Vestibular function testing

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Purpose of review

This review provides an overview of vestibular function testing and highlights the new techniques that have emerged during the past 5 years.

Recent findings

Since the introduction of video-oculography as an alternative to electro-oculography for the assessment of vestibular-induced eye movements, the investigation of the utricle has become a part of vestibular function testing, using unilateral centrifugation. Vestibular evoked myogenic potentials have become an important test for assessing saccular function, although further standardization and methodological issues remain to be clarified. Galvanic stimulation of the labyrinth also is an evolving test that may become useful diagnostically.

Summary

A basic vestibular function testing battery that includes ocular motor tests, caloric testing, positional testing, and earth-vertical axis rotational testing focuses on the horizontal semicircular canal. Newer methods to investigate the otolith organs are being developed. These new tests, when combined with standard testing, will provide a more comprehensive assessment of the complex vestibular organ.

Keywords

saccule, SVV, unilateral centrifugation, utricle, VEMP

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Abbreviations

ENG	electronystagmography
EVAR	earth-vertical axis rotation
GVS	galvanic vestibular stimulation
HORT	head only rotational testing
OCR	ocular counter-rolling
OVAR	off-vertical axis rotation
SCM	sternocleidomastoid muscle
SVH	subjective visual horizontal
SVV	subjective visual vertical
VEMP	vestibular evoked myogenic potential
VOG	video-oculography
VOR	vestibulo-ocular reflex

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Introduction

The purpose of vestibular function testing is to objectively and quantitatively assess the status of the vestibular system. Some techniques provide information regarding peripheral vestibular function while others focus on central processing. This review will primarily address tests of peripheral vestibular function. Since there are five vestibular end organs in each inner ear – three semicircular canals that transduce angular acceleration and two otolith organs (utricle and saccule) that transduce linear acceleration – no single vestibular test can assess the entire labyrinth. Until recently, only the horizontal semicircular canals could be reliably assessed, using caloric testing and earth-vertical axis rotation. During the last decade, vestibular testing has evolved such that the vertical semicircular canals and the otolith organs also can be investigated. Thus, vestibular testing not only can be used to lateralize a lesion but also to deduce which part of the vestibular organ appears to be affected. Although sophisticated equipment is needed to assess the entire vestibular apparatus, clinics specialized in assessing patients with dizziness and disequilibrium are gradually implementing these new tests. After a general description of some techniques that are common for testing the different parts of the peripheral vestibular system, this review will discuss specialized tests of the five anatomical subsystems that comprise the vestibular labyrinth.

Methods of eye movement recording

This section presents the three methods for eye movement recording with emphasis on the more recently evolved video-based technique.

Electronystagmography/electro-oculography

Electronystagmography (ENG), also known as electro-oculography (EOG), was for many decades the primary technique for recording eye movements in patients of all ages. Although proven to be clinically very useful several factors influence the robustness of this method: correct placing of the electrodes, appropriate skin preparation for optimal skin–electrode impedance, increased signal to noise ratio by using two electrodes per eye, and most importantly, repeated calibration, to account for the fluctuation in the corneo-retinal dipole potential. Very little evolution of ENG is expected, especially as other techniques emerge.

Videonystagmography/video-oculography

Videonystagmography (VNG) also known as video-oculography (VOG) recently became the preferred method for recording eye movement during vestibular testing. VOG offers a particular advantage over conventional EOG in that it enables an accurate measurement of vertical eye movements. The main component of a VOG system is a small infra-red sensitive video camera connected to a PC system for determination of eye position based on image processing algorithms [1,2]. Two-dimensional VOG uses pupil-tracking to extract horizontal and vertical eye position. To assure accuracy, VOG systems must account for the shape of the pupil when the eyelids are partially closed or when eye position is not straight ahead. Three-dimensional VOG additionally extracts the torsional component of eye position, generally based on polar cross-correlation techniques using iris pigmentation patterns. For 3D VOG, geometrical correction for eccentric gaze is very important as well as correction for artifacts due to partial eyelid closure [3]. Some VOG systems use goggles that resemble ski glasses with which the camera is placed in front of the eye. Other systems allow unobstructed vision and the camera can image the eye via a specialized mirror. Most commercial VOG systems have a standard frame rate of 50 or 60 Hz, which may limit the use of VOG for some ocular motor tests such as saccades, for which a typical eye movement has a speed of about 200°/s and a duration of about 50 ms for a 10° gaze shift [4]. With a sample rate of only 50 Hz, only two points of the saccade are recorded. Video cameras are rapidly improving in dimensions and performance, including higher resolution and frame rates (>200 Hz). In the next years these new cameras will gradually replace the currently used slower cameras.

It is essential that VOG goggles are firmly attached to the patient's head, since any relative movement of the camera with respect to the head will result in an artifactual eye movement recording. Thus, some VOG systems are attached to the patient's skull by means of a bite board but this technique reduces clinical applicability [5]. VOG can also be used for bedside testing especially for the qualitative assessment of eye movements. Such VOG goggles have been called 'video frenzels'. Most likely, 2D VOG will coexist with ENG for several years since each technique has its strengths and weaknesses. Three-dimensional VOG systems are currently mainly limited to research facilities due to the greater complexity of this technique. Because VOG is new, standardization is an important issue that has not yet been adequately addressed.

Scleral search coil

The scleral search coil method, developed by Robinson [6], is based on the measurement of electric current induced in a small coil of wire placed on the eye. The search coil method has emerged as the gold standard for the accurate recording of eye movements. It is, however, an invasive technique which requires that a wired contact lens be placed on the patient's eye. It causes discomfort for the patient and recording time is limited to approximately 30 min. Also, torsional slippage can lead to artifacts. Still, Halmagyi advocates this method as the most preferable for all semicircular canal testing [7]. Very few laboratories use this technique routinely despite its capabilities [8,9].

Assessment of the horizontal semicircular canal

In most clinical vestibular laboratories the following test battery is performed: ocular motor screening; positional testing; caloric testing; and rotational testing. A detailed description of these tests can be found in Wuyts *et al.* [10].

Ocular motor screening consists of the assessment of spontaneous nystagmus, gaze-evoked nystagmus, saccadic eye movements, pursuit eye movements, and optokinetic nystagmus. The purpose of ocular motor screening is to uncover eye movement abnormalities that may interfere with the interpretation of the positional, caloric, or rotational tests. Furthermore, it can provide some information in and of itself concerning central nervous system abnormalities. Ocular motor screening can be performed using either ENG or VOG with the restrictions described in the previous section.

Caloric testing

The caloric test has been unchanged for decades. It remains a mainstay of vestibular function testing. Each laboratory should establish its own normal values. A less desirable practice is to use normative values derived from a meta-analysis by which the means are weighted based on the number of subjects in the different studies [10]. Reasonable upper limits for normality are *22%* for reduced vestibular response (labyrinth asymmetry) and *26%* for directional preponderance.

The caloric test assesses only the horizontal semicircular canal. Thus, caloric abnormalities do not necessarily imply that the labyrinth is totally dysfunctional and should be interpreted in light of other tests. Fetter and Dichgans [11] investigated 3D eye movements in 16 patients with acute unilateral vestibular lesions and found that none of them had spontaneous nystagmus whose direction indicated a complete unilateral vestibular lesion.

Earth-vertical axis rotational testing

Rotational testing using whole body rotation is usually performed with the patient seated upright during earth-vertical axis rotation (EVAR). This stimulus evaluates primarily the horizontal semicircular canals by assessing the horizontal vestibulo-ocular reflex (VOR). Well known measures obtained from EVAR include gain, phase and asymmetry for sinusoidal rotation at a range of frequencies from about 0.01 Hz to 1.0 Hz and gain and time constant for trapezoidal (constant velocity) rotation.

Although in several clinics the head is tilted forward 30° during rotation, Van der Stappen *et al.* [12] showed that better results were obtained with the head upright. Recently, Peterka [13] introduced a novel method to identify the side-of-lesion in subjects with well compensated unilateral vestibular loss. The cyclic 'pulse-step-sine' stimulus has a bias component and a probe component. The testing uses a higher frequency, more physiologically relevant, stimulus than the low frequency caloric test or standard EVAR.

A drawback of rotational testing is the dependence of the measures on the patient's mental alertness. Patients should be systematically asked to perform mental tasks. Despite some methodological drawbacks of EVAR, the technique provides complementary information to the caloric test. Arriaga *et al.* [14] demonstrated that EVAR has a greater sensitivity whereas caloric testing has a greater specificity for peripheral vestibulopathy.

Head-only rotational testing

Head only rotational testing (HORT) relies on head movement alone to stimulate the vestibular system [15]. This technique is convenient and has relatively low cost. Testing is limited in terms of magnitude and frequency because of physical constraints. HORT is generally performed at higher frequencies than EVAR but at considerably lower velocity than head thrust testing. HORT is used by many laboratories but has not become a standard method because it does not consistently identify labyrinthine dysfunction.

Another evolving technique for assessing the functional status of the VOR is dynamic visual acuity (DVA) [16] and the gaze stability test (GST). Both DVA testing and the GST use a computer-displayed optotype that the subject needs to identify while rotating their head. These tests may be a valuable adjunct to vestibular testing when it is important to assess functional ability. Problems arise however when using these tests for diagnosis when the head movements are active and made by the subject themselves because results can be influenced by nonvestibular factors. For example, active head movements toward the lesioned side can generate both compensatory and anticipatory saccades [17].

The Halmagyi–Curthoys head impulse test [18], when performed at the bedside, does not necessarily require any equipment. The test is of particular value when first investigating a patient with vertigo at the bedside. Although the head impulse test can be especially useful for identifying a loss of function of the horizontal semicircular canal, it should not replace the caloric test [19]. Recently, Ulmer and Chays [20] proved that with a dedicated video camera, the sensitivity of the head impulse test can be improved.

Assessment of vertical semicircular canals

The most reliable yet cumbersome method to test the anterior and posterior semicircular canals consists of a combination of the head impulse test [18] and the scleral search coil technique. This method has been used by Minor and colleagues as well as Halmagyi *et al.* [8,9]. The test is based on brisk movements of the subject's head in the left anterior–right posterior canal or the right anterior–left posterior semicircular canal planes. These planes are approximately 45° from the sagittal plane. Moving the subject in these planes either forward or backward will generate eye movements that result from exciting the posterior or anterior canal on one side and silencing the complementary canal on the other side. Analysis of the eye movements can provide a quantitative assessment of the vertical semicircular canals.

Assessment of the utricle

The utricles can be assessed by observation of the ocular counter rolling during simple head or body lateroflexion, but this method does not prove to be particularly robust because even in cases of unilateral deafferentiation the responses are similar to those obtained in healthy subjects [21]. Other methods therefore emerged.

Unilateral centrifugation

The most current technique for assessing unilateral utricular function uses eccentric rotation as proposed by Wetzig *et al.* [22] and further employed by Clarke *et al.* [5,23] and Wuyts *et al.* [24]. Utricular sensitivity and preponderance of the right or left utricle can be assessed by this so-called 'unilateral centrifugation test'. In this test, subjects are rotated about an earth-vertical axis at a velocity of 300–400°/s. During the ongoing rotation, the subject is gradually translated 3.5–4 cm [25] first to the right, and then to the left, along an interaural axis, to a position at which one utricle becomes aligned with the axis of rotation, and at this point is subjected only to gravitational forces. At 400°/s the contralateral utricle is exposed to the combination of gravity and a centrifugal acceleration of 0.4 *g*, corresponding to an apparent roll-tilt of 21.7°. This stimulus induces ocular counter-rolling (OCR), which reflects the otolith ocular reflex (OOR). OCR is measured using 3D VOG. Some laboratories do not have the equipment to automatically translate the chair to left or right during ongoing rotation but instead before rotation position the chair manually at the eccentric points and then measure either OCR or subjective visual vertical. Unilateral centrifugation is becoming more common since it provides complementary information to the traditional ENG. Signs of any dominance of one or the other utricle should emerge from high speed rotation since an imbalance in the afferent firing rate due to the symmetric loading of both utricles should give rise to OCR. The amount of OCR, however, is small and difficult to measure. Nevertheless, Clarke and coworkers have shown OCR during centered EVAR to be a valuable screening method for otolith organ asymmetry [26]. Any indication of OCR response asymmetry during EVAR with the patient centered should be pursued with unilateral centrifugation [26].

Off-vertical axis rotation

Off-vertical axis rotation (OVAR), when performed at constant velocity, stimulates the otolith organs and not the semicircular canals [27]. The test is easily administered but requires specialized equipment and can produce unpleasant nausea. Both the right and left otolith organs are stimulated. Thus, OVAR does not provide lateralizing information. Moreover, in studies of patients with confirmed unilateral peripheral vestibular loss, OVAR responses are essentially normal, further reducing its clinical utility. OVAR continues to be used in some laboratories as a convenient means of activating the otolith organs and assessing the otolith–ocular reflex [28].

Assessment of the saccule

The sole method that currently is readily available for assessment of the saccule consists of the vestibular evoked myogenic potential (VEMP) test.

Vestibular evoked myogenic potentials

VEMPs, which serve as a tool for investigating saccular function, are inhibitory myogenic potentials measured from the tonically contracted sternocleidomastoid muscle (SCM) in response to loud sound stimuli [29]. The VEMP waveform is biphasic, containing a positive (p13) and a negative (n23) peak occurring after a latency of approximately 13 and 23 ms, respectively, generated by activation of saccular afferents. The VEMP response amplitude is dependent on the magnitude of the stimulus intensity and on the magnitude of the SCM contraction [29]. For left–right amplitude differences to be considered reliable, it is important to provide feedback to the subject regarding the amount of SCM contraction. A simultaneous electromyography and VEMP recording is the most appropriate method. If not possible, a feedback method, based on the use of a blood pressure manometer with an inflatable cuff, has been recommended to control the SCM contraction [30,31]. Another option for activating the SCM is to ask the subject to elevate the head when in a supine position. In this way the SCM muscles on both sides are activated simultaneously. Both clicks (0.1 ms, 105 dBnHL) and tone bursts (95 dB nHL, 500 Hz, ramp, 1 ms, plateau, 2 ms) can be used to evoke VEMPs [32,33]. The stimulus intensity threshold for tone bursts is lower than for clicks. When applying tone bursts, there is a frequency tuning with lowest thresholds at 500–1000 Hz and best responses at 500 Hz. [34••]. Patients with endolymphatic hydrops appear to have an altered frequency tuning and elevated thresholds [34••,35]. Thus, performing VEMPs at multiple frequencies and with threshold determination may enable the discovery of preclinical Menière's disease [36]. In subjects with conductive hearing loss with air-bone gaps 20 dB or higher [37], bone conducted tone burst stimulation at the mastoid (70 dB nHL, 500 Hz, ramp, 1 ms, plateau, 2 ms) is preferred [33]. It is known that in these conditions the bone conducted acoustic stimulation conducts across the skull and stimulates the contralateral side as well [38]. Animal experiments demonstrate that air-conducted sound selectively activates the saccule [39]. There is less information on the site of action of bone conducted sound. Curthoys *et al.* [40•] described that in guinea pigs bone conducted sound preferentially activated irregularly firing utricular as well as saccular afferents. Recently, Rosengren *et al.* [41•] and Curthoys and coworkers [42] described vestibular evoked extraocular potentials in response to bone conducted sounds, so called o-VEMPs (o for ocular) in contrast to c-VEMPs (c for colic). These extraocular excitatory potentials were produced by synchronous activity in extraocular muscles and were dependent upon contralateral otoliths activation. This method of recording vestibular evoked potentials may prove to be an additional and robust test for vestibular function and provides an alternative for measuring VEMPs at the SCM in patients who, for example, are unable to contract their neck muscles.

Vestibular tests with uncertain focus

More global oriented tests are the subjective visual vertical or horizontal test and the galvanic stimulation test.

Subjective visual vertical/subjective visual horizontal

The subjective visual vertical (SVV) and subjective visual horizontal (SVH) have been employed for several years as relatively simple tests for evaluating the otolith system [43]. SVV and SVH can be measured while the subject is in the upright position or with body inclined in the roll plane. A normal subject sitting upright can accurately align in total darkness a dimly illuminated bar with high accuracy to the true gravitational vertical or horizontal [44]. Misalignment of more than 2.5° is considered pathological [44] with the tilt deviation toward the affected side. Tribukait states that the SVV or SVH as measured in the upright position is influenced by the utricles, saccules and horizontal semicircular canals. This has been generalized to all semicircular canals by Pavlou *et al.* [45]. Others state that measuring SVV with body inclination increases its sensitivity [46]. When using a roll tilt of the body to assess SVV, however, the initial position of the light bar influences the outcome [47]. Healthy subjects were able to set the SVV correctly when the light bar had an initial inclination relatively parallel to the body axis. The subject could not, however, properly estimate the true vertical when the light bar was initially inclined in the opposite direction. Also, SVV is subject to variation over time, due to central compensation [48]. Given these methodological as well as physiological reasons, SVV is a less reliable technique for vestibular assessment.

Galvanic stimulation

Galvanic vestibular stimulation (GVS) of the labyrinth, delivered by electrodes placed on the mastoids, modulates the spontaneous discharge rate of the vestibular afferents of all vestibular end organs and produces various behavioural responses such as postural changes, eye movements and perception of movement [49]. Like unilateral centrifugation, caloric testing and VEMPs, GVS is applied unilaterally, which enables the identification of vestibular asymmetries. In contrast to the other methods, however, GVS is a 'broad spectrum' stimulus since it affects both the semicircular canals as well as the otolith organs.

Anthropometric differences among individuals may account for the large between-subject variability as described by MacDougall *et al.* [50]. Galvanic stimulation was shown to serve as a valid model for the walking disturbances as experienced by astronauts upon return from space [51]. Clarke and colleagues used GVS as an alternative to ice water calorics to investigate the degree of remaining brain function in comatose patients [52]. In a recent study, MacDougall *et al.* [53] showed the growing applicability of GVS in the clinic to help identify the location of lesions.

Conclusion

In addition to the basic methods available for assessing the vestibular apparatus, several newer methods have emerged during the past decade, mainly due to the increased use of fast computers in the clinical setting. For tests requiring the measurement of eye movement, video-oculography has the major advantage of allowing the investigation of all eye movements and, therefore, different components of the vestibular system when used in combination with the appropriate stimulus. Unilateral centrifugation is evolving as a utricular test. The saccule can be evaluated with the VEMP method. Subjective visual vertical or horizontal can be regarded as a quasi-otolith test although not a direct measure of otolith organ function, and therefore more prone to other influences, such as compensation. Galvanic stimulation is mainly used for posture and gait studies, but recently also has been used as a complementary vestibular function test. A basic vestibular function testing battery, including ocular motor tests, caloric testing, positional testing, and earth-vertical axis rotational testing, are a solid basis onto which other tests can and should be added to provide a comprehensive assessment of the complex vestibular organ.

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