NEUROLOGICAL INVESTIGATIONS

Investigations of disorders of balance

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To maintain balance in the upright position, a complex and not altogether successful series of neurological mechanisms have evolved. These comprise visual, proprioceptive, and vestibular systems, all of which interact, and information which is analysed by the cerebellum, cerebral cortex, and basal ganglia. As a result of this analysis appropriate motor outputs occur in an attempt to maintain posture and gait. Dysfunction of any part can result in imbalance or a feeling of spatial disorientation.

In this article we consider tests primarily of the vestibular system, which help to determine what abnormalities account for a patient's symptoms. We will not consider in any detail research techniques or analyses that are of little value in the clinical assessment of the patient at the present time. As in all branches of medicine it is essential to obtain an accurate history and to do a thorough general and neurological examination of any patient complaining of impaired balance before embarking on extensive investigation; a complaint of imbalance may signify a wide range of possible diseases including disorders of the cardiovascular and musculoskeletal systems, as well as dysfunction of the nervous system.

Clinical investigation of the vestibular system

The vestibular system comprises two main components; one concerned with detection of angular acceleration (semicircular canals) and one concerned with detection of linear acceleration (otoliths). The semicircular canals comprise three pairs of accelerometers arranged roughly in three orthogonal planes, one set on each side of the head. In humans and other erect primates, the vertical canals are large compared with those in quadrupeds, a point of some relevance in that we have greater ability to assess the horizontal than the vertical canals.¹ Whereas the adequate stimulus is acceleration, because of the nature of flow of fluids through narrow tubes of large radius of curvature, the VIIIth nerve carries velocity (first integral) information to the vestibular nuclei.² Further integration to position occurs at a central level and this information is fed to various motor nuclei in the brain stem and cord as well as to the cerebellum and cerebral cortex.²

Clinical assessment of the integrity of the vestibulospinal connections is not entirely sat-

isfactory. Traditionally this is determined by studying stance and gait with and without fixation. Acute failure of vestibular input from one side results in the patient falling to that side, a situation made worse by removal of fixation. Similarly, when such a patient walks they usually veer to the side of the lesion; again this is accentuated by eye closure. Various clinical tests with eponymous titles have been devised in an attempt to increase the accuracy in determining the side of a unilateral lesion. For example, in Unterburger's test the patient is instructed to march on the spot with the eyes closed; in the case of a unilateral lesion the patient rotates to the side of the lesion. Although these clinical tests may be indicative of abnormality, their ability to predict the side of a unilateral lesion is poor, especially in chronic, progressive, or partially compensated lesions. Removal of proprioceptive cues can also be useful in assessing patients especially those with total vestibular failure. If such patients are placed on a rubber mattress and then fixation is removed they will fall as proprioceptive cues function poorly under these circumstances. Attempts have been made to improve the sensitivity and specificity of stance assessment by the development of various mechanical platforms (see posturography).

Of particular concern to the neurologist are the connections to the extraocular muscle nuclei which permit the vestibulo-ocular reflex (VOR). This reflex functions in the three cardinal planes. Stimulation or inhibition of complementary pairs of canals results in appropriate movement of the eyes ensuring adequate foveation during head movement. The system has a wide dynamic range sufficient to stabilise a retinal image on the fovea through most movements.³ This is necessary as the only other mechanism available for image stabilisation is the pursuit optokinetic system, which functions poorly above 1 Hz. The other major part of the vestibular system is that involved in gravity detection. This system comprises two end organs (sacculi and utricle) which detect linear acceleration (including gravity) by virtue of the otoconia that rest on hair cells of the macula. Each macula can signal acceleration in many directions because of the multiple orientation of hair cells in the end organ.² Connections of these linear accelerometers are less well determined than those from semicircular canals but there are

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connections to the neurons innervating somatic and eye muscles.

CLINICAL ASSESSMENT OF THE VOR

The most useful reflexes clinically to assess the vestibular system are the vestibulo-ocular ones. In the main, these involve activation of the semicircular canals (VOR in the three cardinal planes) by variants of the doll's head manoeuvre. It is difficult, however, clinically to assess canal function in isolation because of the presence of pursuit-optokinetic eye movements in the light and excitation of cervical receptors. Normal neck-eye reflexes are weak but contamination from them can be avoided by using a swivel office chair to rotate the whole patient in the horizontal plane; this is also of value in cases of neck rigidity or poor patient cooperation. Despite these limitations VOR examination is useful in cases of ophthalmoplegia to see if restriction of gaze can be overridden by a rotation of the head in the appropriate plane. For example, in Steele-Richardson syndrome the ophthalmoplegia is initially supranuclear leaving the final common pathway via the extraocular motor nuclei intact; pursuit and especially saccadic movements are limited due to the disconnection of cortical pathways in the mesencephalon and brain stem. Proof that the ophthalmoplegia is indeed supranuclear is obtained by showing full range of movement, or improvement of movement, by the VOR. This is most easily done by getting the subject to fixate an earthbound target and rotating the head in a sinusoidal fashion up and down (the direction in which limitation first occurs) and showing improvement in the excursion of the eye. Clearly, pursuit may play a part in this improvement but the VOR is the most important factor. Information is fed from the vestibular nuclei and lower brain stem to the mesencephalic nuclei responsible for vertical gaze.

Clinically, some information on VOR function can be obtained by turning the patient's head while observing the optic disc during funduscopy.⁴ The patient must be instructed to maintain fixation on an object across the room. Normally, the disc remains steady in space but if, say, the right labyrinth is hypoactive, the disc will seem to jerk during turning of the head (chin) to the right. When the vestibular loss is profound, this jerky eye movement in response to turns of the head can be seen by the naked eye. In this case it is best to instruct the patient to fixate on the examiner's nose.

Assessment of otolith function clinically is even less easily done. Counter rolling of the eyes can be seen when the head is rotated to the ear down on to one shoulder; the eyes slowly deviate in the opposite sense and then there is a rotatory quick phase causing torsional nystagmus. This response is, however, mainly dependent on the vertical semicircular canals rather than the otoliths. Skew deviation of the eyes (vertical divergence of the eyes) without nystagmus is thought to reflect tonic otolith pathway imbalance. It can be seen with utricular nerve lesion⁵ or with lesions of the

mesencephalon, especially those involving the interstitial nucleus of Cajal⁶ and medulla; this type of tonic rotation may be suspected from a head tilt or the eye covering test or seen from tilting of the optic disc.

A further important finding that can be made on the VOR in a clinical setting is assessment of VOR suppression (VORS). In a normal subject the VOR enables fixation to be maintained during head motion. If a subject is rotated through large angles, however, the VOR is interrupted by repetitive saccadic movements in the opposite sense to the slow movement; this is vestibular nystagmus. The VORS is easily tested by getting the subject to fixate a long spatula gripped in the teeth while oscillating the head in the horizontal or vertical plane,⁷ or more simply by fixating their thumbs with arms outstretched while rotating at the waist or on a swivel chair. No nystagmus is seen in the normal subject until the frequency of oscillation approaches 1 Hz or the peak velocity is greater than 60°/s. Similarly, in peripheral disturbances the VORS is intact. In many patients with cerebellar and brain stem lesions VORS is absent—that is, nystagmus is even seen during slow head movements. There is usually a good correlation between VORS and pursuit; absent pursuit usually results in absent VORS. Using electronystagmography (ENG) and other methods of recording eye movement it is possible to obtain an accurate measure of the VORS (see laboratory assessment).

CLINICAL ASSESSMENT OF SPONTANEOUS NYSTAGMUS

One of the cardinal signs of abnormal vestibular function is nystagmus but not all nystagmus signifies vestibular abnormality. To differentiate between types of nystagmus may require an analog or digital recording of the wave form of the movement and an assessment of the effect of the removal of fixation on the nystagmus.

Vestibular nystagmus is caused by an imbalance between the paired vestibular structures (end organ, VIIIth nerve, or relevant brain stem nuclei). Briefly, reduction of vestibular activity on one side of the brain stem causes a slow drift of the eyes to the side of that reduction. This slow movement, which is essentially linear—that is, constant velocity—is followed by a rapid saccadic movement in the opposite direction. Repetition of this results in saw tooth vestibular nystagmus. The nystagmus is called first degree if present only when gaze is directed towards the fast phase, second degree if present in the primary position, or third degree if present when the eyes are deviated in the direction of the slow phase (Alexander's Law).⁸ Removal of fixation typically enhances the nystagmus if the lesion is peripheral and the eyes drift markedly towards the deranged side (fig 1). This can be seen clinically with infrared apparatus or Frenzel's glasses; these have high dioptric convergence lenses which allow a magnified view of the eye of the patient, without the patient being able to fixate due to the blur produced by the lenses.

Figure 1 ENG of vestibular nystagmus due to left peripheral lesion. Note nystagmus is only apparent with eyes deviated to right (R) in presence of fixation but when light is extinguished at D, nystagmus is apparent in primary (P) and on left (L) gaze. The nystagmus is saw toothed—that is, has a linear slow phase, its magnitude increases with deviation of eyes in direction of fast phase, and it is always in the same direction. In all figures for horizontal recordings up deflection is to right.

Figure 2 ENG of gaze paretic nystagmus in cerebellar lesion. Note exponential decline of slow phase and some rebound nystagmus when eyes return to midline.

Alternatively, low amplitude nystagmus can be detected with funduscopy (which makes the nystagmus seem reversed).⁴ In some patients vigorous head shaking may generate a nystagmus that is not clinically apparent. The “head shaking” test (20–30 full cycles at around 2 Hz followed by Frenzel’s glasses observation) is claimed to be a useful addition to the clinical vestibular examination; there is a fair correlation with caloric test findings.^{9 10}

Figure 3 ENG of gaze paretic nystagmus to right and vestibular nystagmus to left (above) in patient with a right sided brain stem glioma shown in the MRI (below).

Figure 4 ENG of internuclear ophthalmoplegia showing up beat nystagmus. On the left the vertical trace (VERT) shows gaze paretic up beat nystagmus on looking upwards. On the right the horizontal eye movement record (HOR) for left (le) and right (re) eyes at rapid paper speed shows slow adduction velocity in the left eye and gaze paretic nystagmus in the right eye.

The wave form of nystagmus is not always saw toothed with a linear (constant) velocity, slow phase; with gaze paretic nystagmus the slow phase has a roughly exponential decline interrupted by repeated fast phases (fig 2). This form of nystagmus is due to a failure of integration of the burst of activity arising from the saccadic generators in the paramedian pontine reticular formation (PPRF).¹¹ This results in insufficient tonic holding activity to maintain the eyes in the eccentric position against the orbital elastic forces tending to return the eye to the orbital mid-position. Failure of integration most commonly occurs in lesions of the brain stem or cerebellum but can also be seen if there is a failure of faithful transmission of activity through the final common pathway to the extraocular muscles—for example, myasthenia gravis—or if the muscles themselves are unable to contract effectively—for example, ocular myopathy. This form of nystagmus occurs in a wide variety of CNS conditions, many of which are associated with imbalance. At the clinical level, bidirectional nystagmus in the horizontal plane is nearly always associated with central dysfunction (fig 3). An exception is congenital nystagmus (see oculography).

Acquired nystagmus in the vertical plane occurs less often than horizontal nystagmus and is almost always an indication of a central disorder. Further, it is invariably accompanied by imbalance. Vertical upbeat nystagmus, especially if present in the primary position, indicates a lesion in the floor of the IVth ventricle or ventral to the aqueduct, or possibly within the superior cerebellar vermis; it is often seen in patients with bilateral internuclear ophthalmoplegia (fig 4).¹² Down beat nystagmus is seen with lesions at the foramen magnum—for example, Arnold-Chiari malformation—or with cerebellar atrophy.¹³ No cause is apparent in probably 40% of all cases; of note is the rarity of this type of nystagmus in patients with multiple sclerosis or intra-axial tumours (table 1). Characteristically, vertical nystagmus is altered by position¹⁴ and down beat nystagmus is increased in amplitude if the eyes are deviated 30° to the left or right of the midline. Convergence can also modify vertical nystagmus. Down beating nystagmus has been associated with syringomyelia but this is not entirely true. In patients with cerebellar ectopia and a syrinx in whom there is nystagmus (about 30% of the total) the nystagmus is often torsional, with the fast phase usually

Table 1 Causes of down beat nystagmus^{13 70}

Diagnosis	%
Cerebellar ectopia	27
Cerebellar degeneration	
Genetic	18
Acquired	10
Tumour	2
Multiple sclerosis	1
Undiagnosed	42

directed towards the side of greater sensory loss in the limbs—that is, clockwise fast phase from the examiner’s viewpoint is associated with left sided sensory loss. Torsional nystagmus is not confined to syringomyelia; it is also typically found in lesions of the medial vestibular nucleus (fig 5), as in Wallenberg’s syndrome, and lesions of the cerebellum.¹⁵

There are some rarer types of nystagmus all of which are often associated with imbalance. Of these, rebound nystagmus is the most frequent.¹⁶ If gaze-paretic nystagmus is induced on looking in one direction and the eyes are kept deviated for a prolonged period the nystagmus sometimes diminishes and ceases. When the eyes are returned to the midline a nystagmus in the reverse direction is seen for a short period, even though nystagmus in the primary position was not initially present (fig 2). Such nystagmus is typical of cerebellar lesions. Pendular nystagmus is nystagmus in which there is no clear distinction between the fast and slow phase. It may be symmetric—that is, identical in each eye or highly asymmetric differing in amplitude, direction, or both in either eye. On occasion complex trajectories are followed—for example, elliptical or figure of eight. This type of nystagmus

occurs in patients with longstanding visual failure and in lesions of the brain stem especially those involving the central tegmental tract.^{17 18} In neurological practice it is most often seen in multiple sclerosis, in which it is often associated with an internuclear ophthalmoplegia. Although some workers think that impaired visual acuity is important in the generation of pendular nystagmus¹⁹ this has not been our experience. Convergence retraction nystagmus due to lesions in the region of the quadrigeminal plate and posterior commissure can readily be seen clinically especially using an optokinetic drum rotated downwards; it is difficult to record without video filming. Periodic alternating nystagmus—that is, nystagmus in which the direction spontaneously and repeatedly reverses despite eye position being constant—is found in various cerebellar disorders and can readily be seen; it is clearly shown by prolonged horizontal eye movement recordings. Finally seesaw nystagmus, in which one eye elevates and intorts and the other is depressed and extorts repeatedly, indicates a lesion in the region of the peduncular fossa and is probably due to damage in the interstitial nucleus of the medial longitudinal fasciculus and the adjacent nucleus of Cajal.⁶ It is readily seen clinically but recordings are necessary to delineate it fully.

Figure 5 Horizontal (H), vertical (V), and torsional (T) eye movement recordings (scleral search coil technique) of a patient with predominantly torsional right beating nystagmus (top) due to a left sided lesion on the floor of the IVth ventricle (bottom). The lesion is likely to have involved the left medial vestibular nucleus.

CLINICAL ASSESSMENT OF INDUCED NYSTAGMUS

Because many patients with imbalance do not have nystagmus, techniques for inducing nystagmus are commonly used in the clinic. The most valuable methods are optokinetic, rotational, caloric, and positional stimuli.

Optokinetic nystagmus

Optokinetic nystagmus can be assessed at the bedside with a small striped drum rotated in front of the patient. This is basically a pursuit task and not surprisingly correlates well with other pursuit measures. It is possible to measure optokinetic responses with a small drum, or with a large visual field rotating about the patient using various special techniques such as electronystagmography (ENG, see later). A common abnormality is a directional preponderance—that is, a greater response in one direction. Typically a right directional preponderance correlates with abnormal pursuit to the right (for example, a right cerebellar or parietal lesion results in greater optokinetic nystagmus towards the right). In normal subjects the eyes deviate in the direction of the fast phase of optokinetic nystagmus but in certain disorders of the basal ganglia the converse happens—that is, deviation is in the direction of the slow phase.²⁰

Nystagmus induced by stimulation of the semi-circular canals

Two clinical methods are available to stimulate the semicircular canals: caloric testing and rotational stimuli. Because much information can be obtained from clinical assessment of the caloric tests they will be considered next. Sophisticated assessment of rotational stim-

uli—for example, ENG—will be considered in a later section.

Caloric testing

This test depends primarily on convection set up in the relevant canal by thermal stimulation. In the clinical setting the test is most commonly used to measure horizontal canal function. The usual method is that described by Fitzgerald and Hallpike in their classic paper²¹ in which the horizontal canal is put in the vertical plane with its ampulla uppermost by lying the patient horizontally on the back and flexing the neck to 30°. One external meatus is irrigated with water at 7° above or below body temperature for 40 seconds, with the flow rate being greater than 6 ml/s. This stimulus sets up a convection current which flows up if hot water is used and stimulates the hair cells; conversely the cold stimulus causes movement of endolymph away from the ampulla and reduces the firing rate of the cells.²² Thermal stimulation of hair cells without any convection would also cause similar effects on the hair cell firing rate but in fact this probably only accounts for a small proportion of the alteration²³ (although it accounts for all of it in conditions of zero gravity such as space travel).²⁴ The interested clinician can prove to himself the importance of convection by doing a caloric test on a colleague and repeatedly turning the subject prone and supine and showing that the nystagmus reverses as the ampulla changes from being inferior to being superior.

The nystagmic response is used to assess the effect of canal irrigation. The eyes are viewed in the light while the subject fixates a spot on the ceiling. During and after completion of irrigation nystagmus is induced to the side opposite the irrigated ear in the case of cold irrigation and vice versa for warm irrigation. The test is carried out sequentially using the left and right ear alternately and leaving about five minutes between irrigations. This interval is not sufficient for all the thermal gradient to disappear but is reasonably satisfactory.²⁵ Several variables can be assessed, of which duration of the nystagmus and slow phase velocity are the two most common. Only duration can be used as a clinical measure without special equipment such as ENG. There is no doubt that slow phase velocity is more physiologically meaningful, but interestingly, not more clinically useful. This is because the variance of duration of nystagmus is less than that of slow phase velocity.²⁶

Three types of abnormality are seen with horizontal canal irrigation. Firstly, there may be an underfunctioning of one canal, conventionally called “canal paresis” (CP). In our laboratory, a 9% difference in the duration of nystagmus between the two sides is significant.* This typically occurs in peripheral lesions and a total failure of function of one horizontal canal is nearly always due to end

organ or VIIIth nerve damage. Secondly, there may be a bias of the nystagmus such that the duration in one direction, say the left (with right cold and left hot irrigation), is greater than that to the opposite side. This is known as directional preponderance (DP) and can be seen in peripheral disorders as well as with lesions at any level of the nervous system. It does, however, show that there is a vestibular bias in one direction and if there is a CP as well it indicates that this is not fully compensated. Finally, there may be hypofunction of both horizontal canals—for example, after aminoglycoside antibiotic treatment. The advantage of caloric testing of horizontal canals is that function of a single canal can be assessed, a situation that applies to no other test routinely available. The primary disadvantages of caloric testing are that the stimulus intensity varies in different subjects—for example, because of differences in meatal diameter, and that water irrigation cannot be used if there is a defect of the tympanic membrane.

Caloric testing can also be used to assess the function of the vertical canals but in this case only pairs of canals, either anterior or posterior, are studied. These canals are set deeper in the petrous temporal bone than the horizontal canals and therefore longer duration and more intense thermal stimuli are required. Both ears are irrigated simultaneously with either cold (20°C) or hot (47°C) water for 60 seconds with the head in the usual position for caloric testing. The cold stimulus causes slow downward deviation of the eyes with upbeat nystagmus and the hot stimulus the reverse. It is essential to perform horizontal irrigation first to ensure that there is no underfunctioning of the horizontal canal; if there is, reduction of duration of irrigation of the relatively “normal” ear is necessary to avoid oblique nystagmus. Bilateral, bithermal caloric testing is particularly useful in patients with ophthalmoplegias to determine if the paresis of the eye movements is nuclear or supranuclear—for example, Steele-Richardson syndrome.²⁰ As will be noted from the temperature of water used for this type of testing the cold stimulus is of greater magnitude. Unfortunately it is not possible to raise the temperature of the hot stimulus above 47°C and even that is very uncomfortable indeed.

During caloric testing it is possible to assess visual suppression (VORS) of nystagmus without contamination from other reflex eye movements.^{27,28} A practicable method is to perform each irrigation with fixation and when the nystagmus ceases, to extinguish the fixation spot and view the eyes in the dark with an infrared viewer, or to use Frenzel's glasses. In a normal subject or patients with a peripheral lesion, the nystagmus will again be seen and its duration without fixation gives a measure of the visual suppression. In the case of central lesions, especially those involving cerebellar connec-

$$* \quad CP = \frac{f(L_{cold} + L_{hot}) - f(R_{cold} + R_{hot})}{f(L_{cold} + L_{hot} + R_{cold} + R_{hot})} \%$$

$$DP = \frac{f(L_{beating \ nystagmus}) - f(R_{beating \ nystagmus})}{f(\text{sum all nystagmus})} \%$$

Table 2 Positional nystagmus

	Benign	Central
Direction	To dependent ear (torsional)	Any
Vertigo	++	+
Latent interval	+	—
Adaptation	+	—
Fatigue	+	—

tions, visual suppression is reduced or absent so that there is pronounced nystagmus with fixation but when the nystagmus stops, removal of fixation does not result in a recurrence of it. The duration of nystagmus is never greater with fixation than without.

Rotational responses

It is possible to obtain a general clinical impression of the degree of symmetry of vestibular ocular function by conducting the doll's head manoeuvre with careful examination of the eye, directly or during ophthalmoscopy,⁴ or by manually rotating the subject at a roughly constant velocity on an office swivel chair and observing the postrotational response. The last is essentially the original Barany test in which subjects are rotated at about 90 or 120°/s (one revolution every three or four seconds) for 30 seconds in one direction and then stopped facing the examiner to time the duration of the observed nystagmus. By comparing the postrotational response in the two directions an idea of symmetry can be obtained. Although now superseded by recording techniques and motorised equipment, this procedure is occasionally used even in well equipped centres when a rapid assessment of vertical semicircular canal function is required. In this case the patient should be rotated with the head extended so that the face is directed towards the ceiling; horizontal rotation of the chair then stimulates the vertical canals. Of course in this case the nystagmus seen is torsional and because its amplitude is usually low the clinician should examine the subject's eyes closely under bright illumination. Asymmetries in the duration of the nystagmus should be 15–20% or more to be of significance.

Positional nystagmus

Nystagmus may readily be induced, or, if already present, modified by changes in position of the head. The conventional method is the Hallpike manoeuvre. In this the patient sits on a couch and the examiner firmly grasps the head which is turned 60° towards one shoulder. The patient is instructed to keep the eyes open and to fixate the examiner's forehead.

The patient's head is rapidly lowered to below the level of the couch and the eyes observed for any nystagmus. After an interval of 30 seconds, if nystagmus is not found, or after the nystagmus ceases (the test may have to be terminated if the nystagmus lasts longer than two minutes) the patient is returned to the sitting position. Again, any nystagmus is noted. The test is repeated if nystagmus is found to see if there is any adaptation. After this the test is performed with the opposite ear dependent. The variables noted are latency to onset of nystagmus, its duration and adaptation, its direction, and finally, associated symptoms. Broadly two types of nystagmus are seen: benign positional nystagmus and central positional nystagmus (table 2).

Typical benign positional nystagmus indicates a peripheral lesion in which debris from the otolith apparatus accumulate on the cupula of the posterior semicircular canal. Two theories have been proposed to account for the nystagmus and both depend on inversion of the posterior canal resulting in either displacement of the cupula of that canal because the debris alter its specific gravity (cupulolithiasis)²⁹ or the passage of debris down that canal acting as a plunger (canalolithiasis).^{30 31} Occasionally what seems to be bilateral benign positional nystagmus occurs. Recently, benign positional nystagmus arising in the horizontal canal system has been reported. It is elicited by brisk turning of the head to one side while in the supine position.³²

Typical central positional nystagmus occurs in a wide variety of lesions, especially those involving the vestibulocerebellum. Of note is the fact that spontaneous vertical nystagmus, either upwards or downwards, can often be modified by positional testing using the conventional Hallpike manoeuvre or by placing the subject supine or prone. If the nystagmus is increased in the prone position it is usually decreased lying supine. Nystagmus induced by canal stimulation can also be profoundly modified by alteration of position of the head, due to otolith/semicircular canal interaction.^{14 33 34}

Laboratory assessment of patients

OCULOGRAPHY AND

ELECTRONYSTAGMOGRAPHY (ENG)

The techniques currently available for recording and the analysis of eye movement have been presented in a previous chapter in this series.³⁵ Table 3 presents a summary of the main advantages and disadvantages of these systems. From the point of view of the investigation of the patient with a balance disorder,

Table 3 Eye movement recording techniques

	Electro-oculography EOG/ENG	Infrared oculography IRO	Scleral search coil SCC	Video-oculography VOG
Signal source	Corneoretinal potential	Limbus infrared light reflection	Contact lens-mounted search coil	Iris/pupil image processing
Advantages	Non-invasive Simple/inexpensive Prolonged recordings Good linearity Low resolution (1°) Noise/drift	Non-invasive Intermediate price Good resolution (10')	Excellent resolution (2') Torsional recordings	Non-invasive Torsional recordings Good resolution (10')
Disadvantages		Poor linearity	Invasive Expensive	Expensive Low temporal resolution

Table 4 Indications for eye movement recordings to investigate imbalance

1	Assessment of eye movements in the dark
	(a) Is there vestibular nystagmus?
	(b) Vestibular function (for example, rotational test)
2	Nystagmus wave form
	(a) Vestibular <i>v</i> gaze paretic
	(b) Acquired or congenital
3	Confirmation/detection of subtle abnormalities of diagnostic value (for example, abnormal pursuit, subclinical INO)
4	Research, quantification, and follow up

in whom an investigation of vestibular responses is required, the technique generally recommended is ENG as it allows recording over a wide range of amplitudes; ENG, also called electro-oculography (EOG), is the cheapest system and one not requiring a great deal of technical or scientific support. It is mainly used for investigation of horizontal eye movements and therefore for assessment of horizontal semicircular canal function. It can produce some reasonable recordings in the vertical plane but it is totally insensitive to torsional movements—that is, those occurring around the visual axis. Thus the recording of abnormalities of eye movements in these planes, related to dysfunction in the vertical canal system or the otoliths, requires the use of more complex techniques such as video oculography or the more invasive scleral search coil system. Fortunately the most common abnormality affecting the vertical canal/otolith system is benign paroxysmal positional vertigo (BPPV), which does not require eye movement recordings for its diagnosis (see positional nystagmus).

It is important to consider when referral for eye movement recording is necessary (table 4).

(1) Recordings may be required when the abnormality seen during clinical examination of the eye movement is ambiguous. For example, the presence of square wave jerks superimposed on the slow phase eye movement of smooth pursuit may give the impression that pursuit is abnormal. As square wave jerks may be seen in anxious but otherwise neurologically normal patients, the suspicion of broken pursuit may lead one incorrectly to think that there is structural brainstem/cerebellar damage. Similarly the presence of a mild internuclear ophthalmoplegia can be difficult to detect clinically and separate eye recordings may be necessary to show the difference in velocity between adduction and abduction movements (see fig 4).

(2) Recording of eye movements can be used to characterise the waveform of a nystagmus or other types of ocular oscillations. A good example of the value of oculography is the recognition of congenital nystagmus. Congenital nystagmus, a condition with no neurological consequences, can show various wave forms but some of them are pathognomonic and this will be of importance when a patient who is not aware of having nystagmus develops a neurological problem. Occasionally patients with congenital nystagmus develop visual symptoms in later life and the finding of a nystagmus in these patients is of concern³⁶. In cases like this eye movement recordings have the value of ruling out structural brainstem cerebellar disease and the positive confir-

Figure 6 Horizontal ENG recordings in a patient with congenital nystagmus. The nystagmus shows increasing velocity slow phase waveforms (arrows). Compare these slow phase waveforms with those of peripheral vestibular origin (which are rectilinear, figs 1 and 7) and those of brainstem-cerebellar origin (which are frequently velocity decreasing, figs 2, 3, and 5).

mation of a congenital nystagmus (fig 6). Oculography is also useful in characterising the wave form of acquired nystagmus, especially in separating gaze evoked from vestibular nystagmus (see clinical assessment of spontaneous nystagmus).

(3) Non-nystagmic oscillations can be accurately diagnosed with oculography. For example, flutter (horizontal saccades without intersaccadic interval) or opsoclonus (polydirectional saccades without intersaccadic interval) can be separated from other saccadic oscillations in which there is a saccadic interval (for example, square wave jerks). The length of the saccadic interval may help to decide if the movements are voluntary as in this case the intersaccadic interval exceeds 150 ms.

(4) Eye movement recordings may be required to see if there is any nystagmus in the dark in patients in whom no nystagmus is seen in the light (fig 7). This is typically found in patients with peripheral vestibular dysfunction (figs 1 and 7). Alternatives to recordings of eye movement for observation of nystagmus in the

Figure 7 Horizontal eye movement recordings (ENG) in a patient with a right sided labyrinthectomy. Top: nystagmus in the presence of fixation is almost entirely suppressed by fixation, as early as seven days postoperatively. Bottom: the process of vestibular compensation accounts for the fact that 28 days after the operation the nystagmus had almost entirely disappeared even in the dark. Visual suppression and vestibular compensation explain the lack of clinical findings in peripheral vestibular disorders and underline the need for special investigations in many of these patients.

absence of optic fixation are Frenzel's glasses, infrared viewers, or an infrared camera attached to a video recorder.

(5) Eye movement recordings are necessary when quantification of eye movement performance or abnormalities is required for research or in follow up of individual patients. In degenerative akinetic rigid or cerebellar syndromes successive eye recordings can show progressive abnormalities.

(6) The most common reason for eye movement recording is the investigation of vestibular function without interference from visually guided eye movements as detailed in the next section.

EXAMINATION OF VESTIBULAR FUNCTION

Caloric response

Much information can be obtained by direct observation of the eyes with the caloric test. Many centres have resorted to eye movement recording techniques so that technical staff can carry out the test, to save medical time, and to quantify the response. The interpretation of the caloric abnormality in terms of CP or DP is the same but usually based on slow phase eye velocity rather than on duration of nystagmus.

Rotational testing

To obtain reliable and quantitative information on vestibular function a motorised chair or turntable and a light-tight room are required. Two variables are used to define rotational stimuli: the waveform of the stimulus, whether sinusoidal, trapezoidal, or square wave (impulsive), and the peak velocity reached during the rotation.

The rotational test described in the clinical section is based on the original Barany stimulus and represents a velocity step—that is, impulsive stimulus. The constant velocity rotation is maintained until the nystagmic response disappears (40–60 s) and then the patient is stopped with a similar sudden deceleration. After the induced nystagmus has ceased, the patient is rotated in the opposite direction so that two sets of right beating responses (right start and stop from the left) and left beating responses (left start and stop from the right) are collected. The actual stimulus variables used vary (40–90°/s) but are a compromise between the highest velocity necessary to detect abnormalities and the emetic potential of this test. Responses can be expressed in terms of duration, peak slow phase velocity achieved, time constant of decay of the initial peak velocity—that is, time to decay to about a third of the induced velocity—or by a combination of these. Some machines are produced commercially that enable a printout of these variables. Understandably, different workers prefer to use the technique with which they have the most experience and there is, therefore, no consensus on the ideal “rotational stimulus”.

If the stimulus is sinusoidal it is important that a range, rather than a single, frequency is tested to achieve a thorough investigation of the vestibular ocular system.³⁷ In our experience, sinusoidal testing in a patient with con-

siderable loss of vestibular function can lead to gross underestimation of the degree of vestibular loss. As discussed in the clinical section, a useful addition to the sinusoidal rotational test is to determine suppression of the VOR by visual fixation—that is, VORS. This is investigated by attaching a visual target to the rotating chair so that the subjects fixate an object that moves with them during the oscillation. The threshold of frequency or velocity at which subjects are no longer able effectively to suppress a vestibular nystagmus or the ratio of one of the nystagmus variables—for example, slow phase velocity achieved by the stimulus with and without fixation—is an extremely useful addition to vestibular examination.^{27 28}

Two types of abnormality are encountered during rotational investigation in patients with a balance disorder. The first is asymmetry of the response—DP—which, as discussed earlier, simply indicates a dynamic asymmetry in the peripheral or central vestibular system. As these rotational responses are induced by stimulation of one canal at the same time as inhibition of the opposite one it is not possible to establish with certainty which labyrinth is primarily responsible. The second type of abnormality is less common and comprises changes in magnitude of the induced response. A reduction of the induced response is the commonest finding. Clinicians often do not consider the possibility of bilateral loss of vestibular function in the differential diagnosis of a patient with a balance or gait disorder. In our recent review of bilateral vestibular failure in a neurological hospital, in addition to well known and usually suspected causes of bilateral vestibular loss such as meningitis or antibiotic ototoxicity, many patients had vestibular failure which was idiopathic or associated with cerebellar system degenerations or peripheral/cranial neuropathies.³⁸ The converse of vestibular failure—enhanced responses—also occurs. Bilaterally enhanced vestibular responses can be seen usually in the course of cerebellar disease perhaps because of disinhibition of the vestibular system.^{39–41} This leads to shortlasting but high velocity responses to rotational or caloric stimuli. It is important to remember that patients with bilateral abnormalities of the VOR, either in the form of diminished or enhanced vestibular responses, may have visual symptoms (oscillopsia) particularly during head movement and thus patients with unusual visual symptoms related to head or body motion, especially if associated with unsteadiness, should also be investigated from a vestibular point of view.⁴²

“Full” or “routine” ENG

Because balance depends on the interaction of vestibular, visual, and proprioceptive signals it is customary to extend the neuro-otological examination to areas other than the purely vestibular. This is particularly true in terms of investigation of smooth pursuit, saccades, and optokinetic nystagmus by means of oculography. Although a detailed description of these abnormalities has been presented in a previous

Table 5 Differences between central and peripheral vestibular disorders

	Peripheral (labyrinthine/VIII nerve only)	Central (CNS)
CNS	Normal	Abnormal
Symptoms/examination		
Auditory	Often abnormal	Usually normal
symptoms/examination		
Vertigo:		
(acute lesion)	++++	-/+ ++
(chronic lesion)	+/-	+/-
Oscillopsia	Rare (head movement induced)	Common (usually spontaneous)
Unsteadiness:		
(acute)	++++	++++
(chronic)	+/-	+++
Nystagmus:		
(acute)	++	+ /+++
(chronic)	+/-	+ /+++
Trajectory	Horizontal or horizontal with a torsional component.	Any direction
Amplitude	+	+++
Wave form	Rectilinear	Frequently exponential
Effect of fixation removal	Appears/enhances	Variable
Eye movements (pursuit, OKN, saccades, INO)	Normal	Usually abnormal

chapter in this series,³⁵ it should be noted here that any significant finding on investigation of oculomotor functions would suggest a central rather than a peripheral vestibular disorder. The same can be said about the important visual/vestibular interaction assessed during VORS. Similarly, the diagnosis of peripheral vestibular disorder implies that saccades, pursuit, optokinetic nystagmus, and VORS will be normal on clinical and ENG investigation. Table 5 gives a brief summary highlighting the criteria that can be used to distinguish between peripheral and central vestibular disorders.

Techniques being developed

POSTUROGRAPHY

The recording of postural sway is not a widely accepted or routine part of the examination of the patient with a balance disorder. Body sway is normally assessed indirectly by recordings of the movement of the centre of foot pressure while the patient stands on a force transducing platform. Other motion transducers (for example, accelerometers) and EMG recordings of the lower limbs and trunk, can be added. In its simplest form, recordings of body sway for periods between 20 and 60 seconds with eyes open and closed provide objective quantification of the Romberg test but add no extra information to the clinical observation of that test. Patients with unilateral or even bilateral vestibular disorders are often normal both clinically and quantitatively on the Romberg test.⁴³ It has been reported that if the recordings separate lateral and anterior/posterior components of sway and include frequency analysis of sway with power spectrum techniques, the information obtained can be useful to distinguish the various forms of cerebellar ataxia.⁴⁴ In the form described, often termed static posturography, there is general agreement that the technique is of no practical value in the diagnosis of balance disorders.⁴⁵ When one or more motion stimuli are applied to the subject standing on a force plate the procedure is called dynamic posturography. Such stimuli

can be visual,⁴⁶⁻⁴⁸ vestibular (for example, galvanic),⁴⁹ somatosensory, or combined—for instance, by rotational or translational displacements of the platform.^{50 51} The most popular but expensive commercial system used combines disorienting somatosensory and visual stimuli, by means of coupling the movements of the supporting surface or of the visual surround to the patient's own body sway.⁵² This effectively reduces the efficiency of the somatosensory or visual loops, respectively, in postural control. It is claimed that when all stimulus combinations are studied different patterns of abnormal postural control can be detected which indicate the primary source of disorder. In this way, if a patient cannot balance in the absence of visual input, or with conflicting visual input, and when the somatosensory input has been made unreliable, a "vestibular pattern" is diagnosed. This, as well as many other claims, has not been supported by rigorous clinical studies.⁴⁵ The use of posturography is therefore debatable. Although clearly of research interest in a specialised environment, we recommend a critical view of claims by manufacturers.

OTOLITH FUNCTION

Some patients attending balance disorder clinics report symptoms of unsteadiness which suggest involvement of otolith rather than semicircular canal function.³⁴ This may include a sense of bobbing up and down, being carried upwards or downwards in a lift, or lateral and sagittal pulsions. Certain disorders of head and eye coordination—for instance, the ocular tilt reaction combining head tilt and ocular skew deviation—are thought to be due to interruption of central graviceptive otolith pathways.⁵³ Similarly, positional nystagmus, particularly of the central type as mentioned earlier, is reduced or modified by tilt of the head with respect to the gravity vector, and is therefore interpreted as under otolith control.³³ Despite all this clinical evidence, reliable and simple tests of otolith function in humans are lacking. This is due to the difficulties in delivering the appropriate stimuli (whole body tilt or linear accelerations) which require large motion devices and simultaneously recording a meaningful response (ocular torsion) which requires eye coils or video-oculography.³³ Perhaps the only technique which does not require extraordinary equipment to investigate otolith function is that described by Gresty and Bronstein.⁵⁴ In this procedure the subject's head is placed eccentrically in front of the axis of rotation of a conventional rotating chair while horizontal eye movements are recorded with standard techniques. The rationale is that in this position the head experiences not only angular acceleration but also a tangential component along the interaural axis which gives rise to stimulation of the utricular macula.⁵⁵ The enhanced VOR elicited in this position has been proved in experimental animals to be due to otolith stimulation.⁵⁶ Although clinical abnormalities can be detected,⁵⁷ full evaluation in the clinical setting has not been undertaken.

Assessment of the "visual vertical" in which

subjects have to set a line vertical in an otherwise totally darkened room is sensitive to acute peripheral or central vestibular deficits, but it is not proved that the abnormalities are specific to the otolith system.³⁴⁻⁵³ Indeed, semicircular canal, visual, or proprioceptive stimuli induce profound modifications of the settings of the visual vertical in normal subjects.⁵⁸⁻⁵⁹ The simplicity of the procedure, the inexpensive techniques involved, and clear abnormalities in some cases make this technique an attractive one for the clinician, even if the meaning of abnormalities is not entirely clear.

SELF GENERATED ROTATIONAL STIMULI

In subjects with good neck mobility the head can be rotated about the shoulders either passively by the examiner, or actively by the patient, to stimulate the semicircular canals. Eye movements can be recorded and therefore VOR measurements can be obtained with relatively simple equipment. Halmagyi *et al*⁶⁰ have used high velocity head displacements while recording eye movements with a scleral search coil system and have shown that profound unilateral lesions—for example, vestibular neurectomy—show a clear hypoactivity of the VOR during rotation towards the damaged side. The sensitivity of this technique with less complex or less invasive eye recording methods, as well as its general use in the balance disorder clinic, has not been established. Self generated head movements can be particularly useful for the assessment of the vertical canal system but here again there is the difficulty of having to resort to complex eye movement recording devices to measure torsion or vertical eye motion accurately.

PERCEPTUAL STUDIES OF VESTIBULAR FUNCTION

Before eye movement recordings became widely available a great deal of the clinical and research assessment of the vestibular system relied on psychophysical estimates.⁶¹ In the past 30 or 40 years such studies became overshadowed by vestibulo-ocular investigations but more recently interest in psychophysical assessment has again emerged, not least because of the relatively poor correlation of patient symptoms and vestibulo-ocular findings.⁶²⁻⁶³ The simplest assessment is to enquire about the type and intensity of the sensation during irrigation of the external canals in the caloric test. Often patients describe sensations during the caloric test that are identical to their own symptoms during dizzy spells, thereby indicating a likely vestibular origin for their symptoms. This can be particularly useful in patients with severe ocular myopathies or with congenital nystagmus in whom vestibulo-ocular function cannot be established. More refined techniques are also currently being developed which allow assessment of symmetry of function in the vestibular system.⁶³⁻⁶⁵

SOUND EVOKED VESTIBULOCOLLIC RESPONSES

Colebatch and coworkers⁶⁶⁻⁶⁸ have further described the phenomenon originally discovered by Bickford *et al*,⁶⁹ that repeated clicks delivered through headphones are able to

stimulate the vestibular apparatus and generate a short latency (6–12 ms) inhibitory potential in muscles of the neck under continuous activation. Although this technique is also under development it has the advantage that, together with the caloric test and galvanic stimulation of the ear, it can stimulate the vestibular system on either side of the head independently. The click evoked vestibular cervical potentials seem to be promising in identification of patients with the Tullio phenomenon (sound induced vestibular symptoms).⁶⁸ The technology required for this procedure is currently available in most EEG departments—that is, a click generator and an averager as used for instance for auditory brain stem evoked responses.

Conclusions

In this chapter we have considered the consequences of vestibular dysfunction in causing imbalance and discussed various methods of assessment of the vestibular system. Inevitably these methods are heavily dependent on the vestibulo-ocular connections both at the clinical and at the investigational level. At the outset we stated that the neuro-otological examination could not be considered in isolation and in this respect we have not considered two areas. Firstly, because of the close association of the auditory and vestibular systems, full auditory function assessment is essential. In particular, middle ear and petrous bone pathology should be sought by expert ear, nose, and throat surgeons. Secondly, imaging of the VIIIth nerve system has been revolutionised by MRI which is an essential part of the full neuro-otological assessment. Both these areas are omitted from the discussion, not because they have little importance, but because they are not part of the remit of this article. Finally, even after exhaustive documentation of the clinical and investigative findings a large proportion of patients remain undiagnosed. Clear cut diagnoses such as Ménière's disease or cerebellopontine angle tumours are relatively easy to make but in our experience a substantial proportion of patients referred to a specialist neuro-otological clinic remain without a specific diagnosis or are given a diagnosis such as vestibular neuronitis that implies an anatomical and aetiological precision that is not often justified. Hopefully this unsatisfactory situation will improve with developments in imaging, neurophysiological techniques, and further understanding of symptomatology.

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