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Functional tests for assessment of the vestibular system – literature review and an example of our experience

Funkcionalni testi za oceno ravnotežnega organa – pregled literature in primer naših izkušenj

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Abstract

Vertigo and other balance disorders, which can have many different origins, are among the most common reasons for seeking medical care. The otorhinolaryngologist mostly deals with disorders of the inner ear and the vestibular nerve while, at the same time, identifying possible diseases of central origin as the cause of symptoms. To make a diagnosis, a combination of several different tests is usually required so that the impairment of different parts of the vestibular system can either be confirmed or excluded. In general, we distinguish between tests to examine the semicircular canals and tests' function to estimate the saccule and utricle's function. We describe a clinical trial whereby we examined 1042 patients with a clear history of benign paroxysmal positional vertigo, which was diagnosed in 36%. Further tests, described in the following article, had to be performed. To interpret the test results, we often rely on the observation and measurement of eye movements. This requires knowledge of mechanisms of certain reflexes responsible for maintaining balance. At the same time, we have to consider the patient's symptoms and complement the tests with other imaging examinations if necessary.

Izvleček

Težave z ravnotežjem sodijo med pogoste vzroke za obisk pri zdravniku, njihov izvor pa je lahko precej raznovrsten. Na področju otorinolaringologije se posvečamo predvsem okvaram notranjega ušesa in ravnotežnega živca ter nakažemo morebitno centralno prizadetost ravnotežnega sistema. Za postavitev diagnoze pogosto ne zadostuje zgolj ena preiskava, pač pa je po navadi potrebna kombinacija različnih testov, s katerimi potrjujemo ali izključujemo prizadetost posameznih delov ravnotežnega sistema. V osnovi razlikujemo med testi, s katerimi ocenjujemo delovanje polkrožnih kanalčkov, in testi za oceno delovanja sakulusa in utrikulusa. Predstavljena je klinična raziskava, v kateri smo pri 1.042 bolnikih z jasno anamnezo za benigni paroksizmalni pozicijski vertigo le-tega dokazali v 36 %. Nujno je bilo opraviti še dodatna testiranja, ki jih predstavlja prispevek. Za razlago njihovih rezultatov se pogosto zanašamo na opazovanje in merjenje gibanja očesnih zrkel, pri čemer je pomembno poznavanje določenih refleksov za ohranjanje ravnotežja. Ob tem moramo upoštevati tudi simptome, ki jih navaja bolnik, in teste po potrebi dopolniti s slikovnodiagnostičnimi preiskavami. Natančne računalniške meritve in grafični zapisi danes nadomeščajo opazovanje s prostim očesom in subjektivno razlaganje opažanj preiskovalca.

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1 Introduction

Vertigo and other balance disorders are among the most common reasons for seeking medical care. Patients describe them as uncomfortable loss of orientation in space and a false feeling of movement of the body and/or the surroundings, such as spinning, wobbling, or inclining. Their prevalence in the general population is about 17%, and in the elderly above 80 years, it grows to 39% (1). Diseases of the vestibular part of the inner ear, together with the vestibulocochlear nerve form part of the peripheral vestibular system, are slightly more frequent than central nervous system diseases (2). In the strict sense, the human balance system includes the vestibulocochlear nerve and its ganglia, four vestibular nuclei in the brainstem, cerebellum, and parts of the cerebral cortex (3). The reasons for its malfunction have varied origins and pathogenesis. When facing balance issues, otorhinolaryngology primarily focuses on the inner ear and vestibular nerve disorders.

Vestibular system dysfunction is generally manifested as a combination of sensory, oculomotor, postural, and autonomous symptoms and signs: vertigo, gait abnormality (ataxia), nausea, and vomiting (1).

The patient's medical history is first used to define the type of symptom, its duration, trigger factors, and a possible concurrent hearing loss, as well as concomitant chronic diseases, with systemic diseases often having a significant effect on balance. Next, we continue with an otoneurologic examination of the patient and basic hearing tests. These are followed by assessing the balance function used to define disorders in individual structures responsible for maintaining balance.

2 Anatomy and physiology of the vestibular system

The vestibular system in the inner ear consists of three semicircular canals and the otolith organs. The semicircular canals (superior, posterior, and lateral) lie perpendicular to one another, always functioning in pairs (posterior with the anterior of the opposite side and both lateral), and include cristas ampullae. These have gelatinous cups and detect angular acceleration through the changes in the endolymph current in the membranous part of the labyrinth with hair cells. In the inner ear's vestibule, the otolith organ comprises the saccule, which lies on the vertical plane, and the utricle, which lies on the horizontal plane. Its sensory organs, the maculae, sense linear acceleration and gravity (4). The vestibular system is connected to the eighth cranial nerve's vestibular nerve through nuclei in the brain stem with the nuclei of some other cranial nerves, the cerebellum, and the cerebral cortex. The human brain does not contain a primary vestibular cerebral cortex area; however, it consists of several separate areas. These regions combine the balance, aural, visual, and somatosensory inputs (5). They demonstrate a strong right hemispheric dominance. The parieto-insular vestibular cortex (PIVC) was among the first areas to be defined as vestibular, and after additional studies, the posterior insular cortex, the temporoparietal junction, the anterior insula, the pre- and postcentral gyrus of the parietal lobe, the ventrolateral part of the occipital lobe, and the inferior frontal gyrus with the inferior part of the precentral sulcus (5).

Understanding how the tests assess the vestibular system work is also essential to understand certain reflexes that ensure stabilization. The first among them is the vestibuloocular reflex, which stabilizes the image on the retina while the head moves by moving the eye bulb in the opposite direction, thereby retaining the image in the central part of the field of vision. Stimuli for the reflex mainly originate in the semicircular canals, then run through the vestibular nerve to the vestibular nuclei in the brainstem. From there, the neurons connect with the nuclei of cranial nerves that ensure the movement of the extraocular muscles, moving the eye bulb appropriately (6).

In certain types of tests, the vestibulospinal reflex is also essential. This is a combination of reflexes whose objective is to stabilize the body. When tilting the head, the semicircular canals on both sides become stimulated. The stimulus is transferred through the vestibular nerve and the vestibular centres along the lateral and medial vestibulospinal tract, activating extensor muscles on the side towards which the head is tilted, and the flexor muscles on the other side. This ensures that the position of the body and the head are stabilized (3).

The most important indicator of the vestibular system function is spontaneous or evoked eye movements. By origin, we roughly divide them into ocular, peripheral vestibular, and central vestibular nystagmus. Peripheral nystagmus is repeated, coordinated eye bulb movements around a horizontal or vertical axis, comprising a slow and fast phase, by which we also define its direction (7). Typical peripheral nystagmus is horizontal, it may have a rotational component, and it intensifies when the gaze fixation is removed (e.g., with closed eyelids, in darkness, or when using high-powered Frenzel's' goggles). The first-degree nystagmus occurs when gazing towards the fast component's direction, and the second degree also when gazing straight, while third-degree nystagmus is present when gazing in all directions (8). According to Alexander's law, the amplitude of nystagmus increases when the eye moves towards the fast phase and decreases when viewing in the opposite direction (9). By nystagmus onset, we divide them into spontaneous nystagmus, which is always pathologic, except in the most eccentric positions and optokinetic, and evoked by the movements of the body or by vibration stimulation of the inner ear (10). Every nystagmus that onsets without proper physiological stimulation is treated as abnormal, or the absence of nystagmus with appropriate stimulation (8). Nystagmus can be observed with the naked eye, or we can use glasses or a CCD camera that follows the pupils and logs the eye movement on a computer.

Because the vestibular system is not a single structure, every part must be tested with different stimulation frequencies when there are balance issues. First, we stimulate the semicircular canals; then, we assess the saccule and the utricle function. The tests for assessing the vestibular system can be divided into the group of tests for assessing the function of semicircular canals and the group for assessing the saccule and the utricle. They are summarized in Table 1.

3 Test for the assessment of the vestibular system

3.1 Tests for the assessment of the semicircular canals

The tests for assessing the function of semicircular canals are divided by the speed with which the canals are stimulated, as they have a different sensitivity to stimulation with low and high frequencies (11). Caloric testing is among the very low-frequency tests. Low-frequency tests include rotation testing, while high-frequency tests include the head impulse test. The medium-frequency dynamic visual acuity test (DVAT), the very high-frequency vestibulo-collic reflex (VCR) test, and the vibration-induced nystagmus test (VIN) (11) are not performed at the Centre of Audiology and Vestibulology, Department of Otorhinolaryngology and Cervicofacial Surgery, University Medical Centre Ljubljana, Slovenia.

3.1.1 Caloric testing

Caloric testing is primarily intended for assessing the function of the lateral semicircular canal. It is based on the principle that changes to the inner ear temperature trigger movement similar to turning the head. This results in the endolymph circulating within the lateral semicircular canal and, through the vestibulo-ocular reflex, induces the response in the form of nystagmus, based on which we can assess the function of the lateral semicircular canal (12).

The examination procedure: the subject is placed supine, with the head elevated at a 30-degree angle. Before we begin the ear irrigation, we check whether the patient has spontaneous nystagmus in a standing or a sitting position using Frenzel's goggles. Then, we irrigate the left ear canal with 30 °C water for half a minute, and for the next half-minute, we count or electronically log the twitches of the subject's eye bulbs. After a brief pause, we repeat the procedure on the opposite ear. When stimulating with cold water, the nystagmus generally occurs in the opposite direction of the stimulated ear. Then, we repeat the procedure on both ears with water heated to 44°C, initiating the nystagmus in the stimulated ear's direction. If we do not initiate a response with ear irrigation in the first two temperatures, we repeat the procedure with 17°C water. When we cannot stimulate a response, even in this case, we can conclude that the labyrinth is not calorically stimulable (11).

This is one of the most frequently performed balance tests conducted for vertigo and instability, loss of hearing on one side, or any other suspicion of impaired function of the peripheral part of the vestibular system.

When reading the results, it is important to compare both sides and consider the nystagmographic response's absolute values, comparing it with average, i.e., normal values. An example of a caloric test result is in Figure 1.

When comparing both semicircular canals, we describe the paresis (labyrinthine paresis/predominance) and preponderance (13). The semicircular canal's paresis is defined as at least a 20% difference in nystagmography response between both canals and represents a reduced function of one labyrinth concerning the opposite labyrinth (14). This is frequent with vestibular neuritis, Menièr's disease, and tumours of the eighth cranial nerve, and can also onset with migraines and cerebrovascular diseases. The directional preponderance describes the higher intensity of the nystagmus in a particular direction than the other side by at least 20–30%. Clinically, the preponderance

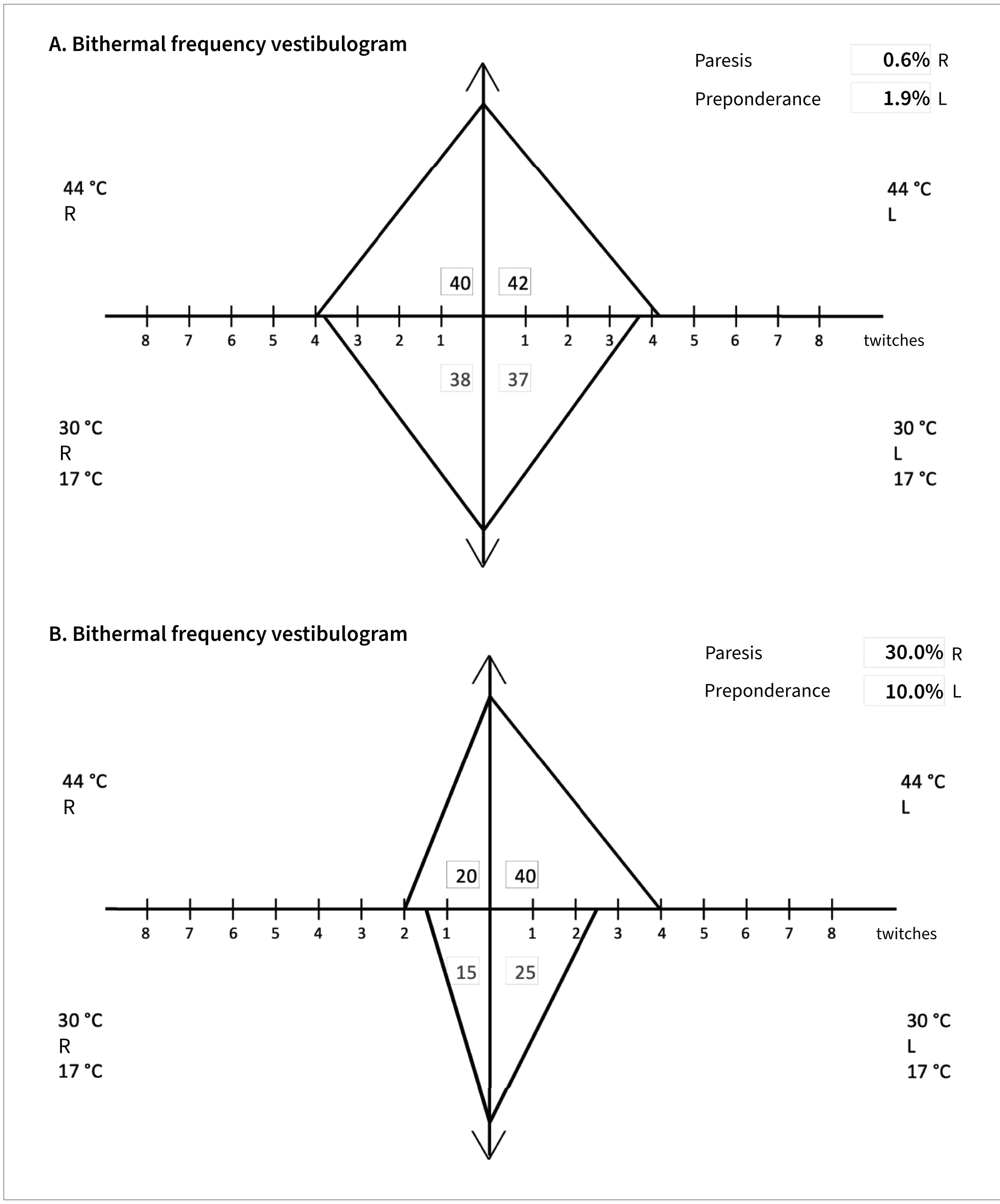


Figure 1: Graphic display of caloric testing of the vestibular system. Less than 20% difference in the nystagmographic (i.e., paresis box) response between both sides indicates a normal response (A); a difference of more than 20% in the response between both sides indicates reduced function or paresis of one of the canals (B).
R – right; L – left.

has several different implications. It may be present in entirely healthy people; it can reflect a single-side peripheral balance impairment on the opposite side, a central impairment, or even damage to the cerebral cortex (13).

Concerning the nystagmography response's absolute values, we describe hyper-, hypo-, and areflexia Hyperreflexia occurs when calorically stimulated nystagmus exceeds the standard value. With peripheral vestibular disorders, it may occur on the opposite side of the affected location. The reason can also be a change in the ear, e.g., after a mastoidectomy or an eardrum perforation. With central vestibular disorders, hyperreflexia can be bilateral. An example of this is an impairment of the cerebellum's flocculus, which in its normal condition inhibits the neurons of the vestibular core, thereby inhibiting the vestibulo-ocular reflex. When it is damaged, this inhibitory effect does not take place.

Hyporeflexia can result from different causes, namely from drugs inhibiting the labyrinth function or their toxic effect on the ear to systemic infection diseases, hypertension, brain tumours, and degenerative diseases of the central nervous system anxiety, also possibly due to the abuse of psychoactive substances. Areflexia, i.e., total unresponsiveness to caloric response, can be part of Usher syndrome resulting from bilateral peripheral vestibular loss or ototoxicity. In 20% of patients, the reasons for it remain unexplained (15). However, it is not always related to a total loss of the balance function (13).

Despite frequent use, caloric testing has certain shortcomings. The effect that the ear irrigation has on the subject's ear differs from person to person. This makes it difficult to compare the sensitivity of different people's labyrinths concerning the absolute values of caloric stimulation responses. We can especially compare the sensitivity of both ears of the same subject, and even this calls for a certain level of caution, as the stimuli received by the left and the right ear are not entirely the same. Also, the frequency with which we excite the semicircular canals in this test is reasonably low. The vestibular system responds best to the head's fast turns with a frequency of between 0.1 and 3 Hz. With caloric testing, we can only stimulate receptors up to a frequency of 0,003 Hz, which is significantly lower than the optimum. We also do not know the stimulation's exact strength and must, therefore, be careful when interpreting results (16).

Certain subjects find the tests especially uncomfortable, as they can trigger vertigo and nausea. If the examiner assesses that testing could trigger significant discomfort in the examinee, testing should be stopped as soon as possible.

Seldom is caloric testing performed on both sides simultaneously. Only with the onset of nystagmus, i.e., with a different stimulation results in one inner ear, is each ear tested separately (17).

3.1.2 Rotatory testing

The rotary chair test is also aimed at assessing the sensitivity of simultaneously stimulated lateral semicircular canals. The angular acceleration is used as a stimulus (when the rotation begins and after it ends) when rotating the whole body. It is generally used in combination with caloric testing, and if needed, the tests are supplemented with other vestibular system examinations.

The rotary chair makes it possible to position the head at a 30-degree angle in which lateral semicircular canals are in a nearly horizontal position. The subject is then rotated ten times in one and ten times in the other direction, with a frequency of approximately one rotation per second. Using nystagmographic goggles, we can watch the nystagmus during the rotation (rotatory nystagmus) and when stopped (post-rotatory nystagmus) and its persistence for each side of rotation (18,19).

Tests can consist of different protocols in which we rotate the subject in both directions with different frequencies and accelerations.

The main indications for rotatory

testing are bilateral paresis of the lateral semicircular canals, unsatisfactory results of the caloric testing, and the fact that small children being rotated in their parent's lap can perform the test as well. The test assesses both vestibular systems at the same time. They provide the residual function data in patients with signs of bilateral failure of the vestibular system measured with caloric testing and the data on the central compensation of unilateral paresis of the vestibular system (19).

3.1.3 Head impulse test

Unlike caloric and rotatory testing, where we stimulate and measure only the lateral semicircular canal function, all three canals are tested in the head impulse test (HIT). Also, the frequencies in this test are higher than with the caloric test. This is an examination in which the vestibulo-ocular reflex (VOR) of each semicircular canal is measured separately during passive, quick and unpredictable head movements by 10 to 20 degrees in different directions (20).

First, the examiner merely monitored the subject's eye movements by observation. Later, eye bulb movements with special wires installed on an eye via lens were introduced. The latest HIT version is called vHIT (video head impulse test), where light-weight and tightly fitting goggles with a camera monitor the eye bulbs' compensation movements during rapid head movements (impulses). The glasses are connected to software that marks the head and eye bulb movements, creating a graphic output from the data.

After proper positioning of the goggles, the subject stares at a point approximately 1 meter away on the wall in front of them. The subject's head is turned 35 degrees left or right, while their eyes remain focused on the point. The examiner then begins performing rapid sagittal head movements (up and down), stimulating both vertical semicircular canals. The head first faces straight ahead; then, the examiner rapidly turns it left and right. This stimulates canals in pairs – both lateral together, the right anterior and the left posterior (RALP – with the starting position of head-turning left) and the left anterior and the right posterior (LART – with the starting position of the head-turning right) at the same time. The examined person performs approximately 7 to 10 unpredictable head movements individually in all directions. The whole procedure is called a head impulse paradigm (HIMP) (21).

With healthy subjects, there is smooth, compensatory eye bulb movement, resulting from a well-functioning VOR. These maintain the focus on a fixed point (22) and are not visible to the examiner with the naked eye. Quite the opposite, patients with paresis of the semicircular canal exhibit corrective saccades at the Impulse's end. When eye bulbs that had previously not been fixed on a point because of the impacted VOR, these occur with head movements, making a compensatory move towards it. These are so-called overt saccades, which an examiner notices when performing the test. These are clinical signs of the paresis of the canal. When moving the head to the impacted side, the left semicircular canal is affected, occurring when moving the head rapidly to the left. Some patients are capable of performing corrective saccades when the head is being turned. These are covert saccades that the examiner cannot see with their naked eye. They are essential for diagnosing impairments to the semicircular canal and can be measured with the vHIT test.

The graphic outputs of the head and eye bulbs' movements, as shown in Figure 2, are the same for healthy subjects, which

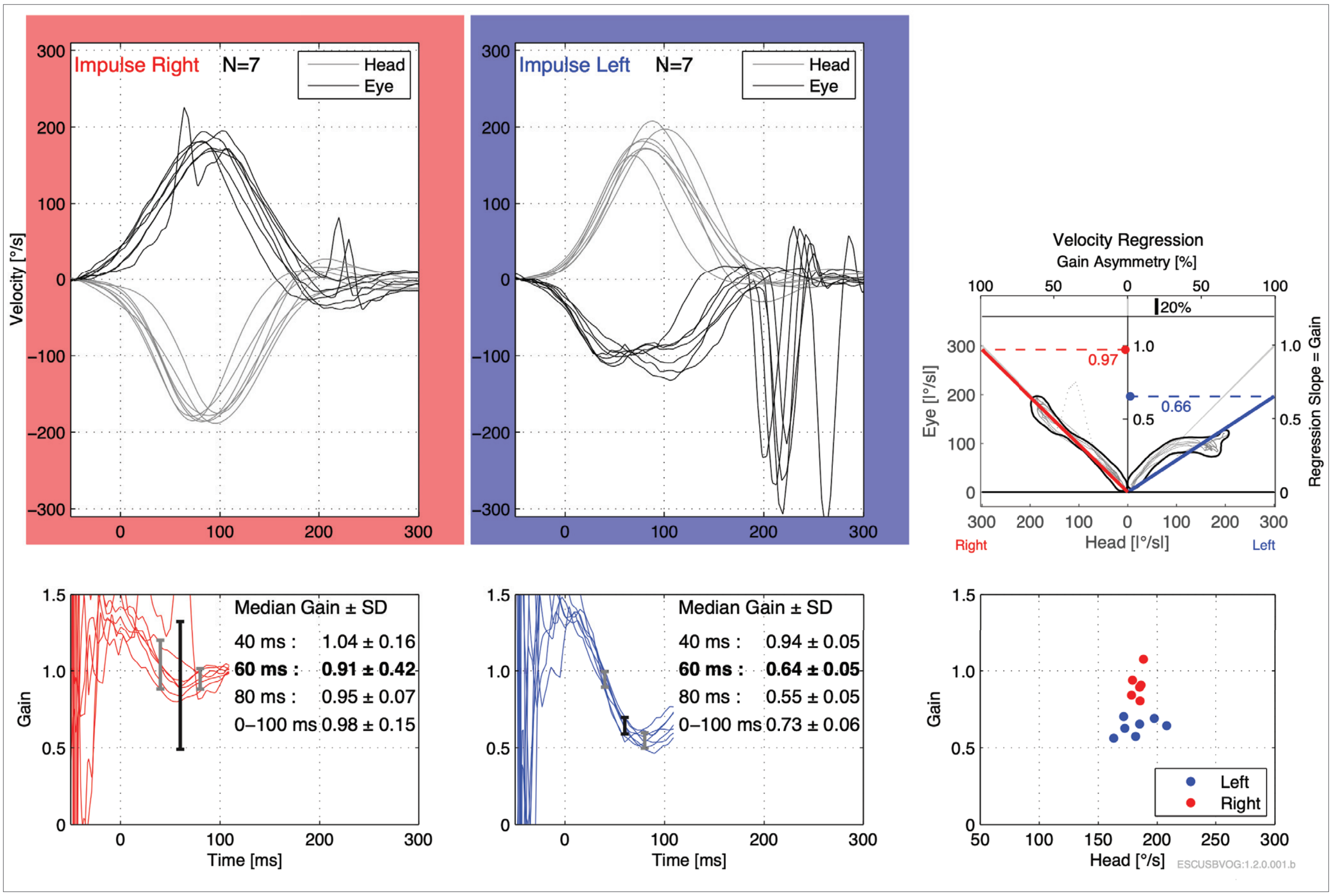


Figure 2: Video Head Impulse Test (vHIT) results. Impulse right graph indicates a subject's results with a normal function of the vestibulo-ocular reflex, where eye bulb movements appropriately follow the head movements. The Impulse left graph indicates the results in a patient with an impaired, left vestibulo-ocular reflex. This patient produces overt saccades to attempt to compensate for the reduced gain (24) appropriately.

means that eye bulbs with VOR appropriately follow head movements. The chart allows us to calculate the so-called gain, i.e., the ratio between the speed of the slow, compensatory phase of the eye bulb and the speed of head movements. The gain value for healthy people is approximately 1, i.e., sit should be above 0.79, meaning that the eye bulb movement's speed follows head movements well (23). When there is the dysfunction of the semicircular canal, the VOR is impaired, and the graphic representation of eye bulb movement shows a record of compensatory saccades. The gain is characteristically lowered, generally much below 1.

There are numerous advantages of vHIT over caloric testing. With vHIT, we can measure the function of all six semicircular canals, while with caloric testing we can only examine the function of the lateral ones. With caloric testing, we predominantly measure the asymmetry between the speeds of the slow phase of nystagmus with the same stimulation in both ears. The vHIT test also detects symmetrical, bilateral impairments of the vestibular system that appear as a normal, symmetric function of both canals in caloric testing. vHIT is quick, objective and repeatable, and can be performed even during acute vertigo attacks. It can assist in differentiating between vertigo from a stroke, i.e., central nervous system lesion, where test results are often normal, vertigo resulting from peripheral vestibular neuritis, and vestibular dysfunction due to the Menière's disease.

The protocol version called the Suppression Head Impulse Paradigm (SHIMP) also must be mentioned. It also uses vHIT technology, but the subject does not fixate their gaze on a point on the wall during the test, instead of following a point that moves together with their head. Results of the SHIMP test are the opposite of those of HIMP. At the end of an impulse, a healthy subject makes a bigger anti-compensatory saccade, while with patients who suffer from loss of vestibular function, we do not see the saccade. The vestibulo-ocular reflex attempts to avert the gaze from the moving point. With healthy subjects, VOR is suppressed, but with a delay of a few tenths of a millisecond; therefore, VOR moves the gaze away from the point during this time. When the subject is instructed to follow the target, there is a conscious reflex suppression, causing an anti-compensatory saccade at the end of the Impulse (the SHIMPs saccade), a sign of a well-functioning VOR. With patients with an impairment of the semicircular canal, and therefore the loss of VOR, it does not avert their gaze from the point, and, therefore, there are no anti-compensatory saccades at the end of the Impulse (23).

The *Functional Head Impulse Test* (fHIT) is a version of the test based on recognizing an optotype briefly flashed on a computer screen. It is a functional measure of the vestibulo-ocular reflex function, mirrored with the ability to retain visual acuity and to read during fast, passive head movements (25).

3.1.4 Dynamic visual acuity test

The dynamic visual acuity test (DVA) is a simpler version of the head impulse test. It is based on the fact that with the vestibular system's peripheral impairments, the retinal slippage during head movements is higher than usual. When the slippage speed is greater than 2–4° per second, visual acuity is reduced. By measuring visual acuity during head movements, we can directly conclude an impairment of the vestibulo-ocular reflex and semicircular canals; however, we must first exclude any impairments in the eye bulb motor function that are not the result of an impairment of the vestibular system. Performing the test includes performing a version of quick passive and active head movements while simultaneously measuring visual acuity using a Snellen chart. This verifies the vestibulo-ocular reflex function and can lead to a conclusion regarding a unilateral or bilateral impairment of the vestibular system (26).

3.1.5 The Dix-Hallpike test

This manoeuvre can confirm benign paroxysmal positional vertigo (BPPV), which is caused by free-floating otoliths in one or several semicircular canals. It can be performed on patients who feel short-term vertigo when changing their head position. At the start of the test, the patient sits on a bed, with the head tilted towards the tested ear at a 45-degree angle. The examiner then lies the patient down with a quick movement so that the subject's head gazes across the edge of the bed, and the examiner extends it by 20 to 30 degrees below the horizon. When performing this manoeuvre with a short pause, we can see the onset of typical nystagmus, which does not persist for more than a minute with BPPV; however, it may persist in a milder form sometime after the completion of the test. The test is then repeated on the opposite side. The impacted semicircular canal can be determined according to the direction of the nystagmus (11).

3.1.6 Videonystagmography (VNG)

The vestibular system function can be assessed with videonystagmography (VNG), where we analyze eye bulb movements in detail using nystagmography goggles. They follow the movements of the eye with an infra-red camera (27). VNG includes three standard tests: the oculomotor test, the optokinetic positional test, and caloric testing. With the oculomotor test, we follow the eye muscle motor function independently from the vestibular function. Oculomotor abnormalities could affect the results of vestibular function test results, which are interpreted based on eye movements. First, we verify spontaneous nystagmus's presence without fixation (in the dark), then while fixing the gaze at a 30° angle. These are followed by tracking a moving point (smooth and saccadic following) and forming the optokinetic nystagmus when viewing moving lines, vertical and horizontal, separately. The computer-generated results enable assessment of the nystagmus' symmetry when rotating to the left and right, and we can compare the speed of eye bulb movement relative to the head's speed. We can compare measurements recorded in a dark room (preventing the gaze from fixing) and the measurements recorded with a fixed gaze. Nystagmus with a fixed gaze, abnormalities in gaze following, and optokinetic nystagmus generally occur in central nervous system impairment. This is followed by a position test, where we observe the onset of nystagmus when the head and the body are tilted into different positions. Persistent nystagmus is non-specific and is not particularly helpful for determining the location of the impairment in the vestibular system. We can also observe eye movements when performing the Dix-Hallpike manoeuvre. Delayed nystagmus, rotational nystagmus, or weakened nystagmus in a particular position of the head point to BPPV, especially if the patient also manifests corresponding symptoms (28).

This is followed by performing the caloric and rotational tests described above.

3.2 Tests for the assessment of the otolith organ

3.2.1 Vestibular-evoked myogenic potentials – VEMP

Vestibular-evoked myogenic potentials (VEMP) are electromyographic responses evoked by sound, vibrations, or electricity, of the stimulated vestibular system (29). In this test, there are two types of electromyographic responses. The cervical VEMP (cVEMP) runs through saccule stimulation, the inferior vestibular nerve (n. *vestibularis inferior*), the vestibular nuclei in the brain stem, and up to activating the vestibulospinal tract and the glossopharyngeal nerve nucleus (n. IX, n. *glossopharyngeus*) with an inhibition response of the sternocleidomastoid muscle on the same side (the vestibulo-collic reflex). The ocular VEMP (oVEMP) runs through utricle stimulation and the superior vestibular nerve (*n. vestibularis superior*), the vestibular nuclei, and the medial longitudinal fascicle to the oculomotor nerve nucleus (*n. oculomotorius*) with excitation response to the opposite inferior oblique muscle (the otolith-ocular reflex). We measure the sternocleidomastoid muscle's electromyographic response or the external eye bulb muscles' response to the aural stimulation of the otolith organ.

Both otolith organs respond to stimulation with loud, by air- or bone-transmitted low-frequency tone. However, cVEMP is generally more specific for measuring the saccule function, and oVEMP for the utricle (30).

When cVEMP is performed using headphones, the saccule is stimulated, generally using 95–100 dB loud, short tones with a frequency of 500–1,000 Hz. Individual tones are played with 5-second pauses, and together approximately 200 repeats per ear are produced. It is recommended that one ear at a time is stimulated. We place an electrode on the mid-third of the sternocleidomastoid muscle to measure the muscle's electromyographic responses to the aural stimuli, and these are then displayed on the computer screen. Because the vestibulo-collic reflex causes an inhibition response of the sternocleidomastoid muscle, the subject must contract the muscle during the test. Via the same electrode, we also monitor the muscle contraction so that the subject can maintain the proper contraction during the test. If the muscle contraction is insufficient during the test, the VEMP responses are not suitable for analysis (31).

The most interesting parts of the test results depicted in Figure 3 are the characteristic waves P13 and N23. They enable an analysis of various parameters, such as the latency and amplitude of both waves, the latency between them, the difference in latencies and amplitudes between ears, and the difference between their values and their threshold values.

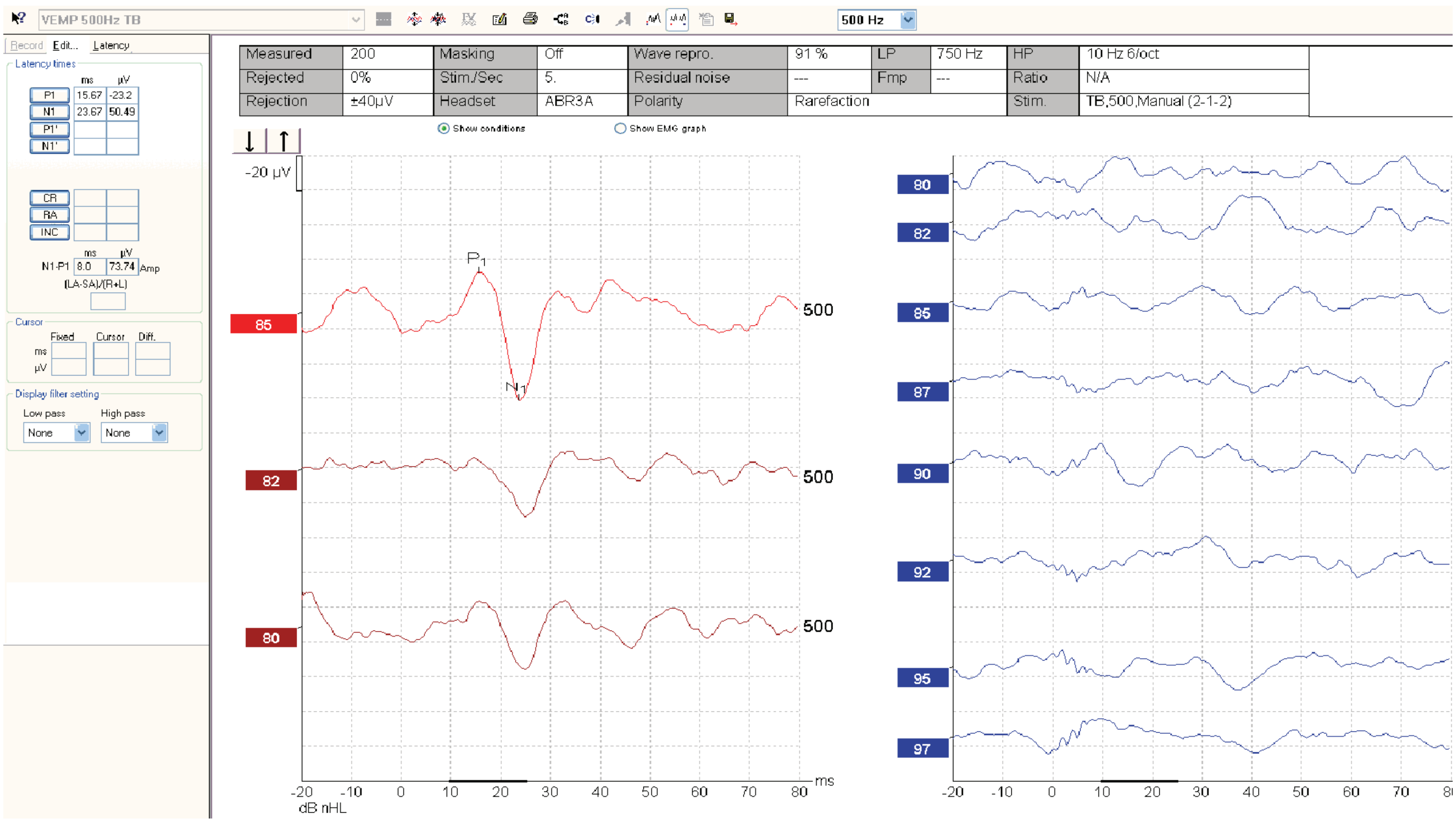
oVEMP is conducted similarly, except the electrodes are placed beneath both eyes and on the forehead to measure the inferior oblique muscle's electromyographic response. The patient must keep the gaze upwards during the examination to retain the inferior oblique muscle contracted. The results show the frequency at which the response with the highest wave amplitude and latency occurs. The frequencies through which we stimulate the vestibular system in oVEMP are similar to cVEMP, and the results reflect mainly the stimulability of the utricle (32).

A cVEMP test is used when diagnosing both peripheral and central lesions of the vestibular system (29). When diagnosing Menière's disease or endolymphatic hydrops, we can lose the VEMP response to stimulation. With Menière's disease, we can also notice the highest amplitude response transition at usually 500–700 Hz to 1000 Hz. Comparing test results before and after an attack is especially crucial, as with endolymphatic hydrops, the cVEMP amplitude is restored at the impacted side after the attack. This also normalizes the frequency at which we get the response with the highest amplitude (33).

With vestibular neuritis, cVEMP can significantly assist in diagnosing the affected location of the vestibular organ. The inferior vestibular nerve mainly supplies nerve fibres to the saccule and the posterior semicircular canal, while the superior vestibular nerve supplies nerve fibbers mainly to the lateral and the anterior semicircular canal and the utricle. With a pathological cVEMP, which is more specific for the saccule, in combination with normal results of the caloric test, specific for the lateral canal, we can conclude that the inferior vestibular nerve is affected (29).

With migraine patients suffering from vertigo, the cVEMP results can change in the sense of lower amplitudes (34). With a vestibular migraine, cVEMP can show extended latency and increased frequency at which the response with the highest amplitude occurs (similar to Menièr's disease), which points to the possibility of

Figure 3: Graphic display of the result of the cVEMP test. The highlighted waves are P13 and N23 of the muscle on the right side of the neck after stimulation of the right ear. After stimulation of the left ear, there is no cVEMP response on the muscle.



the vestibular migraine originating both centrally and peripherally (35).

There are also reports on normal values of cVEMP and oVEMP with patients with a spinning feeling in the transversal or sagittal plane without rotational vertigo (so-called idiopathic otolithic vertigo).

cVEMP results can also help diagnose lesions of the central nervous system that affect areas included in the vestibulo-collic or vestibulo-ocular reflex. The most often studied is multiple sclerosis which can be manifested with extended latency of P13 and N23 waves (36).

In combination with computed tomography (CT), oVEMP is most important in diagnosing the superior semicircular canal's dehiscence. It also plays an essential role in diagnosing BPPV. It can also be used for detecting other vestibular impairments in the event of vestibular nerve lesions, otolith diseases, and central nervous system lesions (37).

3.2.2 Subjective visual vertical test (SVV)

Patients with utricle impairment often do not have vertigo issues but instead describe a general instability during movement, a feeling of swinging, and are more in danger of falling. In particular, the subjective visual vertical test (SVV) is intended to test the utricular function. It is based on the assessment of the patient's ability to determine true vertical, i.e., determining how much the patient's subjective (i.e., visual) vertical differs from the real (i.e., gravitational) vertical (38). The patient inspects a straight line in front and aims to position it vertically. The angle between the subjective and the true verticality reflects the utricular function.

This test's simple version is the bucket test, where the examiner encloses the subject's whole visual field with a bucket. A straight line is drawn on the bottom of the bucket. In the beginning, the examiner turns the bucket so that the line on the bottom is not aligned with true verticality. Then the examiner slowly rotates the bucket, and the subject must say when the line is aligned vertically. There is an angle meter on the outside of the bucket that the examiner uses to measure how much the patient's verticality differs from the gravitational. They can also use a weighted string, installed on the outside bottom of the bucket, aligned with 0° on the angle meter. They can use it to read the discrepancy of the subject's verticality from true verticality (39).

A newer, digitalized version of the SVV test is increasingly replacing the bucket test. It consists of digital goggles that block all light, and on the inside, the subject sees a straight line. Using a wireless remote, they have to place the line into presumed true verticality. Setting the verticality occurs while the head is tilted at different angles, 0, 15, 30, and 45 degrees left and right. A gyroscope located in the goggles supports measuring the head tilt angle, ensuring the correct head position during testing. The higher the head-tilt angle, the more difficult it is for the subject to determine true verticality.

Results are measured using software, which records the angle of the tilt of the patient's head and the angle of the derogation of their verticality from true verticality (Figure 4). Angle deviation beyond 2° is defined as pathological, and the direction of the deviation depends on the location of the vestibular system's impairment. With unilateral peripheral or pontomedullary changes, the visual vertical is generally tilted to the affected side; with pontomesencephalic impairments, it is tilted to the opposite direction thalamic changes, it may be tilted to the affected or unaffected side. The test is described as especially useful in the literature when

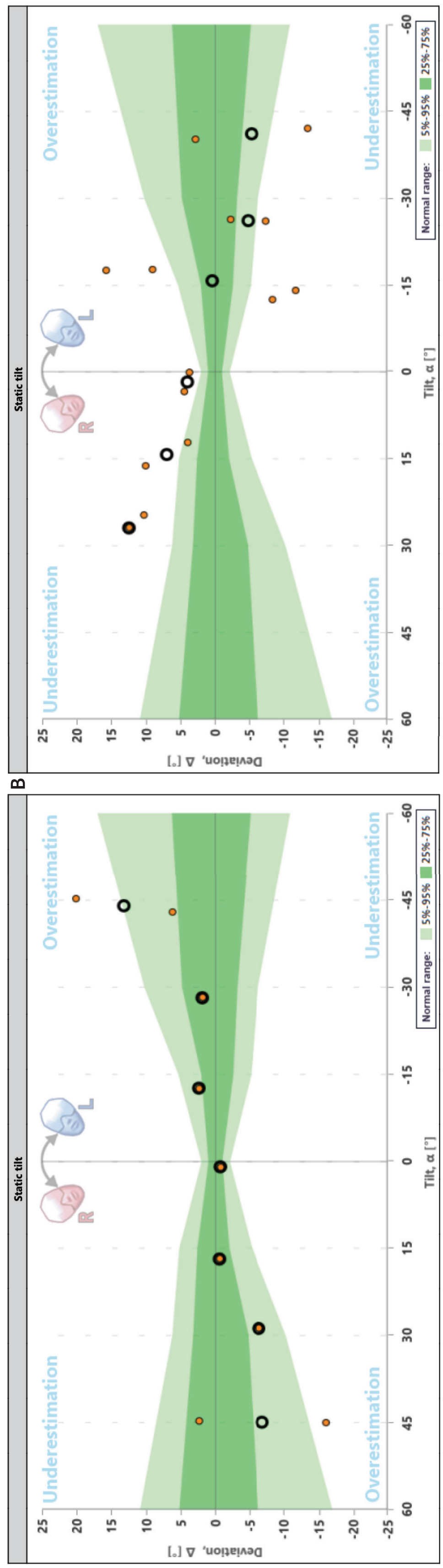


Figure 4: Graphic display of the results of the subjective visual vertical test (SVV). Recognizing subjective verticality within 2° angle from true verticality is recognized as normal (left), while angle deviations above 2° are pathological (right).

diagnosing certain peripheral vestibular system lesions, such as BPPV and the unilateral vestibular loss, and in certain central nervous system lesions. It is also used as the follow-up instrument in the treatment of these diseases (39).

3.3 Balance assessment robot

Besides the tests mentioned above, we should also focus on the balance assessment robot (BAR), developed by Slovenian researchers at University Rehabilitation Institute Soča (URI-Soča). This is a device for testing and enhancement the vestibular function of patients after a stroke. The primary objective of training with the robot is to reduce the number of patients' falls. The training is based on the fact that when unpredictable forces (i.e., perturbations) act on a body during walking, an individual responds with a combination of adjusting their centre of pressure (COP) in the leg that is currently on the ground and by redirecting the raised leg to a location where it will be able to support the body to counteract the unpredictable force appropriately. With patients who have suffered a stroke, the mechanisms that provide such responses can be impaired. To learn how to perform the movements required to respond appropriately, their training must consist of realistic situations that make it possible to lose balance. Depending on their physical impairment, they can then develop a good balance response.

The device is essentially a combination of a treadmill and a movable frame that supports the patient's pelvis. It has embedded sensors for graphing the pelvis's position on a screen, the length of the step, the duration of steps, and the COP in the foot. It supports comprehensive measurements of steps and provides pressure jolts to the pelvis and assessing the response to them (40).

Training on this device consists of three phases. During the first phase, the patient walks straight along the treadmill while their position and movement are captured. The device exerts pressure on the pelvis when an abnormal gait is detected. This stimulates them to take all steps as equally as possible since they are otherwise asymmetric after a stroke. Meanwhile, the patient monitors their pelvis's position on the monitor, striving to maintain it in the correct position. In the second phase, the patient walks a "virtual terrain" with a screen's aid. They see their path on the screen, e.g., uphill, while the BAR exerts forces to the body that simulates walking uphill. In the third phase, the BAR provides unpredictable jolts from all directions while the patient is walking, and they have to respond to them appropriately to correct their posture and gait.

Exercise on the BAR is entirely safe and makes it easier to develop the whole vestibular system's effective responses to unpredictable events.

3.4 Vestibular evoked potentials

Vestibular-evoked potentials (VsEPs) of the central nervous system are EEG responses, i.e., neurogenic potentials recorded with electrodes placed on the scalp when stimulating the vestibular system. The vestibular system can be stimulated with numerous quick and short head turns. The average of electronic neuron responses and concurrent dissipation of background noise draws the curve of their path. The neurogenic response cannot be measured for patients with an impairment to the peripheral and/or central vestibular pathways. With these types of examinations, a frequent issue is the artifacts in the results, which also hinders the interpretation of the results; therefore, this method is seldom used to assess vestibular system function (41).

4 Example of using several diagnostic tests

4.1 Patients and methods

We performed a retrospective analysis of the data for 1,042 patients who were treated for balance disorders at the Centre of Audiology and Vestibulology, Department of Otorhinolaryngology and Cervicofacial Surgery, University Medical Centre Ljubljana, Slovenia, between 2006 and 2015, and who reported a typical history for short-term benign paroxysmal positional vertigo (BPPV). We performed the Dix-Hallpike manoeuvre for diagnosing BPPV (11). We continued with the therapeutic Epley repositioning manoeuvre with a positive manoeuvre (11), and the patients were scheduled for a check-up within three weeks. Because determining which semicircular canal or canals are impacted can be difficult in clinical practice, especially with bilateral positive position tests, we divided all performed diagnostic maneuver results into positive (unilateral or bilateral) and negative. At the follow-up or even at the first examination, most patients had a caloric testing (i.e., bi-thermal frequency vestibulogram (VTG: Varitherm plus and Varioair)) performed, and in some videonystagmography (VNG: Interacoustics VN415/VO425) has been performed (11). The patients' data for whom we confirmed BPPV was then analyzed in more detail by age, sex, side of the impairment, the treatment success, level of repeatability, history of head injury, and osteoporosis. To alleviate the results' interpretation, we assumed that the repositioning manoeuvre instructed at the first examination was successful for patients who did not attend

Table 1: Classification of the vestibular system assessment test by the speed of stimulation and the inner ear's anatomical location.

Tests for the assessment of the semicircular canals	
Caloric testing	By changing the liquid's temperature in the inner ear and observing the evoked nystagmus, we can assess the lateral semicircular canal dysfunction.
Rotatory testing	By rotating on a chair, we simultaneously stimulate both lateral semicircular canals. This provides the assessment of the residual function of the semicircular canals in a bilateral impairment of the vestibular system or provides an assessment of a central compensation of unilateral vestibular paresis.
Head impulse test	With rapid head movements in different directions, we stimulate all six semicircular canals in pairs. We monitor their function by changing vestibulo-ocular reflex, i.e., eye bulb compensation saccades during head movements.
Functional head impulse test	Using optotypes, we measure the ability to retain visual acuity during rapid head movements, thereby assessing the vestibulo-ocular reflex's function.
A dynamic visual acuity test	By measuring visual acuity during rapid head movements, we obtain the data on the impairment of the vestibulo-ocular reflex, i.e., the semicircular canals' function.
The Dix-Hallpike test	Using a special manoeuvre, we can evoke nystagmus in patients with suspected benign paroxysmal positional vertigo, and based on the result; we can assess the impairment of semicircular canals.
Tests for the assessment of the otolith organ	
Vestibular-evoked myogenic potentials	Using short, loud tones, we stimulate the saccule or utricle and measure characteristic electromyographic responses of the sternocleidomastoid muscle or external eye bulb muscles.
Subjective Visual Vertical test (SVV)	By measuring the difference between the subject's subjective and true verticality, we measure the utricular function.
Balance assessment robot	The device makes it possible to measure exact steps and apply different forces to the body through the pelvis and is aimed at balance enhancement and practicing the steady gait for patients who have suffered a stroke.
Vestibular-evoked potentials	When stimulating the vestibular system with fast turns of the head, we measure the EEG of the cerebral cortex.

their check-ups. In this retrospective, the National Medical Ethics Committee approved the Republic of Slovenia's clinical study (No. 0120-032/2016-2, March 21st, 2016).

4.2 Results

We performed a diagnostic manoeuvre for BPPV on our subjects, and the expected typically evoked nystagmus occurred in 376 (36%) of 1,042 patients, of whom 267 (71%) were women. Patients' median age with a positive test was 58.5 years (± 15, with a range between 16-92). Manoeuvres on the right side were positive with 188 (50%), and on the left side with 145 (38.6%), bilaterally with 42 (11.1%) patients, while with one patient (0.23%), the only note is that the manoeuvre was positive, which can be interpreted as the presence of so-called subjective BPPV, i.e., the onset of vertigo without visible nystagmus. Repositioning manoeuvres were successful with 335 patients (89%). Improvements with occasional vertigo (with some depending on the position, with some not) or a feeling of instability were mentioned by 20 (5.3%) patients, while with 21 (5.6%), there was no improvement. Test results were divided into normal results, vestibular system paresis, and central impairment. 52 (13.8%) patients had a recurrence of BPPV. With 40 (10.6%) patients, the onset of BPPV occurred after head trauma. 9 (2.4 %) patients had osteoporosis.

After performing appropriate therapeutic manoeuvres, 217 (57.7%) patients had VTG done, and 51 (13.6%) VNG. Among the patients whose vertigo was successfully eliminated, 204 (60.9%) had normal VTG and VNG results. For 20 (6%), VTG proved vestibular system paresis, while for 4 (1.2%), VNG established central vestibular impairments, and with 2 (0.6%), there was a combination of vestibular system paresis and central impairment. With 105 (31.3%) patients without persistent vertigo, we could not perform the VTG or the VNG test. Among the patients who still had issues with BPPV after the therapeutic manoeuvres, VTG and VNG results were normal for 4 and 5, respectively, for a total of 9 (45%), while a total of 7 (35%), 2 with VTG and 5 with VNG, had paresis. For one patient (5%), VNG proved they had a central impairment. Neither VTG nor VNG was performed for 3 (15%) patients. Of the patients with persisting vertigo, 8 (38.1%) had normal results of both tests, 6 (28.6%) had a paresis, which was proven with a VTG, 5 (23.8%) had central vestibular impairments, which were proven with VNG, while 1 (4.8%) had a combination of paresis and central vestibular impairments, also proven with a VNG test. We did not conduct additional tests on one (4.8%) patient from the group with persistent vertigo. The results of these tests are compiled in Table 2.

5 Conclusion

The reason for short-term positional vertigo is not always BPPV, as we only diagnosed it in 36% of cases using diagnostic manoeuvres on patients with related issues. We did not perform a detailed analysis on patients with negative diagnostics tests for BPPV in this study's scope. Along with caloric testing and videonystagmography, the additional

Table 2: The diagnostic manoeuvre was positive, i.e., pathological, for 376 patients (36%) of 1,042. Among these, repositioning manoeuvres were successful with 335 (89%) patients. Additional tests (VTG or VNG) were performed with 268 (71.3%) patients with a positive diagnostic manoeuvre, and using tests; we were able to additionally define the source of the problem with 46 (12.2%) patients.

	Diagnostic maneuver			Therapeutic (repositioning) maneuver	VTG	VNG
Positive/ pathologic	right	left	bilateral	335 (89%)	28 (12.9%)	18 (35.3%)
	188 (50%)	145 (38.6%)	42 (11.1%)			
	Total					
	376 (36%)					
Negative/ normal	666 (64%)			41 (11%)	189 (87.1%)	33 (64.7%)
Total	**1.042**			**376**	**217**	**51**

definition of the origin of short-term positional vertigo would also be possible with newer tests described in this article, which can be used to more precisely confirm or exclude impairment of an individual or several semicircular canals.

For all patients for whom the peripheral vestibular disorder has not been elucidated or excluded, we will perform all the described tests to assess the function of distinctive parts of the vestibular system. The results and the basic guidelines for treating patients whose medical history points to BPPV are shown below.

The significant progress in the development of balance assessment tests developed over the past few years has made it possible to define the cause of the balance disorder more clearly. Continued research of the vestibular system is required to yield an even more detailed assessment of the results obtained from the existing tests. Regarding the patients we tested, we expect to increase the percentage of etiologically explained balance disorders through additional balance assessment tests. At the same time, we are looking to develop new tests that will utilize computer technology and functional-magnetic imaging to improve treatment and the possibilities for the rehabilitation of patients with vestibular disorders.

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