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Testing of the Semicircular Canal Function in Vertigo and Dizziness

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Abstract

Testing the function of the semicircular canals (SCC) in vertigo and dizziness is an important step towards a diagnosis. There are different vestibular tests available: rotatory testing, bithermal caloric irrigation (CI) and the video-head-impulse test (vHIT). This chapter describes the basic methods, the current knowledge and economic aspects focused on the vHIT and CI. After a general section, common vertigo diseases are discussed with respect to the functional tests. From this chapter, it is clear that not only one method has to be applied to test vestibular function but a battery including the CI and the vHIT in three dimensions.

Keywords: video-head-impulse test, bithermal caloric irrigation, vestibular tests, vertigo, dizziness, vestibular disease

1. Introduction

One major step in diagnosing dizziness and vestibular disease, in addition to a detailed clinical history and neurologic, neuro-ophthalmologic and neuro-otologic examination, is to test the sensors of the labyrinth quantitatively. There are two sets of sensors: the linear/gravity sensors (otoliths, sacculus and utriculus) and the rotational sensors (semicircular canals; SSCs). Both sensor types are important to keep balance and help to orient oneself in space. To test the sensors, different specific tests are available and it is often unclear what methods should be used. This chapter summarizes current knowledge of the testing opportunities and techniques in respect to vestibular function of the SCCs and to different disease. First the different techniques, second the lesion patterns in different vertigo/dizziness disease and third economic aspects are described.

2. Testing of the SCCs

2.1. Anatomical and physiological basics

The SCCs are part of the three-neuron reflex that stabilizes the eyes in space during rotatory self motion, the vestibulo-ocular reflex (VOR). The VOR is quantified as a gain, the ratio of eye-to-head velocity. During normal functioning, the VOR gain is one; eye and head move in opposite direction but with equal velocity [1]. The reflex starts at the sensors, the three SCCs, which are located on each side of the head in the temporal bone. While the horizontal SCCs (HC) are found in a slightly upward tilted horizontal plane (30°), the vertical SCCs are orthogonal to the HC. The SCCs are located in the sagittal plane, which is rotated 45° to either the right or the left. Accordingly, there are two anterior (AC) and two posterior SCCs (PC) found. The main stimulus for the SCCs is the rotational acceleration around an axis orthogonal to the canals plane.

The SCCs are stimulated by the endolymphatic flow relative to the crista ampullaris which is caused by the inertia during rotational stimuli [1]. This flow causes the crista ampullaris to be deflected. Endolymphatic flow in the HC in direction to the ampulla (ampullopetal) causes excitation and away from the ampulla (ampullofugal) inhibition. It is important to mention that in case of the vertical SCCs this direction is inversed.

Neuronal signals originating in the crista ampullaris are transferred to the vestibular nuclei by the vestibular nerve. This nerve has a steady-state neuronal firing rate of about 100 spike/s at rest [1]. Excitation of the SCCs can increase the spike rate up to about 400 spikes/s, inhibition of the SCCs decreases the spike rate, but no less than zero spikes/s [2].

The vestibular nerve has two divisions: the superior receives afferents from the utricle, the horizontal and anterior SCC, the inferior division from the sacculus and the posterior semi-circular canals. Some details are still discussed controversial, for example, if the sacculus projection to the superior vestibular nerve division is of clinical relevance [1].

2.2. Different methods

2.2.1. Rotatory tests

Testing the SCCs could be obtained by passive rotational stimuli which both labyrinths together. This kind of test has been applied for years, but the sensitivity to identify unilateral vestibular failure is low. The test depends on the velocity profile, the disease itself, the stage of the disease, the cooperation and alertness of the patients [1, 3–8]. By analysing the postrotatory response to step stimuli not only side differences but additionally the central processing of the VOR, including the 'velocity storage', could be quantified [9]. The 'velocity storage' is known as the indirect pathway, which acts parallel to the direct VOR pathway [10] and is realized by a commissural inhibitory network [11–14] under cerebellar control of the uvula and nodulus [15]. One function of the 'velocity storage' is to increase the cupula time constant to improve the ability to transduce the low-frequency components of the VOR [16]. Other functions of the 'velocity storage' are to reorient the eye velocity in direction of the gravito-

inertial acceleration and to differentiate linear acceleration from gravity [9]. Remember, these rotational tests have special advantages for certain disease, but examine only the two horizontal SCCs of the right and the left inner ear together. Furthermore, the rotational chairs are currently too slow and the available eye movement-recording systems are very restricted in spatial and temporal resolution, to stimulate just one SCC.

2.2.2. Bithermal caloric test (CI)

A common test to test the horizontal SCCs *unilaterally* is the bithermal caloric irrigation (CI). For describing the mechanism of the caloric test, Róbert Bárány received the Nobel Prize in Medicine in 1916. This test uses a very low-frequency range, is not physiological, but important in a vestibular test battery. Remember, this test was the standard test to diagnose vestibular hypofunction before modern commercial methods became available around 2010.

The response of the horizontal SCCs to thermal irrigation depends on the amount of thermal energy which reaches the inner ear to elicit the VOR. Depending on the anatomy or disease, the thermal conductance through the middle and inner ear could be different.

There are two mechanisms discussed to elicit the caloric response. The major response is caused by temperature-induced endolymphatic flow, the other by a direct thermal stimulation of the vestibular nerve. The latter was identified in microgravity during space flight [17, 18].

The test protocol is standardized, but normative values should be measured in each laboratory separately. Caloric bithermal testing is performed in the supine position with the head flexed 30° upward to orient the horizontal SCCs vertically [19]. Irrigation of the external auditory duct of each ear is performed with water at a temperature of 30 or 44°C for 1 min. In between the irrigations, there is an interval of at least 5 min. To obtain a side difference between the right and left ear, the unilateral weakness is calculated using the best responses of the slow-phase velocities with the Jongkees formula: $UW = ((RW + RC) - (LW + LC)) / (RW + LW + RC + LC) \times 100$ (R: right; L: left ear; water at 44°C (warm, W) and 30°C (cold, C)) [19]. In our laboratory, a value of 25% or higher is pathological. To measure directional asymmetry, the directional preponderance (DP) is quantified ($DP = ((RW - LW) - (RC - LC)) / (RW + LW + RC + LC) \times 100$) [19]. Normal values in our laboratory are up to 30% (absolute values).

It is known from various studies that the sensitivity and specificity are higher in bithermal compared to monothermal irrigations [20, 21]. In our laboratory, we have a sensitivity of 80%, a specificity of 81% and a false-negative rate of 21% for bithermal versus monothermal CI. Monothermal CI could not be applied efficiently if the maximal caloric slow-phase velocities are below 11°/s or if nystagmus is present [22]. The false-negative rate, which ranges in the literature from 10 to 30%, as in our study, precludes the routine use [22, 23].

Another question, which is also discussed, is whether air or water should be used for optimal CI. One major problem was the high test-retest variability of air irrigation [24]. The problem is the amount of thermal energy to be transferred through the middle to the inner ear to elicit the VOR. Hence, higher and lower temperatures compared to water irrigation can be used in air irrigation in order to achieve comparable results [25]. Other and our laboratory prefer still water irrigation for the obvious reasons [26].

2.2.3. Video-head-impulse test (vHIT)

In 1988, M. Halmagyi published the first report of a clinical bedside test to evaluate the horizontal SCCs. This test is known as the 'Halmagyi-test', the 'Halmagyi-Curthoys test' or the 'head-impulse test.' In this test, high-acceleration, small-amplitude head pulses around an earth-vertical axis are applied while the patient is fixating a stationary target. If the eye no longer compensates the head movement, a correcting saccade is observed and the test is rated pathologic. This bedside test (bHIT) for the HC does not identify all unilateral vestibular failures. It has a moderate sensitivity (35–45%) and a high specificity (90%) [27, 28]. To achieve better sensitivity and specificity than the bHIT, the HIT measured with a video system (vHIT) was developed [29–31]. The increase in sensitivity and specificity is mainly attributed to the fact that correcting saccades are clearly identified and the VOR gain can be measured. The vHIT has been shown to be comparable to those HIT measurements with the complicated and time-consuming scleral-search-coil technique [32]. There are meanwhile several companies which sell measuring devices based on video oculography (e.g. GN-Otometrics®, EyeSee-Cam®, Synapsis®, Firefly MV® and Vorteque®).

In contrast to the bHIT, the examiner stands behind the patient during the vHIT, while the patient fixates a point in 1-m distance at the wall. Eye movements are recorded in most systems by a small video camera mounted in goggles worn by the patient during the test. This modern vestibular test examines not only the HC but also the AC and the PC to identify unilateral or bilateral vestibular (BV) hypofunction of individuals SCCs [33]. The direction of the head movements defines the SCC stimulated. Rotating the head around an earth vertical axis to the right or left tests the right or left HC, rotating around an earth horizontal axis (forward and backward) while the head is constantly turned by 45° to the right or left around an earth vertical axis, activates either the right AC or left PC (RALP) or the left AC or right PC (LARP).

It is critically important to reach high enough head acceleration and velocities values to obtain valid examinations. Velocities of 200–250°/s for the horizontal and 150°/s for the vertical vHIT are recommended. To reach such values is sometimes a problem in older patients with high muscle tone in the neck. Patients with neck problems, especially degenerative disease of the cervical spine, should not be tested in order to avoid injuring the patient [31].

In case of a pathological test, the gain is decreased and re-fixating saccades (RFSs) are observed [33, 34]. For each different company selling vHIT measuring devices, there are different normative values for the gains. The cut-off values are about 0.8 for horizontal and 0.6 for vertical vHIT. These values might decrease with an increasing age in some but not all studies and depending on the type of measuring device used [35–40]. RFS might occur during the head impulse or after the end of the head impulse and are referred to as covert and overt RFS [29]. RFSs are much more reliable than the VOR gain values in between different testers [41]. One problem is RFS, which increase in higher age without a VOR gain decrease and could clinically mimic a pathological vHIT [35]. To diagnose a vestibular hypofunction with a vHIT a low VOR gain, compensatory RFS and an optimally performance of the head impulses are necessary.

2.2.4. Differences between CI and vHIT

Both tests measure unilateral HC but in different ways. Therefore, it is clear that the overall sensitivity and specificity for a unilateral failure are different. Measuring such parameters needs a golden standard, which is hard to define as both tests are important on their own.

The vHIT compared to the CI has an overall sensitivity of 41% and a specificity of 92% which is very similar to data of the bHIT in comparison to the CI (sensitivity of 35%; specificity of 95–100% [27, 28]). It is known that the probability of a pathologic bHIT increases with UW and that a UW of 42.5% ensures a pathological bHIT [31, 42]. Our data support this finding also for the vHIT. A unilateral weakness of 57% was observed in the pathological vHIT and 42% in the normal vHIT group. The vHIT is also affected by the disease stage (acute versus non-acute). The frequency of vHIT increases with increasing UW for all patients but more for the acute subgroup compared to the non-acute subgroup [31].

Why the two tests dissociate is controversially discussed. The vHIT and CI might test the VOR at different temporal frequencies, the HIT tests high frequencies up to 5 Hz [43] and the CI tests the lower frequency range at about 0.003 Hz. Stimulation of control subjects on a rotatory chair around an earth vertical axis at 0.003 Hz does not cause the slow-phase velocities obtained by CI (personal communication D. Straumann). One reason for this difference might be attributed to the fact that CI also stimulates the nerve directly [44]. There is some evidence from animal experiments that different vestibular nerve fibres might be important. Higher gains at low frequency are found in regular vestibular afferent fibres and higher gains at higher frequencies in irregular fibres [45]. The contribution of the different fibres to vestibular function and the vHIT and CI remains unclear at the moment [46].

There is another explanation discussed, which could explain different findings. During endolymphatic hydrops, the diameter of the semicircular duct expands, which might lead to an endolymphatic circulation in the duct itself. This results in a lowered or absent caloric response, but an unremarkable vHIT [47].

2.3. Specific disease

2.3.1. Vestibular neuritis (VN)

In vestibular neuritis (VN), mostly an ipsilesional UW and a pathological horizontal vHIT is found. There are, however, sometimes differences in the results of a pathological UW and horizontal vHIT [31, 48–50]. In a series including acute, not acute and follow-up VN patients, we found 47% with a pathological horizontal vHIT and UW (>25%), 25% with a pathological UW only and 8% with an isolated pathological vHIT. In an earlier case series using the scleral-search-coil technique and defining the pathological HIT by the VOR-gain only, all patients with VN had a pathological HIT. In the acute, but not in the late stage, there was also an UW (100 vs. 64%) [51]. The pathological vHIT and UW are not correlated with the clinical picture and symptoms [31, 49]. The time course of recovery of vHIT and UW and was also not correlated in a retrospective study after the onset of VN [50]. In a pathological vHIT covert or overt RFSs

are observed. To link the different correcting saccade patterns to clinical outcome has failed so far [50, 52].

The advantage of the three-dimensional (3-D) vHIT is additionally to test the AC and PC. One can therefore differentiate the lesion based on the affected SCCs in an inferior (PC), superior (HC and AC) or combined VN. In studies, the lesion pattern was shown to be in the superior in 90–48%, inferior in 1–18% and combined inferior and superior vestibular nerve divisions in 34% of the patients [53–56]. The lesion pattern affects the outcome. It was shown that the time to recovery increased from inferior over superior to combined VN [54].

UW without a vHIT is often found in patients of higher age (mean age 64 years) and without a history of Meniere disease (MD) as a first time acute vestibular syndrome. The disease is undefined and might be caused by an endolymphatic hydrops or an incomplete VN. Patients with such a lesion pattern are hospitalized for less time than patients with an additional pathological horizontal vHIT [56].

2.3.2. Meniere disease (MD)

In general, during an attack, there is a decreased UW (64–67%) on the affected side [57, 58], which is caused by the endolymphatic hydrops by an expanse of the endolymph volume, which led to local circulation of the thermal-induced endolymphatic flow [47]. The results of the vHIT are contradictory. The horizontal VOR gain of the affected ear might be mostly slightly reduced [57], or in some cases be increased [59]. During the hydrops, there might be an increase in VOR gain in the vHIT (14%), it might be either normal (67%) or decreased (19%) in the healthy ear [57]. The VOR gains for the AC and PC did not differ between the sides during the attacks [57]. In between the attacks, the vHIT was normal in 33%, pathologic of at least one SCC on the affected side in 33% and pathologic in one SCC on the affected and unaffected side in 31%. The distribution of abnormal findings was dependent on the disease duration and hearing loss [60]. In summary, the findings of CI and vHIT are heterogeneous.

2.3.3. Vestibular migraine (VM)

Vestibular migraine (VM) is a disease which could be confused with MD. To make it even more complicated, there is high co-morbidity of the two diseases and it is sometimes hard to come up with a diagnosis [61]. Vestibular and oculomotor tests could be in between the VM attacks pathological [20, 62, 63] but vestibular dysfunction is not a prognostic factor for migraine patients [64].

To dissociate both diseases based on the CI and vHIT in early or late stage is not possible. An UW and vHIT pathology is more often found in MD (67 and 37%) compared to VM (22 and 9%) [58]. In general, the caloric peak slow-phase velocity values tend to be elevated in VM patients compared to MD [65, 66]. Remember, there is also a portion of common migraine patients which have a UW in between the attacks (16%) [67].

2.3.4. Vestibular schwannoma (VS)

The vestibular schwannoma (VS) can be divided in the intracochlear (50%), the vestibular type (19%) and more diffuse forms (31%). Deafness was the most common symptom and caloric tests were abnormal in 78% of cases. In the vestibular type, hearing was significant, but vestibular function was more altered [68]. It was shown that even very small and localized VS heavily compromise labyrinthine functions [68, 69]. VS initially show a pathological UW and a normal vHIT. However, with increasing size the vHIT might become pathological [69–71]. It is controversially discussed if UW is a predictor for tumour size [70, 72] or not [73]. It was shown that the VOR gain of vHIT is not correlated with the tumour size [70] but rated together with the CI there was a correlation. [71].

The 3-D vHIT might indicate some more information in conjunction with vestibular-evoked potentials (VEMPs). In a study on 50 patients, 58% of patients had test abnormalities which were referable to both superior and inferior vestibular nerve divisions. Selective inferior nerve dysfunction was identified in 10% and superior in 13%, indicating that lesions of the superior and inferior vestibular nerve evolved in parallel. The sensitivity of the test battery increased with tumour size and all patients with medium to large schwannoma had at least two abnormal vestibular test results [74]. From this finding, it might be clinically useful to use a more extended test battery and not a single test.

2.3.5. Sudden sensorineural hearing loss (SSNHL)

In contrast to the VN, which mostly affects the HC and AC, the lesion pattern in hearing loss is different. In a study on acute sensorineural hearing loss, 14% had a complete vestibular loss defined as involvement of all three SCCs, 31% a partial vestibular loss defined as involvement of one or two SCCs and 55% no measurable SCC loss. In the group with a partial lesion, all patients had the PC affected [75]. In another study on acute unilateral hearing loss *with* vestibular symptoms, there is an impairment of the PC in 74%, of the HC in 41% and of the AC in 30% [76]. Comparable data for CI were in both studies not available.

2.3.6. Bilateral vestibular (BV) failure

Recently, a caloric hypofunction of both ears (sum of all four best slow-phase velocity responses has to be less than 20°/s with bithermal CI) and deficits in rotatory tests were recommended to diagnose a BV [77]. With the current vHIT, which often clearly diagnoses a BV [78], things get more complicated. A consensus was reached on a pathological vHIT on both sides in addition to a caloric hypofunction to diagnose a BV and will be published in the newest form from the Barany Society soon (personal communication Prof. Dr. M. Strupp). These criteria are suboptimal; the vestibular organ could be hypo-responsive only to certain head frequency ranges, which make a rotatory testing necessary. Positive bilateral vHIT does not always correlate with caloric or rotatory chair test results in BV. This indicates that a spectrum of vestibulopathies exists according to the stimulation frequency of the deficit [79].

The results of the 3D-vHIT are very scattered with respect to SCC pathology [80]. In one current publication, the 3-D vHIT was characterized in a group including different aetiologies of BV.

The PC was most affected (89%), less the HC (85%) and least the AC (39%). Preserved AC function was associated with aminoglycoside toxicity, MD and BVL of unknown origin. No such sparing of specific SCCs was found for inner ear infections, cerebellar ataxia with neuropathy and bilateral vestibular areflexia syndrome (CANVAS) and sensorineural hearing loss [81]. CANVAS is a late-onset ataxia with a neuropathy and a BV [82].

2.3.7. *Inferior cerebellar stroke*

Stroke with an acute vestibular syndrome is found in about 16% of inferior cerebellar stroke. The main question is how to dissociate stroke from a peripheral vestibular lesion, which accounts for about 25% [83]. This is very important for stroke treatment as there is only a short time frame (4.5 h after symptom onset in Germany) to apply revascularization therapy with the systemic intravenous thrombolysis.

To differentiate the peripheral disease from stroke, the horizontal vHIT is used, together with central signs, for example, the gaze evoked nystagmus and the tonic skew deviation, a vertical divergence of the eyes. This test battery is also known as the HINTS test. In general, the vHIT is normal in stroke. There are some rare exceptions with lesions of the brainstem (e.g. vestibular nuclei) or cerebellum, mostly in the territory of the anterior inferior cerebellar artery (AICA). It is important that the auditory artery is a branch of the AICA which supplies the labyrinth and cochlea. For further discussion on this topic, I recommend the current literature [83–86].

3. Economic aspects

The CI nor the vHIT could replace each other. On the average, the time needed to perform a horizontal vHIT is 6 ± 1 min (mean \pm standard deviation), 3-D vHIT 10 ± 2 min and a caloric irrigation 22 ± 2 min. The examination and documentation of the results by the clinician including removing error traces and setting markers right were estimated at 5–10 min for each test. Rotatory tests, which are more time consuming (10–20 min), might be important in only limited number of disease, for example, BV or central vestibular disease, which is not reviewed in detail here.

In certain disease and depending on the question, not all tests have to be applied, to save time. The saved time could be used to diagnose additional patients. From an economic point of view, just to identify a unilateral vestibular failure and with the mixture of diagnosis in a specialized vertigo/dizziness clinic, I recommend using the vHIT-first approach. In case of an unremarkable vHIT, you additionally should use the CI. There is one exception, if you clinically suspect an MD, you should use the CI first (for details see [20]). From these data, I suggest a disease-dependent approach to save diagnostic time and decrease stress of the patient.

4. Summary

From the reviewed data presented here, it is recommended to use a vestibular-testing battery depending on the question asked. The bithermal CI does not replace the vHIT and vice versa, both techniques are needed. In future, the more detailed vestibular test profiles will help to diagnose disease with a higher sensitivity and specificity, to predict outcome and to identify new disease with new therapeutic options.

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