RAPID REPORT

Otolith and canal reflexes in human standing

Ian Cathers[1,2], Brian L. Day[3] and Richard C. Fitzpatrick[1]

[1] *Prince of Wales Medical Research Institute and University of New South Wales, Sydney, Australia*
[2] *School of Biomedical Sciences, Faculty of Health Sciences, University of Sydney, Sydney, Australia*
[3] *MRC Human Movement Group, Sobell Department of Motor Neuroscience and Movement Disorders, Institute of Neurology, University College London, UK*

We used galvanic vestibular stimulation (GVS) to identify human balance reflexes of the semicircular canals and otolith organs. The experiment used a model of vestibular signals arising from GVS modulation of the net signal from vestibular afferents. With the head upright, the model predicts that the GVS-evoked canal signal indicates lateral head rotation while the otolith signal indicates lateral tilt or acceleration. Both signify body sway transverse to the head. With the head bent forward, the model predicts that the canal signal indicates body spin about a vertical axis but the otolith signal still signifies lateral body motion. Thus, we compared electromyograms (EMG) in the leg muscles and body sway evoked by GVS when subjects stood with the head upright or bent forward. With the head upright, GVS evoked a large sway in the direction of the anodal electrode. This response was abolished with the head bent forward leaving only small, oppositely directed, transient responses at the start and end of the stimulus. With the head upright, GVS evoked short-latency (60–70 ms), followed by medium-latency (120 ms) EMG responses, of opposite polarity. Bending the head forward abolished the medium-latency but preserved the short-latency response. This is compatible with GVS evoking separate otolithic and canal reflexes, indicating that balance is controlled by independent canal and otolith reflexes, probably through different pathways. We propose that the short-latency reflex and small transient sway are driven by the otolith organs and the medium-latency response and the large sway are driven by the semicircular canals.

(Resubmitted 18 November 2004; accepted after revision 22 December 2004; first published online 23 December 2004)
Corresponding author R. C. Fitzpatrick: Prince of Wales Medical Research Institute, Easy Street, Randwick, NSW 2031 Australia. Email: r.fitzpatrick@unsw.edu.au

The semicircular canals and otolith organs respond to angular and linear head acceleration, respectively. Since both these vestibular organs would respond to dynamic tilt of the body in the gravitational field, we assume that both are relevant for human bipedal balance control. However, there is little understanding of whether, or by which mechanisms, these two types of vestibular signal contribute to the control of upright balance. A major obstacle is the problem of isolating vestibular inputs from other sensory inputs without disturbing balance, an impossible feat with natural stimuli. Galvanic vestibular stimulation (GVS) provides a suitable tool to overcome this obstacle and it is well established that GVS evokes strong balance responses (Britton *et al.* 1993; Fitzpatrick *et al.* 1994). Here we use this technique to separate the contributions of the semicircular canals and otolith organs to human balance control. GVS has been found to modulate the firing rates of both types of end organ afferents in animals (Goldberg *et al.* 1982). We therefore assume that the GVS signal contains signals from the semicircular canals and otolith organs and that the GVS-evoked balance response in a standing subject is driven to a greater or lesser extent by each of these signals.

The electrically induced vestibular signal is the same irrespective of the orientation of the head. Thus, GVS produces vestibular signals that are referenced to a craniocentric coordinate frame (Lund & Broberg, 1983). Consider what happens if the subject stands with the head orientated differently with respect to vertical. From a balance perspective, we would expect that the functional significance of the GVS-evoked semicircular and otolith signals, which are fixed in skull coordinates, will change with head orientation. This head-orientation manoeuvre therefore has the potential to change the relative contributions of the two signals to the GVS-evoked balance response.

To clarify this argument, we refer to a recently developed model of the net vestibular signals arising from the

 DOI: 10.1113/jphysiol.2004.079525

modulatory action of GVS on the firing of semicircular canal and otolith afferents (Fitzpatrick & Day, 2004). The model predicts that the net signal arising from vectorial summation of all semicircular canal afferents is equivalent to head rotation about a mid-sagittal axis. Specifically, the axis is directed backwards and upwards by 18 deg above the line joining the lower orbital margin and the external auditory meatus (Fig. 1*A*). The net otolithic signal, which appears to be dominated by the utricular response, is equivalent to lateral head acceleration along the interaural axis or the equivalent tilt in gravity (Fig. 1*B*). With this model we may now consider the functional significance for balance of these two signals when the head is held at two orthogonal positions, head upright or facing down. With the head upright, the GVS canal signal would indicate rotation about an approximately horizontal axis and therefore be relevant to the balance system. With the head down, this same GVS canal signal would indicate a yaw rotation about a vertical axis and therefore be of little relevance to the balance system. The GVS utricular signal would indicate horizontal linear acceleration or its equivalent tilt in gravity, a signal which is relevant for balance. However, in contrast with the semicircular canal signal, the functional significance of this otolith signal remains the same for both head positions. We use this approach here to identify an otolith and a semicircular canal contribution to the human balance control process. Part of this work has been communicated to the Physiological Society (Fitzpatrick *et al.* 2004).

Methods

Eight healthy adults, aged 24–48 years, having no history of vestibular or neurological disorders, participated in the experiment. Subjects gave written informed consent before participating. The experiment conformed to the standards set by the Declaration of Helsinki and had been approved by the institute's human ethics committee.

Setup and protocol

Surface electrodes (3 cm^2 Ag/AgCl) were attached to the mastoid processes and stabilized with a headband. A computer-controlled current source was used to deliver 2 mA step impulses between the electrodes. This bipolar

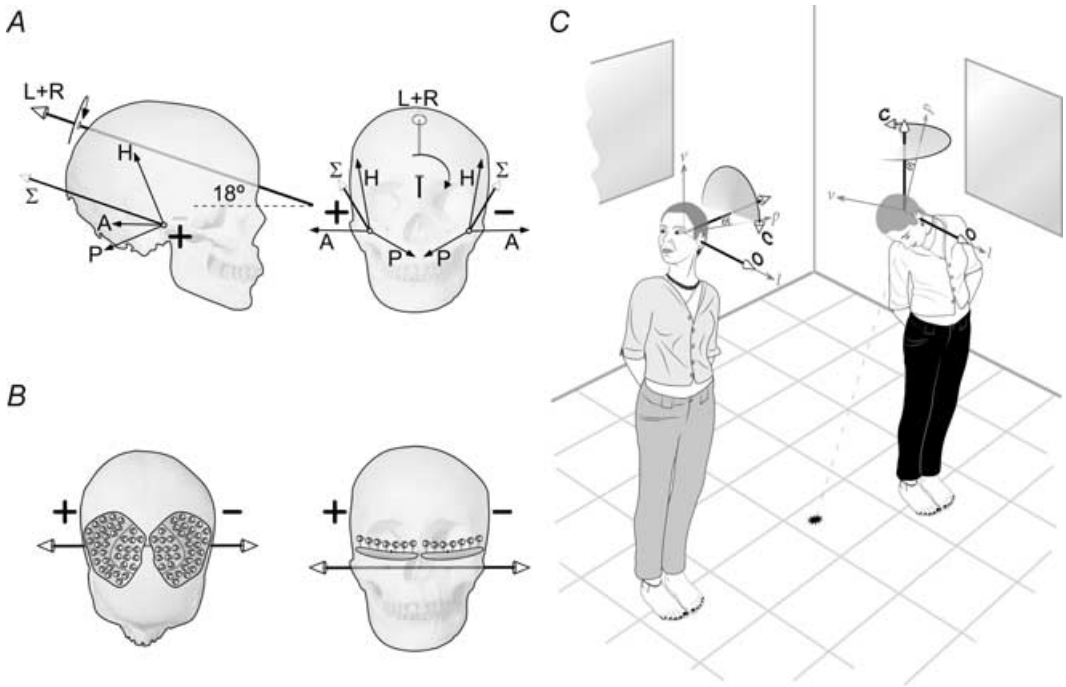

Figure 1. Predictions and methods
A, predicted GVS-evoked signal from the semicircular canals. The anatomical orientation of the three canals and their receptor cells will produce specific rotational vectors from the horizontal (H), anterior (A) and posterior (P) canals. These are shown for bilateral bipolar GVS with anodal current (+) on the right and cathodal current (−) on the left. The vector sums from each side ($\sum$) add to create a final resultant (L + R). This GVS canal vector is directed backward and upwards by 18 deg from Reid's plane (dashed line). It is in the sagittal plane and will therefore change orientation with head pitch. *B*, the predicted GVS signal from the utricles relies on the imbalance between medially and laterally orientated hair cells. It is horizontal in the coronal plane and therefore does not change with head pitch. *C*, in this experiment, GVS is delivered with the head in two positions. *Head-up* has the canal vector (C) horizontal and *head-down* has it vertical, whereas the otolith vector (O) is the same in both positions. Arrows *v*, *l* and *p* indicate vertical, lateral and posterior in head coordinates. The plane *lp* is Reid's plane.

stimulus was applied with the anode on the left or on the right. The stimulus was felt as sharp cutaneous paraesthesia at the onset of the stimulus.

Subjects stood with the feet together and the hands clasped behind the back. The head was orientated in one of two positions, described as *head-up* and *head-down* (Fig. 1). In both positions, the head was turned 90 deg to face over the right shoulder. This was achieved by a combination of head and trunk rotation, the head component being the greatest. Head rotation was checked by a camera positioned above the subject. For *head-up*, the plane defined by the external auditory meatus and the lower orbital margins (Reid's plane) had an 18 deg angle of elevation. For *head-down*, Reid's plane had a 72 deg angle of depression. To achieve precise head angles, targets were placed on the floor (Fig. 1*C*) and wall by holding a level and protractor against the head. Subjects directed the beam of a laser pointer that was attached to the head at the targets. These head positions will cause the predicted GVS canal vector (Vector C, Fig. 1*C*), to be horizontal with *head-up* and vertical with *head-down* but the predicted GVS otolithic vector (Vector O) will be horizontal in both situations.

Each subject was tested with 16 trials each of four conditions: *head-up* or *head down* paired with *anode-left* or *anode-right* stimuli. The 64 trials were randomised. To avoid fatigue, subjects moved about between trials and several seated rest periods were provided.

At the beginning of each trial, subjects attained the target position and then shut the eyes. To ensure that the head did not drift from the desired position, subjects wore a light headpiece with paired tilt switches that alarmed if pitch angle deviated by more than 2 deg. To ensure that the body load was carried by both legs, the experimenter checked that EMG activities from the leg muscles were comparable. If not, the subject was instructed to adjust the posture and then move to the target position. When the subject indicated *ready* and the experimenter was happy, GVS was delivered after a random delay of between 4 and 7 s. The stimulus was a $\pm$ 2 mA current step that lasted 2 s. Data were recorded for 6 s: 2 s prestimulus, 2 s during the stimulus period, and 2 s poststimulus. At the end of the trial, subjects opened the eyes, moved and looked around the room before the next trial.

Measurement and analysis

Anterior–posterior body sway was recorded from an optical displacement device (MEL Mikroelektronik, Eching, Germany: M5L/200) that was targeted at a marker over the upper sacrum. Electromyographic activity (EMG) from the left and right tibialis anterior (TA) and soleus muscles was recorded from surface electrodes (Ag/AgCl, 2 cm^2) placed 5–6 cm apart over the belly of TA and the upper end of soleus. EMG signals were amplified ($\times$ 1000–5000) and band-pass filtered 30 Hz to 1 kHz (Grass, IP511).

All signals were sampled at 2 kHz using a 16-bit analog–digital interface and stored for later analysis. Sway, which was measured as a linear displacement at the pelvis, was averaged across trials for each subject and stimulus polarity. These averages were then normalized for stimulus polarity and averaged across subjects. EMG signals were rectified and then high-pass and low-pass filtered (10 Hz, 500 Hz) with 8-pole, zero-phase Butterworth filters. These signals were then normalized to prestimulus levels (1 for anode-left, -1 for anode-right) before averaging within and across subjects. After normalizing these to stimulus polarity, a mean response in the anodal direction was calculated.

Results

With the head up, bilateral bipolar GVS evoked a large sway response in the anodal direction with a return to the prestimulus position when the stimulus stopped (Fig. 2). With the head down, the large sway response was abolished. This was also observed in the individual responses of each subject with each stimulus polarity (binomial $P < 0.001$). There remained, however, small transient responses following the start and end of the stimulus. These transients were in a direction opposite to those of the large responses that were observed with the head up. It is apparent from the group-average traces that these transient responses coexist with the large sway response evoked with the head up.

Averaged EMG responses evoked in soleus, normalized to anode left giving forward sway with head up, show a short-latency reflex commencing 64 ms after the start of the stimulus (Fig. 3, top). With the head up, a

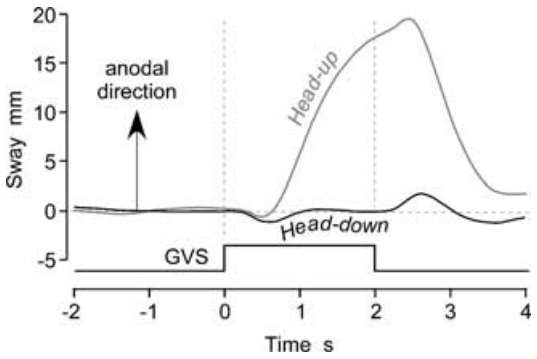

Figure 2. Average sway responses
Antero-posterior body sway has been normalized then averaged across subjects and stimulus polarities to indicate sway in the direction of the anodal electrode. The stimulus time is below and the head-up and head-down responses are indicated. Large sway responses following *stimulus-on* and *stimulus-off* are seen with the head up. These are abolished with the head down leaving small transient responses in the opposite directions.

larger medium-latency reflex of opposite polarity follows with total activity being inhibited after 124 ms and not returning to baseline until 287 ms. With the head down, the short-latency response is preserved whereas the medium-latency response is abolished. This reveals a larger and longer lasting short-latency response (up to 163 ms) than is seen when the medium latency response is also present. At approximately 90 ms after the stimulus start, the EMG activities for head-up and head-down deviate (arrow in Fig. 3). This provides an estimate of the earliest onset of the medium-latency response.

The inhibitory component of the responses in soleus is seen as reciprocal excitation in tibialis anterior (Fig. 3, bottom). Reciprocal inhibition is not seen in tibialis anterior because that muscle is inactive most of the time at the normal position of balance and only becomes active when the body leans backwards of this position.

Discussion

An explanation of the results

The two angles of head pitch tested here were selected so that, when the head was turned at right angles to the body, the GVS-evoked signal from the semicircular canals would indicate pure whole-body pitch with the head up, and pure whole-body yaw with the head down. These angles were calculated from the anatomical planes of the semicircular canals in the head (Blanks *et al.* 1975) and the orientation of their hair cells, and by assuming that, on average, GVS modulates the firing of all vestibular afferents equally. The model (Fitzpatrick & Day, 2004) predicts that maximal GVS canal responses would be evoked with the head up but these would disappear with the head down because balance responses are not required for yaw disturbances. Thus, we propose that the large GVS sway response in the anodal direction and the consistent medium-latency EMG response arise through GVS modulation of semicircular canal afferents. As predicted by the model, these responses are seen with the head up and disappear with the head down.

The galvanic otolith signal is modelled as the vector sum of the responses of the entire population of hair cells across the surfaces of both maculae (Fitzpatrick & Day, 2004). Accurate population data are available from Tribukait & Rosenhall (2001) who describe the proportions of afferents in human utricles that respond to accelerations in various directions across the planes of the maculae. The model predicts that the net galvanic otolith discharge signals head acceleration along the interaural axis. Thus, this vector will not change when the head is bowed forward in pitch. In the head-down GVS response, the residual transient movements correspond with the direction and timing of the short-latency EMG response that is seen in the head-up GVS response. These are unchanged by head pitch. Therefore, we propose that these responses originate from GVS modulation of utricular afferents.

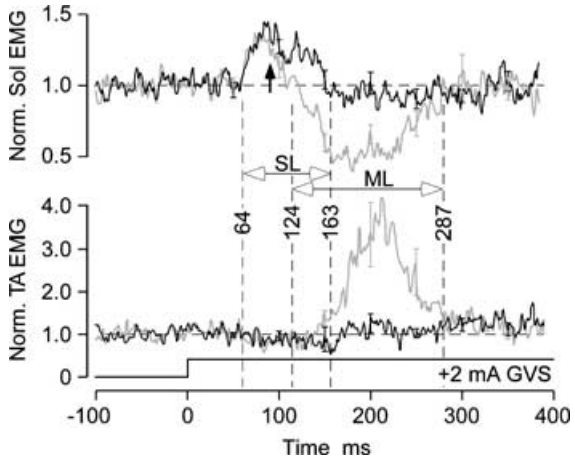

Figure 3. Average EMG responses in soleus and tibialis anterior
Rectified electromyograms have been normalized then averaged across subjects, legs and stimulus polarities to produce responses corresponding to GVS with the anodal electrode anterior. Thus, the excitatory short-latency EMG response (SL, 64 ms) in soleus would correspond with backward body sway and the inhibitory medium-latency response (ML) corresponds with anterior body sway. The grey traces are head-up, the black are head-down. Error bars (± S.E.M.) are shown every 50 s post-stimulus. The medium-latency response is abolished with the head down but the short-latency response is preserved. The arrow marks the point at which the head-up and head-down responses deviate.

Timing and amplitude

These data indicate that the medium-latency response appears at about 90 ms (Fig. 3, arrow), earlier than previous estimates of 100–120 ms (Nashner & Wolfson, 1974; Britton *et al.* 1993; Fitzpatrick *et al.* 1994; Welgampola & Colebatch, 2002). However, it is still later than the short-latency response. Why should a vestibular perturbation evoke two distinct postural responses having opposite sign and differing latency? Different central pathways from vestibular afferents to the spinal cord may explain the latency difference. Britton *et al.* (1993) proposed vestibulospinal and reticulospinal tracts as possible candidates for two such routes. As canal and otolithic signals have different implications for body movement and serve different functions, it is not unexpected for them to be processed and transmitted differently.

It is important to note that the amplitudes of the canal and otolith responses evoked by GVS do not reflect their relative importance for balance in normal situations. The sizes of the GVS responses reflect the nature of the electrical stimulus and the different anatomical arrangements of the two systems. Likewise, the larger canal response with the

head bent forward does not indicate a more important role for the semicircular canals with the head in this position. Clearly, we need to be cautious interpreting previous results of GVS where head pitch has not been controlled.

From a functional viewpoint, the opposite sign of the short- and medium-latency responses is more difficult to understand. Of course, the opposite sign of the responses is an 'artefact' of this particular unnatural electrical disturbance. However, the fact that two apparently oppositely directed responses can coexist implies some functional role for independent balance responses from the semicircular canals and otolith organs. It is likely that this independence is relevant in the real world, where countless combinations of tilt or translation of the body and tilt or translation of the support surface require a diverse range of compensatory responses to maintain balance.

In most previous studies, GVS has produced plateau-like sway responses in which the subject attains a new steady-state realignment of the body (Inglis *et al.* 1995; Day *et al.* 1997). However, in some circumstances, the GVS response can include large continuous ramp-like as well as plateau-like movements. In a single deafferented subject, GVS produces extremely large continuous responses (Day & Cole, 2002). Similar continuous responses are evoked in situations of increased stability but where somatosensory information about sway is limited (Wardman *et al.* 2003). Thus, the plateau response is likely to arise because the continuous sway response, primarily from the continuous canal signal, is arrested prematurely by sensory input from other sources that conflict with the vestibular signal.

Coordinate transformation

Cuneo-cerebellar afferents conveying neck somatosensory information converge with labyrinthine signals in the cerebellum. These signals are processed so that Purkinje units of the cerebellar vermis and their targets in the fastigial nucleus respond to vestibular input as if the signal has been transformed into whole-body coordinates (Manzoni *et al.* 1999; Kleine *et al.* 2004). The output of this palaeocerebellar processing projects to medullary vestibulospinal and reticulospinal units and, presumably through these pathways, alignment of the head on the body modulates the pattern of vestibulospinal reflexes so that they appear to be appropriate for the reference frame of the body rather than the head (Manzoni *et al.* 1998). Both the short-latency and medium-latency GVS reflexes are modulated by head-on-body orientation (Britton *et al.* 1993; Fitzpatrick *et al.* 1994) making similar cerebellar processing likely but, beyond that, we are unable to speculate on the different pathways and processes that produce them. If both responses are indeed processed by the palaeocerebellar network described above, we do not know how vestibulospinal and reticulospinal pathways contribute to the responses. However, vestibulocerebellar fibres from the vestibular ganglia and nuclei also project to the flocculonodular lobe of the cerebellum. Thus, archicerebellar Purkinje projections back to the vestibular nuclei could also mediate balance reflexes via vestibulospinal pathways. Rostral projections of signals from the labyrinth and neck, with or without cerebellar processing, are also available to contribute to these responses.

Einstein's equivalence principle implies that, at the level of the receptors, the otolithic signal could indicate tilt in gravity or linear acceleration. In some situations, it may be necessary to resolve this otolithic ambiguity to generate appropriate motor responses. The semicircular canal signal is the prime candidate because it will indicate concurrent head rotation. There is also cellular evidence that neurones can distinguish these two forms of linear acceleration (Angelaki *et al.* 2004). Of course, sensory sources such as postural proprioceptors could do likewise, but *a priori* knowledge of context and the current motor task may determine how the otolithic signal is interpreted. Thus, the head-down response, which shows only transient effects (Fig. 2), may apply to a condition in which there is no rotation signal from the canals or elsewhere. With the head-up, the rotation signal from the canals could generate a different interpretation of the otolithic signal. This would mean that the large head-up sway response is not exclusively from the canals but may contain an otolithic response contingent on the canal signal. In other words, the CNS may use both the canal and otolith information evoked by GVS for both the short- and medium-latency response but interpret the total vestibular signal differently depending on the whole-body somatosensory map of equilibrium.

Conclusion

The vestibular apparatus comprises different organs: the neuroepithelial surfaces of the semicircular canals, the utricle and the saccule. The latter two, although of different embryological origins, are structurally similar and considered to have a common 'otolithic' function. Human standing is maintained by a coordinated response to vestibular, visual and somatosensory inputs. This almost universal opening to a discussion of human balance, by sleight of pen, carries an assumption that the vestibular system imposes a unitary control on balance. However, the semicircular canal and otolith organs should be considered as separate sensory systems. The present study indicates that both systems exert automatic reflex control of human balance and that these processes are independent. The different latencies of the two responses also suggests that the canals and otolith systems exert their effects on balance through different pathways, reflecting the notion

that balance involves separate position and movement controls.

References

Angelaki DE, Shaikh AG, Green AM & Dickman JD (2004). Neurons compute internal models of the physical laws of motion. *Nature* **430**, 560–564.

Blanks RH, Curthoys IS & Markham CH (1975). Planar relationships of the semicircular canals in man. *Acta Otolaryngol* **80**, 185–196.

Britton TC, Day BL, Brown P, Rothwell JC, Thompson PD & Marsden CD (1993). Postural electromyographic responses in the arm and leg following galvanic vestibular stimulation in man. *Exp Brain Res* **94**, 143–151.

Day BL & Cole J (2002). Vestibular-evoked postural responses in the absence of somatosensory information. *Brain* **125**, 2081–2088.

Day BL, Severac Cauquil A, Bartolomei L, Pastor MA & Lyon IN (1997). Human body-segment tilts induced by galvanic stimulation: a vestibularly driven balance protection mechanism. *J Physiol* **500**, 661–672.

Fitzpatrick R, Burke D & Gandevia SC (1994). Task-dependent reflex responses and movement illusions evoked by galvanic vestibular stimulation in standing humans. *J Physiol* **478**, 363–372.

Fitzpatrick RC & Day BL (2004). Probing the human vestibular system with galvanic stimulation. *J Appl Physiol* **96**, 2301–2316.

Goldberg JM, Fernandez C & Smith CE (1982). Responses of vestibular-nerve afferents in the squirrel monkey to externally applied galvanic currents. *Brain Res* **252**, 156–160.

Inglis JT, Shupert CL, Hlavacka F & Horak FB (1995). Effect of galvanic vestibular stimulation on human postural responses during support surface translations. *J Neurophysiol* **73**, 896–901.

Kleine JF, Guan Y, Kipiani E, Glonti L, Hoshi M & Buttner U (2004). Trunk position influences vestibular responses of fastigial nucleus neurons in the alert monkey. *J Neurophysiol* **91**, 2090–2100.

Lund S & Broberg C (1983). Effects of different head positions on postural sway in man induced by a reproducible vestibular error signal. *Acta Physiol Scand* **117**, 307–309.

Manzoni D, Pompeiano O & Andre P (1998). Neck influences on the spatial properties of vestibulospinal reflexes in decerebrate cats: role of the cerebellar anterior vermis. *J Vestib Res* **8**, 283–297.

Manzoni D, Pompeiano O, Bruschini L & Andre P (1999). Neck input modifies the reference frame for coding labyrinthine signals in the cerebellar vermis: a cellular analysis. *Neuroscience* **93**, 1095–1107.

Nashner LM & Wolfson P (1974). Influence of head position and proprioceptive cues on short latency postural reflexes evoked by galvanic stimulation of the human labyrinth. *Brain Res* **67**, 255–268.

Tribukait A & Rosenhall U (2001). Directional sensitivity of the human macula utriculi based on morphological characteristics. *Audiol Neurootol* **6**, 98–107.

Wardman DL, Day BL & Fitzpatrick RC (2003). Position and velocity responses to galvanic vestibular stimulation in human subjects during standing. *J Physiol* **547**, 293–299.

Welgampola MS & Colebatch JG (2002). Selective effects of ageing on vestibular-dependent lower limb responses following galvanic stimulation. *Clin Neurophysiol* **113**, 528–534.

Acknowledgements

This work was supported by the National Health and Medical Research Council of Australia and the Medical Research Council of Great Britain. We thank Dr Jane Butler for her help in designing the experiment.