with CHARGE syndrome.
The model predicts that a patient with absent SCCs associated with the CHARGE syndrome (a combination of various congenital abnormalities, including ear anomalies) should not show substantial eye-velocity response components to GVS delivered to either side, but should show normal otolith-related eye-movement response components. We tested a patient with CHARGE syndrome with absent SCCs (visualized on scans) and absent responses to rotations but preserved VEMPs. The subject’s data show absent velocity responses but preserved OTP changes in response to GVS; however, it should be noted that testing was carried out with fixation present in this instance, and this would tend to suppress velocity responses (Fig. 1E).

CONCLUSION AND DISCUSSION

The predictions generated by the present model of eye-movement response to GVS are consistent with the responses obtained by testing patients with known vestibular dysfunction. The results of the present study lend weight to the validity of the model and thereby support the argument that surface GVS tends to stimulate all end organs in an idiosyncratic, yet predictable, fashion. In each case, the response predicted by the model was derived by modifying the sensitivity of the sensory regions affected by the diagnosed dysfunction. The idealized response could then be modelled on the subject’s observed response by making minor modifications to the sensitivity of sensory regions that was consistent with the variability in sensitivity seen in a normal population (MacDougall et al., submitted for publication). It is important to bear in mind that patients are unlikely to show any GVS response from end-organs which have been surgically ablated unless some nerve endings remain (in that GVS is thought to act on the spike trigger zone of primary afferents). Patients with vestibular loss which has been inferred from other tests might show responses to GVS; thus any diagnosis is likely to remain a question of evidence from a number of sources. Developments in 3-D eye-movement recording systems and GVS delivery methods are making it possible to understand the variability and apparent complexity of the responses to this stimulus. GVS may be more reliable than might be inferred from recent findings and may potentially have some useful application in a clinical, diagnostic, or therapeutic setting.

ACKNOWLEDGMENTS

Mr. Hamish MacDougall was supported by a Research Scholarship provided by the Garnett Passe and Rodney Williams Memorial Foundation during the period of this study. This work was also supported by a NHMRC (of Australia) Clinical Excellence Grant. We gratefully acknowledge the assistance of Imelda Hannigan, Robbie Yavor, Ann Burgess, Laura Mezey, Americo Migliaccio, and the subjects.
REFERENCES


