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Comparative Literature Analysis of Peripheral Vestibular Function Assessment Tools

Riddhi Chinoy
Governors State University

COMPARATIVE LITERATURE ANALYSIS OF PERIPHERAL VESTIBULAR FUNCTION ASSESSMENT TOOLS

By

Riddhi Chinoy, PT, M.S.
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ABSTRACT

Objective/Purpose

One main function of the peripheral vestibular system's semicircular canals is to stabilize images on a target during head movements through the important vestibulo-ocular reflex (VOR) in order to maintain clear vision. Abnormal VOR response results in fast, compensatory, catch-up saccadic eye movements suggesting dysfunction in the semicircular canals. Several functional assessment tools have been developed since the twentieth century to measure the VOR response and saccadic eye movement, and some are still widely used currently, such as the caloric test, rotary chair test, bedside head impulse test (bHIT), scleral search coil technique, and video head impulse test (vHIT). However, with advancing technology and evidence-based medicine, what was traditionally used lack validity and reliability or clinical applicability. This paper aims to 1. evaluate each of the five assessment tools individually in describing its historical use, set-up parameters, benefits, and limitations, and 2. to compare current literature on the validity of the newest vHIT assessment tool against the other four, age-tested peripheral vestibular function assessment tools.

Methods

A comparative literature analysis was performed, using a computerized literature search from Medline, CINAHL, PubMed, Google Scholar, and PEDro. Studies describing search words such as vestibular system, peripheral vestibular function, semicircular canal, VOR, saccades, assessment tools, caloric test, rotary chair test, bedside head impulse test (bHIT), scleral search coil technique, and video head impulse test (vHIT) were included. Human subjects and English language restrictions were imposed. 27 studies, textbooks and manuscripts were included.

Results

In the current literature, the newest vHIT assessment tool was consistently found to provide accurate and objective data in identifying peripheral vestibular dysfunction of the semicircular canals, in both middle-aged and older healthy controls, as well as in patients in an acute and non-acute peripheral vestibular disease stage. In comparison to the other four assessment tools, the vHIT was also found to be portable, simple, affordable, quick, non-invasive, and clinically easy-to-use.

Conclusion

The findings of the comparative literature search suggest the newest assessment tool, the vHIT, can be considered the "best available" reference standard for an assessment tool in identifying peripheral vestibular dysfunction of the semicircular canals, based on its validity, reliability and widespread clinical applicability. Further clinical research is needed to determine if the theoretical comparisons are true.

SECTION 1: Introduction

The vestibular system, located in the inner ears, is comprised of a peripheral and a central component.[1] Together these components provide the central nervous system with information regarding head, body, and eye movements.[1] There are three main functions of the vestibular system: "(1) to stabilize visual images on the fovea of the retina during head movement to allow clear vision, (2) to maintain postural stability, especially during movement of the head, and (3) to provide information used for spatial orientation."[1, p822] The peripheral vestibular system is the most common origin for patient signs and symptoms of vestibular dysfunction[1] and will serve as the primary focus of this paper.

The peripheral vestibular system contains two different sensory systems on each side: three semicircular canals (anterior, posterior, lateral (also referred to as horizontal)) and two otolith organs (saccule and utricle).[1] The total six semicircular canals provide information about head angular velocity (yaw, pitch, roll) which is primarily used for gaze stability, while the four otolith organs provide information about head tilt and linear acceleration which is used for postural stability.[1,2]

The semicircular canals drive the movement of the eyes to stabilize vision during rapid head movements through the vestibulo-ocular reflex (VOR).[1-3] In a typical, intact vestibular system, as the head moves in one direction, the VOR triggers the eyes to move in the opposite direction with velocity and amplitude equal to the head movement to maintain a stable gaze and clear vision of a stationary target.[1-3] This relationship of eye velocity to head velocity is defined as the vestibular gain (eye velocity / head velocity = 1).[1-3] The VOR typically operates at head velocities from 60 to as great as 400 degrees per second; less than 60 degrees per second involves another mechanism called smooth pursuit, while velocities beyond 400 degrees per second reduces the VOR gain and deteriorates the gaze stability.[1]

The six semicircular canals work in pairs: the right anterior semicircular canal pairs with the left posterior semicircular canal, the right posterior with the left anterior, and the two lateral canals with each other.[1] For example, as the head turns to the right, both lateral semicircular canals are stimulated (the right lateral will have an increased firing rate of the peripheral vestibular neurons while the left lateral has a decreased firing rate), causing the VOR to signal both eyes to move at equal speed and distance as the head to the opposing left side which allows the eyes to maintain clear vision of a target.[1-3] A "normal" VOR response in a typical healthy subject is shown in Figure 1.[3] Following a manually delivered head rotation movement to the right (Figure 1a to 1b), the eyes reflexively move toward the opposing left side (Figure 1c).[3]

Figure 1 a, b, c VOR response on a normal healthy subject

From: Curthoys *et al*., 2011

In a malfunctioning semicircular canal, the VOR presents differently. For example, if the right lateral semicircular canal loses typical functionality, such as in a peripheral vestibular disorder, turning the head to the right does not stimulate the right lateral canal to signal the VOR to drive the eyes to the opposite left direction.[1,3] Instead, *the eyes would move with the head initially*, and the compensatory response to re-fixate the lost vision back on the target would be a fast eye movement to the opposing left side, defined as a corrective catch-up saccade.[1-3] Figure 2 below illustrates this abnormal VOR response in a patient with right-sided vestibular dysfunction by the presence of a corrective catch-up saccade (Figure 2f) during a manually delivered head rotation movement to the right.[3]

Figure 2 d, e, f Abnormal VOR response with corrective catch-up saccade on a patient with right peripheral vestibular dysfunction

From: Curthoys *et al*., 2011

If a corrective catch-up saccade occurs at the *end* of the head movement, it is known as an overt saccade as it is easily detected during a clinical examination.[2,3] If a corrective catch-up saccade occurs *during* the head movement, it is known as a covert saccade and is undetectable by the naked eye, thus missed by the clinician.[2,3] Both overt and covert saccadic eye movements in response to an abnormal VOR indicate a dysfunctional semicircular canal.[1,4] The canal that is diagnosed as dysfunctional is dependent on the plane of paired semicircular canals being tested and in which head position the presence of a saccadic eye movement is detected.[3,4] This interaction is outside of the scope of this paper. Instead, the purpose of this paper is to describe methods of objectively and clinically measuring the adequacy of the VOR response and the presence of saccadic eye movement to determine overall semicircular canal function, which can be difficult.[3]

The function of the peripheral vestibular system's semicircular canals must be evaluated by clinicians using a thorough patient history, a variety of clinical examinations, *and* formal quantitative testing.[3,4] Several functional assessment tools were introduced in early 20th century and are still currently used to specifically measure the VOR response and saccadic eye movement.[1-5] However, with the advent of technology and new medical research, the traditional "gold standard" tools may not be as effective today.[3-5] Thus, the aim of this paper is to compare current literature regarding four commonly used peripheral vestibular function assessment tools-- the caloric test, rotary chair test, bedside head impulse test (bHIT), and scleral search coil technique-- to the newest assessment tool, the video head impulse test (vHIT), and to explore the potentiality of the vHIT becoming the next "gold standard" tool.

SECTION 2: Peripheral Vestibular Function Assessment Tools

Five commonly known peripheral vestibular function assessment tools are currently used clinically to specifically analyze VOR response and saccadic eye movement to determine the overall functionality of semicircular canals. These assessment tools are: the caloric test, the rotary chair test, the bedside head impulse test (bHIT), the sclera search coil technique, and the video head impulse test (vHIT). In this section, recent literature on these tests will be evaluated, and the tests will be compared specifically on the characteristics of the historical use, test set-up, benefits, and limitations (Table 1).

Caloric Test

Caloric testing is historically one of the oldest assessment tools of early 20th century used to evaluate asymmetric function in the peripheral vestibular system, specifically of the lateral semicircular canals.[5] This test involves irrigation of the external ear canal with cold and warm water or air. This irrigation stimulates a fluid density change inside the inner ear triggering endolymph fluid movement of the lateral semicircular canal of that ear as shown in Figure 3.[5] The endolymph fluid movement results in fast, side-to-side eye movements called nystagmus, and corrective saccades[5,6] Under typical test conditions, cold (30^{o}C) irrigated water will cause fast corrective saccades away from the stimulated ear, while warm (44^{o}C) irrigated water will cause fast corrective saccades toward the side of stimulated ear (adhering to the mnemonic word "COWS:" cold opposite, warm same).[5,6] The latency, duration, frequency, and velocity of the eye movements are recorded (either through electronystagmography electrodes or video camera), compared to the other ear, and analyzed against normative data.[5,6]

Figure 3 Schematic diagram of warm water and cold water caloric irrigation

Diagram of warm (44˚C) and cold (30˚C) water irrigation into the external ear canal and stimulation of endolymph flow in the lateral (horizontal) semicircular canal.
From: Jacobson *et al*., 1993

The caloric test is usually performed with the patient in supine with the head elevated slightly to 30 degrees to bring the lateral semicircular canals parallel to earth-vertical axis (or alternatively patient can sit up with head extended 60 degrees).[7,8] In a set sequence, each ear is irrigated for a 20-40 second duration with cold and then warm water (or air if indicated) at a designated volume with a designated time interval between irrigations.[5,7,8] The set-up for the caloric test is shown in Figure 4 specifically for (a) water and (b) air irrigation.[5] The velocity of the eye movements evoked by the irrigation method is analyzed to determine the presence of unilateral lateral semicircular canal dysfunction through a mathematical calculation of Jongkees formula,[5,7,8]

$$CP = [(W_L + C_L) - (W_R + C_R)] / [W_L + C_L + W_R + C_R] \cdot 100$$

in which canal paresis (CP) is defined as 25% or greater asymmetry between the eye velocities for the left and right ears.[5,7] W_R is the recorded eye nystagmus velocity during warm water irrigation in the right ear, W_L for warm water irrigation in the left ear, C_R for cold water irrigation in the right ear, and C_L for cold water irrigation in the left ear.[5,7,8]

Figure 4 (a) Water caloric irrigation set-up

(b) Air caloric irrigation set-up

From: Jacobson *et al*., 1993

The benefits of the caloric test include the ability to induce an analogous corrective saccade, as well as to record and assess the differences between left and right ear responses separately in a qualitative and quantitative manner, [5,8-10] as illustrated in Figure 5.[10] If the right ear is irrigated with water or air, fluid movement in the right lateral semicircular canal triggers a slow deviation of the eyes toward the right and fast correcting saccade toward the left.[5] Then both the left and right lateral semicircular canal functions can be examined and analyzed separately to accurately identify and localize the peripheral vestibular lesion.[8]

Figure 5 Sample caloric data recording

Induced eye movements following irrigation of cold and warm water in right (top left plot graph) and left (top right plot graph) ears. Red arrow indicates left unilateral weakness.
From: Craig *et al.*, 2015

Major limitations of this caloric test include lack of normal physiological response, patient discomfort, and being time-consuming.[5,6,8-10] While this test provides qualitative and quantitative evaluation of peripheral vestibular function by comparing the left and right lateral semicircular canals, it tests at a low, nonphysiological head rotation frequency below what is considered normal.[5,8,9] A normal peripheral vestibular system responds to natural head movements covering a wide frequency range of approximately 0.01 to 8 Hz.[5] However, the head rotation frequency from a caloric stimulation produces only 0.003 Hz.[5] Also, the quantitative assumption of peripheral vestibular dysfunction is based only on the evaluation of the lateral semicircular canals, as the caloric test lacks the ability to measure the other two anterior and posterior canals and the otolith organs.[5,10]

Patients often report discomfort in the ears during cold or warm water and air irrigation, and may also experience brief symptoms of vertigo, nausea, and blurred vision due to the nystagmus provocation as a response of water and air irrigation.[6,9] The time to complete a caloric test exclusively is approximately 30 minutes,[10] but this test exists as a subtest of the standardized electronystagmography (ENG) test battery, which in total can take up to two-three hours.[5,10]

Rotary Chair Test

Rotary chair testing is another historically common peripheral vestibular function assessment tool of early 20th century.[11,12] It provides precise, quantitative analysis of the VOR response by evaluating the vestibular gain (in terms of rotary chair, eye velocity / chair velocity), phase (timing between eye velocity and head velocity), and asymmetry (directional preponderance between left and right eye nystagmus movement).[11,12] The test also assesses the eyes' VOR and/or corrective saccade response via physiological rotational stimuli of the patient's body and head en bloc - through a computer-controlled motorized chair.[13] The rotational stimuli can span a wide frequency range to simulate a more natural head rotation of a normal vestibular system.[13,14] A standard rotary chair places the patient in a vertical-axis rotation to allow direct assessment of the lateral semicircular canal function as shown in Figure 6.[13] The eye movements generated by the rotating patient in the chair are recorded by electro-oculography, while a software program digitally analyzes the objective data which measure vestibular gain, phase, and asymmetry[11,13] as shown in Figure 7.[13] The data are then compared to a large set of normative data for adults to determine any clinical abnormalities of the peripheral vestibular system.[13]

The main benefit of the rotary chair testing is the ability to simulate a dynamic range of head rotational frequencies comparable to a normal vestibular system during natural head rotation movements.[13,14] This rotational frequency range varies by rotary chair manufacturers, but the most common range is from 0.01 to 0.64 Hz.[14] Also, many manufacturers have produced rotary chairs that can also perform off-vertical axis rotation to allow assessment of otolith organ function (which is outside of the scope of this paper) in addition to lateral semicircular canal function.[13] Figure 8 provides an example of a multi-axis rotary chair.[13]

Figure 6 Standard vertical-axis rotary chair

From: Phillips, 2013

Figure 7 Sample rotary test data recording of eye position and velocity

From: Phillips, 2013

Figure 8 Multi-axis rotary chair

From: Phillips, 2013

Major limitations of the rotary chair test include being the cost to own and operate, the large amount of space the chair requires, restrictions within the available range of head rotation frequencies, set-up barriers, and limited clinical applicability.[13] While the rotary chair can produce a wide range of head rotational frequencies, it lacks the ability to operate at higher frequencies greater than 1 Hz.[13] Therefore, this rotary chair test fails to truly achieve a normal head movement frequency which ranges from approximately 0.01 to 8 Hz.[5] The physiological rotational stimulus delivered to the body and head en bloc triggers both ears simultaneously, such that single ear stimulation is not possible.[13] Also rotary chairs are limited to stimulating and analyzing only the lateral semicircular canals.[13] Barriers in the set-up include: difficulty stabilizing the head for sustained periods, which is necessary for accurate data collection (typically around 30 minutes); unpleasantness of sitting in a spinning chair; and keeping patients awake with eyes open in a dark and quiet environment.[13] Most importantly, a large number of rotary chair testing facilities exist in the U.S., however there are currently no standards on the nature of the rotational stimuli, nor the analysis techniques to process the eye movement data.[12] This variability in the VOR data collected discourages suitable quantitative analysis across laboratories, making clinical use, reliability, and validity questionable.[12]

Bedside Head Impulse Test (bHIT)

The bedside head impulse test (bHIT) was first described by Halmagyi and Curthoys in 1988 as a clinical assessment tool for the VOR response to detect deficient peripheral vestibular function, specifically in the semicircular canals.[3] Since then to present date, it is still widely used. bHIT is synonymous with other commonly referred names of the same test, such as Halmagyi-Curthoys test, Halmagyi test, head thrust test, head impulse test (HIT), VOR fast test, and clinical head impulse test (cHIT).[3,15-21]

For this test, the seated patient receives instruction to fixate his gaze upon a target in front of him, usually the nose of the clinician, while the clinician holds the patient's head in his hands and provides small, brisk, unpredictable, manual head rotations (referred to as "head impulses" or "head thrusts"),[1,3] as shown in Figure 9.[1] The bHIT involves 1-2 head thrusts in each paired canal planes (as seen in Figure 10[1]), delivered at high velocity (ranging from 3,000 to 10,000 degrees per square second) and low amplitude (approximately 10-30 degrees).[15,17] During the head thrusts, the clinician observes the patient's eyes to identify either the typical VOR response (the normal response of eyes moving in opposing direction of head direction) as previously illustrated in Figure 1 a, b, c above, or the lack of VOR response by the presence of an overt corrective catch-up saccade at the end of the head thrust (abnormal response) as depicted in Figure 2 d, e, f above.[3]

Figure 9 Bedside head impulse test

The clinician manually delivers a short and rapid head thrust to the left (large arrow) and the normal VOR response triggers the eyes to move to the right to fixate gaze on the clinician's nose.
From: O'Sullivan *et al*., 2000

Figure 10 Schematic diagram of the paired semicircular canal orientation planes

The right anterior canal (AC) pairs with the left posterior canal (PC), the right PC with the left AC, and the two lateral canals (HC). The pairs are stimulated based on direction of head rotation which triggers the canals that are oriented in the plane parallel with the pull of gravity. For example, left and right HC are triggered during horizontal head movements (such as when spinning in a rotating chair).
From: O'Sullivan *et al.*, 2000

The main benefits of the bHIT are the ability to perform in a quick and easy, non-invasive manner, and upon the discretion of the clinician during an examination.[2,16,20] There is no need for any equipment as it only requires the clinician's hands and assessment expertise.[2] Most importantly, unlike the caloric test and rotary chair test, the bHIT provides ability to assess the function of all six semicircular canals, not just the lateral canals.[15,18,21]

While the benefits suggest an easy to use clinical assessment tool for peripheral vestibular dysfunction, the bHIT does present with some substantial limitations. First, for a patient with a neck injury or limitations in cervical range of motion the manual head thrusts of the bHIT method would be a general clinical precaution or a contraindication.[10] Thus, this method would not be applicable for a patient with those types of limitations and other assessment tools would need to be used.[10] Second, an overt saccadic eye movement is fairly easy to detect at the end of the head impulse, however covert saccades that occur during the head impulse are not identifiable even by a well trained clinician's naked eye; a false-negative result could confound the diagnosis entirely.[2,3,16-19] Third, the bHIT relies on the clinician's skills and visual acuity to provide the proper manual head thrust and to detect the small and quick overt corrective saccade which only lasts approximately 150 ms.[17] Fourth, since the bHIT is a subjective test, the velocity and amplitude provided during the head thrusts can vary greatly among clinicians.[16,18,19] Fifth, the bHIT lacks an *objective* measure of both the VOR gain and the overt corrective saccade.[3,16,18] Finally, the bHIT only relies on a few head thrusts in the planes of each paired canals but does not give a range of stimuli for generating a stimulus-response function like that of a natural head rotation.[16,19]

Scleral Search Coil Technique

The bedside head impulse test (bHIT) contributed to the inception of the scleral search coil technique, which is currently considered the gold standard for head impulse test measurements.[2,9,16,22,23] Since the VOR response requires coaction between the six semicircular canals and the twelve extraocular muscles to stabilize gaze on a target, a tool which provides accurate, objective measurement of head rotations and eye movements is necessary.[24] Unlike the subjective bHIT, the scleral search coil technique provides quantifiable and recordable data to allow precise assessment of peripheral vestibular dysfunction.[2,16,22,24] Moreover, this technique also detects and records the elusive covert corrective saccades which are undetectable with the bHIT.[16,22,23]

The scleral search coil technique requires sophisticated instrumentation consisting of precalibrated dual-search coils which record head and eye positions onto a computer software-driven device (as shown in Figures 11 and 12[24]).[22,24] For this test, a patient is adorned with a head coil secured either on a head mounting band or to a dental impression bite bar.[16,21,22] Search coils mounted on a contact lens are placed in the patient's right eye after application of a topical anesthetic eye drop.[16,21,22] The patient is then seated in a chair such that the pupillary axis of the right eye is positioned in the center of a magnetic field coil frame.[16,21,22] After the device set-up, the room is dimly lit or darkened, and the patient is instructed to fixate forward on a laser dot projected onto a screen approximately one meter away.[16,21,22] Then 20-50 manual head thrusts with randomized amplitude, velocity, and acceleration are delivered to the patient in the planes of the three paired semicircular canals.[16,21,22] The head velocity and eye movements are recorded and analyzed for overt and covert corrective saccades as illustrated in Figure 13.[16]

Figure 11 Simplified schematic diagram of a scleral field coil

From: Robinson, 1963

Figure 12 Complete schematic diagram of a scleral search coil instrument

From: Robinson, 1963

Figure 13 Sample scleral search coil technique head and eye velocity data recording

From: MacDougall *et al*., 2009

In contrast to the preceding bHIT method, the scleral search coil technique provides an objective and quantifiable method of measuring eye and head movements to more accurately detect a peripheral vestibular dysfunction.[2,16,22,24] The scleral search coil technique also holds the unique benefit of measuring the function of all six semicircular canals as well as detecting the covert corrective saccades that are otherwise missed with the bHIT method.[16,21-23] The scleral search coil technique maintains the exclusive ability to withstand high-speed head rotation frequencies up to 1000 Hz, which is ideal for matching the natural rotational velocity of normal head movements.[16,22,23]

While the scleral search coil technique provides objective and quantifiable data regarding the peripheral vestibular dysfunction, it has several clinical limitations. Most importantly and similar to the bHIT method, a neck injury or limitations in cervical range of motion would be a general clinical precaution or a contraindication to the manual head thrusts during the scleral search coil technique.[10] Also, this assessment tool is invasive and uncomfortable because of the eye coil contact lens and topical anesthetic eye drop application.[2,23] The elaborate instrument is technically demanding and expensive with limited availability and practical use in the clinical field.[2,16,22,23] The procedure is time-intensive from set-up to data recording,[16] and some studies have indicated minor eye coil slippage during eye movement which can result in lower than actual eye velocity and vestibular gain findings.[21,22]

Video Head Impulse Test (vHIT)

The lack of broad clinical applicability of the scleral search coil technique led several researchers to develop the video head impulse test (vHIT) assessment tool.[2,16,20] Based on the same principles and manual techniques as the bHIT, with the addition of the objective, high-speed recordings of ocular and head velocity data as with the scleral search coil technique, the vHIT assessment tool allows for more practical and widespread use to quantitatively assess peripheral vestibular dysfunction.[2,9,16,20,23]

The vHIT entails the use of video-oculography, which is taking measurements of right eye and head movements by a small, lightweight, high-speed, digital video camera mounted onto a pair of equally lightweight eye goggles.[3,16] A patient dons the eye goggles and secures the attached elastic strap snug over the head to minimize slippage of the camera as seen in Figure 14.[3] Then, similar to the scleral search coil technique after set-up, the patient is seated in a chair and instructed to fixate on a dot approximately one meter away, while 15-20 short range, high-velocity, high-acceleration, unpredictable head thrusts are manually delivered to the patient (as seen in Figures 15 (a) and (b)[3)]) in the plane of each of the three paired semicircular canals, as described in Figure 10 above.[1,3,9,16,21,22] The eye and head movement data are recorded by a computer software program which analyzes vestibular gain and both covert and overt saccadic eye movements (see Figures 16 (a)[20] and (b)[3]).

Figure 14 vHIT video-oculography goggles

From: Curthoys *et al*., 2011

Figure 15 (a) Clinician-delivered manual head thrusts during vHIT

(b) vHIT head thrust amplitude, velocity, and acceleration example

From: Curthoys *et al*., 2011

Figure 16 (a) Sample vHIT data recording of head and eye velocity and gain

From: Perez-Fernandez *et al*., 2012

(b) Sample vHIT data recording of overt and covert saccades

From: Curthoys *et al*., 2011

The most significant benefit of the vHIT is the resolution of the known difficulties of both the bHIT method and the scleral search coil technique.[16,20] The vHIT is non-invasive, quick (approximately 10 minutes to complete), and portable to allow practical and widespread clinical use.[10,16] Given the enhanced technology of the high-speed camera, only small 15-20 degree amplitude head thrusts are necessary, which makes the test more pleasant for the patient.[10] Also, due to decreased patient discomfort and presence of easy-to-use functionality, the vHIT can be performed multiple times on a patient with a peripheral vestibular condition, such as for initial diagnosis of vertigo symptoms, during vestibular rehabilitation, and/or post-recovery from such rehabilitation, as seen in Figure 17.[3] Instant results are available using the computer software, thus providing real-time visual feedback of each single head thrust for the clinician to standardize each successive head thrust.[16] Also, the function of each individual semicircular canal can be detected and analyzed in isolation to provide more precise information for abnormalities, even when tested in pairs, as shown in Figure 18.[10] Lastly, the high speed head rotational frequency of up to 250 Hz can easily replicate a natural head rotation movement range of 0.01 to 8 Hz.[5,10,16,22,23]

Figure 17 Sample vHIT data recording over time (acute phase versus recovered)

From: Curthoys *et al*., 2011

Figure 18 Sample vHIT data recording of each semicircular canal

LA is left anterior, RA is right anterior, LP is left posterior, RP is right posterior, Left is left lateral, and Right is right lateral. LARP is paired left anterior and right posterior canals. RALP is paired right anterior and left posterior canals.
From: Craig *et al*., 2015

The major limitation to note about the vHIT is similar to both the bHIT method and the scleral search coil technique regarding a patient with a neck injury or limitations in cervical range of motion. The manual head thrusts during the vHIT would be a general clinical precaution or a contraindication and thus should not be performed on such patients.[10] A minor limitation of the vHIT is the minimal slippage of the goggles, which usually occurs if there is not a snug fit of the goggles on the head.[3,10,16,21,23] This slippage creates artifactual results as if the eyes have moved off the fixed dot, underestimating the vestibular gain, however a quick adjustment of the goggles can easily fix this problem.[3,10,16,21,23]

The vHIT assessment tool has evolved from the benefits of both the bHIT method and the scleral search coil technique, while eliminating the major limitations of both. Given its noteworthy advantages and minimal limitations, the vHIT tool opens the possibility of potentially being the next "gold standard" for identifying peripheral vestibular dysfunction of the semicircular canals. The next section will evaluate recent literature comparing each of the four described peripheral vestibular function assessment tools-- the caloric test, rotary chair test, bedside head impulse test (bHIT), and scleral search coil technique-- against the newest tool, the vHIT.

Table 1: Comparison of 5 common peripheral vestibular function assessment tools

Assessment Tool	Historical Use	Test Characteristics	Test Procedure	Benefits	Limitations
Caloric Test[5-10]	• One of the oldest assessment tools of the 20th century • Evaluates asymmetric function between left and right lateral semicircular canals	• Stimulates ipsilateral lateral semicircular canals by cold or warm water or air irrigation into left and right external ear canals ○ causes a fluid density change inside the ipsilateral inner ear ○ triggers endolymph fluid movement inside ipsilateral lateral semicircular canal ○ culminates in fast, side-to-side eye nystagmus and corrective saccades • 30 degrees Celsius of cold irrigated water causes fast corrective saccades away from the stimulated ear • 44 degrees Celsius of warm irrigated water causes fast corrective saccades toward the side of stimulated ear • Latency, duration, frequency, and velocity of evoked eye movements are recorded, compared to the other ear, and analyzed against normative data to determine left to right ear differences (>25% ear difference is abnormal)	• Patient supine, head elevated approximately 30 degrees • Each ear receives cold then warm water and/or air irrigation for 20-40 second duration at a designated volume with a set wait time between irrigations • Evoked eye movement data are recorded and analyzed	• Induces an analogous corrective saccade in a qualitative and quantitative manner • Left and right lateral semicircular canal functions can be examined and analyzed separately	• Low 0.003Hz nonphysiological head rotation frequency • (normal head movement ranges 0.01 to 8Hz) • Lacks ability to measure other two anterior and posterior canals • Patient discomfort with brief vertigo, nausea, and blurred vision symptoms during irrigation • Time-consuming of 30 minutes • Caloric test exists as a subtest of a standardized ENG test battery which can take up to 2-3 hours
Rotary Chair Test[11-14]	• Common assessment tool of early 20th century	• Computer-controlled motorized chair provides physiological rotational stimuli of the patient's body and head en bloc	• Patient seated in motorized rotary chair in a vertical-axis rotation to allow assessment of lateral	• Simulates a dynamic 0.01 to 0.64Hz range of head rotational frequencies	• Expensive to own and operate • Large physical space is

	• Assesses otolith organ and lateral semicircular canal function	○ evokes either a normal VOR response (normal) or corrective saccades (abnormal) • Vestibular gain, phase, and asymmetry are recorded by electro-oculography, and data are digitally analyzed by software program against normative data	semicircular canal function • Rotational stimuli of chair can span a wide frequency range to simulate natural head rotation • Evoked eye movement data are recorded and analyzed	• Some chairs can also perform off-vertical axis rotation to allow assessment of otolith organ function	required for motorized chair • Lacks ability to operate head (through body) frequencies > 1Hz • Lacks ability to examine and analyze left and right lateral semicircular canals separately, or other canals • Difficult to stabilize patient's head for sustained rotational periods during procedure, and keep patient awake in dark room • No US standards exist for the nature of the rotational stimuli, or the analytics of eye movement data • Limited clinical applicability
Bedside Head Impulse Test (bHIT)[1-3,10,15-21]	• Introduced in 1988 • Widely used clinical assessment tool currently to assess semicircular canal function • Known by several names: Halmagyi-Curthoys test, Halmagyi test, head thrust test, head impulse test (HIT),	• Clinician manually delivers small, brisk, unpredictable head thrusts in the plane of the paired semicircular canals being tested ○ evokes either a normal VOR response (normal) or overt corrective saccades at the end of the head thrust (abnormal)	• Patient seated at bedside or in office/clinic chair • Patient is instructed to fixate gaze upon a target in front of him (usually the nose of the clinician) • Clinician holds the patient's head in his hands and provides 1-2 manual head thrusts in each paired canal planes, at high velocity (ranging from 3,000 to	• Quick and easy test (<2 minutes) • Non-invasive method • Can be performed during a regular clinician examination • No need for any equipment • Able to assess the function of all 6	• Lacks objective, quantifiable measure of the VOR response • Lacks ability to detect covert saccades which occur during the head thrust ○ can lead to a false-negative result, confound the assessment outcome • Requires proper manual head thrust skills and the visual acuity to detect the

	VOR Fast test, clinical head impulse test (cHIT)		10,000 degrees per square second) and low amplitude (approximately 10-30 degrees) • Clinician observes the patient's eyes for either a normal VOR response, or abnormal overt corrective saccades at the end of a head thrust	semicircular canals (left/right anterior, left/right posterior, left/right lateral)	small and quick overt corrective saccade • Lacks a range of stimuli for generating a stimulus-response function like a natural head rotation • Clinical contraindication / precaution if patient has neck pain, instability, injury

Scleral Search Coil Technique[2,9,10,16, 22-24]	• Evolved from bHIT concept after 1988
	• Currently considered the gold standard for objective measurement of vestibular head rotations and eye movements
	• Assesses semicircular canal function
		• Utilizes sophisticated instrumentation consisting of precalibrated dual-search coils which record head velocity and eye movements onto a computer software device
		• Head velocity and eye movements are generated by clinician manually delivering same bHIT-style head thrusts in the plane of the paired semicircular canals being tested
		  ○ evokes either a normal VOR response (normal) or overt and/or covert corrective saccades (abnormal)
			• Patient wears a head coil secured either on a head mounting band or to a dental impression bite bar
			• Search coils on a contact lens are placed in the patient's right eye after topical anesthetic eye drop application
			• Patient is then seated in a chair such that the pupillary axis of the right eye is positioned in the center of a magnetic field coil frame
			• Patient is instructed to fixate gaze upon a target approx. 1 meter in front of him (usually a laser dot on a screen) in a dimly light-to-darkened room
			• Clinician stands behind patient, holds the patient's head in his hands and provides a range of 20-50
				• Provides an objective, quantifiable bHIT method of measuring eye and head movements
				• Able to assess the function of all 6 semicircular canals
				• Able to detect the presence of elusive covert corrective saccades which occur during head thrusts
				• Can withstand high-speed head rotation frequencies up to 1000Hz
					• Invasive
					• Uncomfortable in right eye to wear an eye coil contact lens after topical anesthetic eye drop application
					• Technically demanding and expensive instrument
					• Limited availability and practical use in the clinical field
					• Time-intensive
					• Potential for minor eye coil slippage during eye movement
					  ○ can lead to underestimated eye velocity and vestibular gain
					• Clinical precaution/contraindication if patient has neck pain, instability, injury

			manual head thrusts in each paired canal planes, with randomized amplitude, velocity, and acceleration • Head velocity and eye movements are recorded and analyzed for overt and covert corrective saccades		
Video Head Impulse Test (vHIT)[1-3, 9, 10, 16, 20-23]	• Evolved from bHIT method and Scleral Search Coil Technique • Currently being considered a candidate for "gold standard" assessment tool of semicircular canal function	• Utilizes video-oculography by use of a small, lightweight, high-speed, digital video camera mounted onto a pair of equally lightweight eye goggles, which records head velocity and eye movements onto a laptop software device • Head velocity and eye movements are generated by clinician manually delivering same bHIT-style and Scleral Search Coil Technique-style head thrusts in the plane of the paired semicircular canals being tested ○ evokes either a normal VOR response (normal) or overt and/or covert corrective saccades (abnormal)	• Patient dons the video-oculography eye goggles and secures the attached elastic strap snug over the head to minimize slippage of the camera • Patient is seated in a chair and instructed to fixate gaze upon a target approximately 1 meter in front of him (usually a laser dot on a screen) • Clinician stands behind patient, holds the patient's head in his hands and provides approximately 20 manual head thrusts in each paired canal planes, with randomized amplitude, velocity, and acceleration • Head velocity and eye movements are recorded and analyzed for overt and covert corrective saccades	• Quick and easy test (approx. 10 minutes) • Non-invasive method • Portable, practical and widespread clinical use • Able to assess function of all 6 semicircular canals individually • High-speed camera, requires only small 15-20 degree amplitude head thrusts • Can withstand high speed head rotational frequencies of 250Hz • Minimal-to-no patient discomfort • Multiple tests/retests can be performed (e.g. at initial diagnosis, during vestibular rehabilitation, and/or post-recovery of dizzy symptoms)	• Potential for minimal slippage of goggle if not a snug fit during head thrusts ○ can lead to underestimated eye velocity and vestibular gain • Clinical precaution / contraindication if patient has neck pain, instability, injury

SECTION 3: Comparative Literature Search

Recent literature analyzing the potential of the video head impulse test (vHIT) as the next "gold standard" for identifying peripheral vestibular dysfunction of the semicircular canals is evaluated in this section. The included studies compare the vHIT against the four commonly known function assessment tools described above: caloric test, rotary chair test, bedside head impulse test (bHIT), and scleral search coil technique (Table 2).

vHIT versus Caloric Test

Mahringer et al.[25] examined the sensitivity and specificity of the vHIT against the well-known caloric test to identify pathological unilateral vestibular hypofunction of the lateral semicircular canals. In general, sensitivity refers to how well a test screens for pathology (sensitivity equals the number of abnormal tests divided by the number of subjects with the pathological condition).[14] In contrast, specificity refers to how well a test identifies subjects without the pathology (specificity equals the number of normal tests divided by the number of subjects without the pathological condition).[14] Therefore, a test with a high sensitivity indicates adequate capacity to correctly identify patients with the condition of interest with an abnormal test result, while a low sensitivity provides poor capability. In contrast, a test with a high specificity offers adequate capacity in detecting patients without the condition with a normal test result, while a low specificity suggests poor capability.

Mahringer et al.[25] based their vHIT versus caloric test study on the foundation of two previous studies by Harvey et al.[26] and Beynon et al.[27] analyzing the *bHIT* against the caloric test, which revealed a low sensitivity (35–45%) but a high specificity (90%). This suggests that the bHIT was not as sensitive at detecting unilateral semicircular dysfunction as the caloric test in patients with abnormal results, but the bHIT was adequately capable of detecting patients *without* the dysfunction with a normal test result. Mahringer et al.[25] analyzed 172 patients from a vertigo/dizzy clinic under the age of 70 who demonstrated meeting the inclusion criteria of 25% or greater pathological caloric response during a caloric test (based on the validated Jonkees formula and normative data[5,7,8] suggesting a value of 25% or greater left to right ear caloric difference constitutes a unilateral lateral semicircular canal weakness). Each patient also underwent vHIT performance by the same examiner on the same day. The authors defined a pathological vHIT if the calculated VOR vestibular gain (eye velocity / head velocity) was less than 0.8 value for either the left or right lateral semicircular canal. Figure 19 illustrates an example of vHIT plot graph recordings for (a) normal, (b) pathological, and (c) vestibular gain results.[25]

Figure 19 vHIT plot graph. (a) normal, (b) pathological, and (c) vestibular gain

For (a) and (b) black line is eye velocity, gray line is head velocity. For (c) open circle is single gain value of normal, black circle is mean gain value of normal. Gray square is singe gain value of pathological, and black square is mean value of pathological.
From: Mahringer *et al*., 2014

Of the 172 patients with a diagnosed pathological caloric response, the vHIT diagnosed a pathological response for only 41% of the patients, of which 63% were classified as being in an acute disease stage (symptom onset within the last 5 days) and 33% in a non-acute disease stage (symptom onset larger than 5 days), as illustrated by Figure 20.[25] Statistical analyses showed that the vHIT produced a low sensitivity of 41% and a high specificity of 92% when compared to the caloric test. These results indicated that the vHIT was not as sensitive at detecting unilateral semicircular dysfunction as the caloric test in patients with abnormal results. However, the vHIT was adequately capable of detecting patients *without* the dysfunction with a normal test result.[25]

Figure 20 Pathological vHIT against caloric unilateral weakness (UW)

Black bar represents all patients, gray bar is acute subgroup, and white bar non-acute subgroup.
From: Mahringer *et al*., 2014

Mahringer et al.[25] noted that several general limitations of caloric testing are known to alter the pathological weakness response, such as "technically wrong irrigation, failure of the measurement system, unequal transmission of the thermal energy to the labyrinth, or [poor patient] alertness."[p 470] The differences between the results of the pathological vHIT and the pathological caloric test were hypothesized to be due to several factors. First, the two tests are evaluated at different temporal frequencies-- the vHIT with the short head thrusts at high 5 Hz frequencies, while the caloric irrigation at low 0.003 Hz frequencies. Second, the study analyzed two different disease stages-- acute versus non-acute. Lastly, the two tests differ in the method of test stimulation-- the vHIT generates a physiologic endolymphatic flow from a rapid head thrust, while the caloric test induces a non-physiological endolymphatic flow due to a temperature gradient from one side of the canal to the other. The authors concluded that the vHIT and caloric test assessment tools complemented each other in identifying vestibular hypofunction of the lateral semicircular canals; the vHIT identifies dysfunction at high frequencies, while caloric test identifies dysfunction at low frequencies. They postulated that to save time clinically, the vHIT should be performed first and, if unremarkable, a caloric test should then be undertaken.

Another study by McCaslin et al.[9] also evaluated the sensitivity and specificity of the vHIT against what they considered the "gold standard" caloric test for detecting peripheral vestibular dysfunction of the lateral semicircular canals, with an added component of a self-reported dizziness handicap outcome measure (Dizziness Handicap Inventory) which is outside the scope of this paper. 115 patients under the age of 65 with symptoms of dizziness and negative MRI findings were enrolled and underwent both caloric testing and vHIT assessment at the same appointment. For statistical analysis, researchers were blinded of the results of the caloric test during interpretation of vHIT data. Patients were placed into four groups based on calculated caloric asymmetry between the left and right ears, as Group 1: 0–25%, Group 2: 26–50%, Group 3: 51–75%, and Group 4: 76–100%. The vHIT test was considered abnormal if VOR vestibular gain dropped below 0.7, and if covert and overt saccades were present for >50% of the head thrust trials.

Findings revealed that the more severe the caloric asymmetry from the four groups the further the VOR vestibular gain reduced, and the more the presence of overt and/or covert corrective saccades increased. These results suggested impaired peripheral vestibular function of the lateral semicircular canals as depicted in Figure 21.[9] Statistical analyses showed the vHIT produced a high sensitivity of 78% and a higher specificity of

95% when compared to the caloric test at cutoff point of 39.50% caloric asymmetry. The high sensitivity indicates the vHIT can adequately detect unilateral semicircular dysfunction as the caloric test can in patients with at least 39.50% caloric asymmetry. The high specificity suggests the vHIT is also adequately capable of detecting patients *without* the dysfunction with a normal test result. Additionally, no significant correlations were found between the two test results and the self-reported dizziness handicap outcome measure, as hypothesized.[9]

Figure 21 Normal versus abnormal vHIT against 4 groups of caloric asymmetry

From: McCaslin *et al*., 2014

McCaslin et al.[9] questioned the discrepancy in the findings which deemed the caloric test as abnormal while the vHIT as normal, specifically at caloric asymmetries between 25 and 40%. Long historical use of caloric testing has established the value of 25% or greater ear differential as being a valid indicator of pathological unilateral lateral semicircular canal impairment. The authors acknowledged the commonly known limitations of the caloric test (such as non-physiological and low frequencies, time-intensiveness, and patient discomfort) but also highlighted some issues with vHIT testing. Some of these issues included difficulty relaxing neck musculature and adhering to instructions of fixating gaze on the target, which can both negatively affect head thrust performance. They concluded that vHIT and caloric data are not redundant such that the vHIT should replace the caloric test for the "gold standard" distinction, but instead, the tests are complementary. They did, however, offer the many evolved advantages the vHIT has over caloric testing, such as high specificity in pathological peripheral vestibular cases, quick test time, non-invasive procedures, and the ability to test vertical semicircular canals which caloric testing cannot do.

<u>vHIT versus Rotary Chair Test</u>

A literature search reveals few comparisons between the vHIT (or even the bHIT) and the rotary chair test. However, many studies comparing the rotary chair test with the caloric test exist. Generally, these two tests are performed in a standardized protocol that includes a list of several subset tests (such as ocular saccades, smooth pursuit, tracking, and optokinetic function) which are beyond the focus of this paper. Arriaga et al.[14] studied the sensitivity and specificity of the rotary chair test (ROTO) against the caloric test (as part of an electronystagmography (ENG) test battery) in identifying peripheral vestibular pathology, exclusively analyzing the VOR response as described in Figure 22 (a) and (b), respectively.[14] In this study, a retrospective chart review of 1000 patients from a hearing and balance center enrolled 478 patients who underwent both ROTO and

ENG testing. The ROTO test was defined as abnormal if there were two frequencies with abnormal gain, phase, or symmetry on VOR testing. The ENG test was defined as abnormal if the caloric left versus right ear differential was greater than 25%.

Figure 22 ROTO (a) versus ENG (b) test battery protocol

(a)

Rotational Chair (ROTO) Protocol

Note:
Step 7 highlights parameters for VOR testing. All other steps are beyond the focus of this paper.

(b)

Electronystagmography (ENG) Protocol

<u>Note:</u>
Step 7 highlights parameters for caloric testing. All other steps are beyond the focus of this paper.
From: Arriaga *et al*., 2005

Statistical findings revealed that of the 266 patients with abnormal ROTO test, 73.3% had normal ENG results. In contrast, of the 212 patients with normal ROTO test, 13.7% had abnormal ENG results. The sensitivity for peripheral vestibulopathy was calculated as 71% for ROTO and 31% for ENG, and the specificity as 54% for ROTO and 86% for ENG. Arriaga et al.[14] acknowledged that, as with any diagnostic study, the sensitivity and specificity characteristics of a test rely on the level of normal/abnormal parameters set by the researchers. Despite limitations in this study's testing methods, the retrospective nature of the study, and the expensive cost of the ROTO technology, the authors concluded that the ROTO test was a more sensitive diagnostic test for identifying peripheral vestibular pathology than the ENG test battery which includes caloric testing. The higher specificity of the ENG test suggested that the ROTO test could be used as the primary vestibular assessment test while the ENG test could serve as a supplemental test to confirm the initial ROTO findings.

Despite the lack of literature comparing the vHIT to the rotary chair test, the rotary chair test in itself presents with many limitations as previously mentioned (such as being very costly to own and operate, the large amount of space the chair requires, restrictions within the available range of head rotation frequencies, set-up barriers, and limited clinical applicability).[13] Such substantial barriers restrict the rotary chair test from being an ideal and practical assessment tool in today's fast-paced, evidence-based, technologically advanced, and patient-driven medical field.[5,12,13]

<u>vHIT versus bHIT</u>

The bHIT has been widely used as a highly specific clinical assessment tool for the VOR response in detecting peripheral vestibular dysfunction of the semicircular canals since its inception in 1988.[3,16,20] However, as a result of low sensitivity and lack of objective and quantifiable data, the limitations in the bHIT fueled the evolution of the vHIT.[3,16,18]

Perez-Fernandez et al.[20] performed a comparative study of the bHIT against the vHIT in 179 patients with various types of balance and dizziness peripheral vestibular disorders. The bHIT method was performed on all patients with three manual, randomized head thrusts in the left and right horizontal directions, with visual examination by the experimenter to determine whether the test was normal (absence of ocular overt saccades at end of the head movement in at least two thrusts) or abnormal (presence of overt saccades). The vHIT method was then performed on the same patients using a pair of video goggles with built-in, high-definition, high-speed camera which recorded eye and head movements during 20 quick, experimenter-delivered, random, manual head thrusts in the same left and right horizontal directions as the bHIT method. VOR vestibular gains below 0.6 were considered abnormal, and corrective saccadic eye movements, if present, were classified as either overt or covert.

The results of this study by Perez-Fernandez et al.[20] showed variances in normal and abnormal bHIT and vHIT findings with an overlap of only 67.9% of head thrusts performed. The majority of the findings showed the bHIT as normal while the vHIT as abnormal. The authors raised several reasons for this discrepancy. First, only three thrusts were performed to each side in the bHIT method versus 20 in the vHIT method. Second, there was no quantifiable measure of the head movement velocity in the bHIT method as there was with the recorded thrusts delivered during the vHIT method. This then eliminates the ability of the bHIT method to calculate the crucial VOR gain equation that is vital in studying the functionality of the peripheral vestibular system. Third, and most importantly, the bHIT lacks the ability to detect covert saccades by simple visual observation by an experimenter, which can lead to a false negative diagnosis of "normal" peripheral vestibular function. These covert saccades, however, are easily recordable with the vHIT method. The authors concluded that the methodology of the vHIT device provided the necessary objective data in a simplistic, time-sensitive, and versatile manner while still allowing it to be as clinically applicable as the bHIT method.

Another study by Blodow et al.[18] also evaluated the accuracy of the vHIT assessment tool on 117 patients with diagnosed peripheral vestibular dysfunction (based on previously performed caloric test, cranial MRI, and bHIT results) and 20 healthy subjects. All participants underwent a vHIT assessment which included wearing a lightweight video goggle with an attached video-oculography camera. A minimum of 10 manual and unpredictable head thrusts in the left and right horizontal plane were delivered as the patient fixated gaze on a dot located on a wall 1.2 meters ahead. Statistical data defined a VOR vestibular gain of less than 0.79 and the presence of covert and/or overt saccades as an abnormal VOR response. The results found that the healthy subjects had a high VOR vestibular gain of 0.96 for left and right lateral semicircular canals. For the patients with varying types of peripheral vestibular dysfunction, the VOR vestibular gain was found to have a low overall mean of 0.44. The authors concluded that the vHIT assessment tool can accurately detect abnormal VOR responses and record the covert saccades that are missed by exclusive visual examination of the bHIT tool, making diagnosis of peripheral vestibular dysfunction more definitive.

vHIT versus Scleral Search Coil Technique

Two highly acclaimed and widely referenced research studies compared the effectiveness of the vHIT assessment tool to the current gold standard scleral search coil technique.[16,23] The MacDougall et al.[16] study was a prospective, cross-sectional comparison study that enrolled 16 participants ranging from 29 to 66 years of age, of which eight were patients with confirmed peripheral vestibular dysfunction (ranging from five months to 27 years of symptoms), and eight were healthy subjects that served as the control group. Both groups wore the video-oculographic goggles with the built-in, high-speed camera, as well as the scleral search coil contact lens in the right eye to allow for simultaneous recording of both tests, the vHIT and the scleral search coil technique. All participants were instructed to fixate on a laser dot on a screen 91 cm in front of them in dim light while approximately 50 horizontal manual head thrusts at random velocity, amplitude, and frequency were delivered to them by the same experimenter. Two data sets were obtained for each recording session to show the reliability of the calculated gains of the video-oculography and the search coil methods. Criterion for abnormal VOR vestibular gain was 0.68 or less.

Findings from this MacDougall et al.[16] study revealed that the simultaneous recordings of VOR response and presence of saccadic eye movements from the vHIT and scleral search coil technique were closely comparable, and without any significant differences between the control and patient groups (as shown in Figures 23 and 24, respectively[16]). The sensitivity and specificity of both these tests were 1.0 (95% confidence interval 0.69–1.0). The authors concluded that if the vHIT and the scleral search coil technique produced equal results in both healthy subjects and patients with pre-diagnosed impaired peripheral vestibular function, then the vHIT could be considered an accurate and valid assessment tool.

Figure 23 Simultaneous scleral search coil (Coils) and vHIT (Video) data recordings in a normal subject

From: MacDougall *et al*., 2009

Figure 24 Simultaneous scleral search coil (Coils) and vHIT (Video) data recordings in a patient with left vestibular neuritis

From: MacDougall *et al*., 2009

The other well-known study by Agrawal et al.[23] also evaluated the validity of the vHIT assessment tool against the current gold standard scleral search coil technique with specific focus on individuals aged 70 and older, given the higher prevalence of semicircular canal dysfunction in this age group. As a cross-sectional study, six healthy subjects were enrolled that fit the inclusion criteria of absent cervical spine instability and no loss of vision. Similar to the experimental procedures in the MacDougall et al.[16] study described above, this study by Agrawal et al.[23] also simultaneously recorded eye and head movements using 3D magnetic search coils (via contact lens in the right eye) and

2D video-oculography (via video goggles with built-in, high-speed camera over the left eye). Subjects were instructed to fixate gaze at a dot located 124 cm directly in front of them at eye level. Recordings were performed twice to measure test-retest reliability for both of the tests. Comparison measurement criterion was the 'best value' angular VOR vestibular gain (AVOR gain) for each head thrust.

Results of the Agrawal et al.[23] study showed a significant correlation between the vHIT and scleral search coil technique at an AVOR gain of 0.86. The recordings also showed similar graph traces of the shape of the head and eye movements on the computer software system as shown in Figure 25.[23] Based on the findings, the authors concluded the vHIT tool can serve as a "reasonable proxy"[p283] for the scleral search coil technique in older healthy adults. The authors implied that given the lack on test invasiveness and patient discomfort with the vHIT as with the scleral search coil technique, the vHIT tool was more clinically applicable.

Figure 25 Individual head velocity and eye velocity traces during simultaneous scleral search coil (Search Coil) and vHIT (VOG for video oculography) data recordings of a normal subject. Yaw, Pitch, Roll represent head angular velocity positions.

From: Agrawal *et al*., 2014

Table 2: Characteristics of included comparative literature studies on common peripheral vestibular function assessment tools

Authors (Year of Publication)	Assessment Tools Compared	Study Population	Methods & Measures	Assessment Criteria	Results	Authors' Conclusion
Agrawal et al.[23] (2014)	• vHIT versus Scleral Search Coil technique	• Cross-sectional study of 6 healthy community-dwelling subjects with inclusion criteria of absent cervical spine instability and no loss of vision • 70 years and older, 4 males (age range 71-80 years)	• All subjects with simultaneous recording of eye and head movements using 3D magnetic search coils (via contact lens in right eye) and 2D video-oculography (via video goggles with built-in camera over left eye) • Subject instructed to fixate gaze at a dot located 124 cm directly in front of them at eye level, while 10-15 manual, randomized head thrusts in the left and right horizontal plane were delivered by examiner • Recordings were performed twice for test-retest reliability	• Comparison measurement criterion was the 'best value' angular VOR vestibular gain (AVOR gain) for each head thrust	• Significant correlation between vHIT and scleral search coil technique at AVOR gain of 0.86 • Recordings also showed similar graph traces of the shape of the head and eye movements on computer software program	• vHIT assessment tool can serve as a "reasonable proxy" [p283] for the gold standard scleral search coil technique in older healthy adults • vHIT assessment tool is portable, easy to use, and less invasive, unlike scleral search coil technique
Arriaga et al.[14] (2005)	• Rotary Chair test (ROTO) versus Caloric test (as part of an ENG test battery) • Only VOR responses analyzed	• Retrospective chart review of 1000 patients undergoing vestibular evaluation at a hearing and balance center • Enrolled 478 patients who underwent both	*ROTO test:* • Patients seated in a computer-controlled rotary chair which provides head/body rotational stimuli from 0.01 to 0.64Hz frequencies to evoke a VOR response • Horizontal eye movements are	*Abnormal caloric response:* • ≥25% left to right ear caloric difference from Jonkees formula and normative data calculations	• Of 266 patients with abnormal ROTO test, 73.3% had normal ENG results • Of 212 patients with normal ROTO test, 13.7% had abnormal ENG results	• ROTO test is a sensitive diagnostic test for identifying peripheral vestibular pathology • Higher specificity of the caloric test suggestive of ROTO

		ROTO and ENG testing	recorded using standard ENG electrodes to detect presence of corrective saccades *Caloric test:* • Alternate Binaural Bithermal (cool 30°C, warm 44°C) caloric irrigations using open loop water irrigation (cool right, cool left, warm right and warm left) • Responses recorded for eye nystagmus movement	*Abnormal ROTO test:* • 2 head/body rotational frequencies with abnormal gain, phase, or symmetry	• Sensitivity for peripheral vestibulopathy was calculated as 71% for ROTO and 31% for ENG; specificity as 54% for ROTO and 86% for ENG	test to be performed as primary vestibular assessment test, while caloric test to be a supplemental test to confirm the initial ROTO findings • Rotary chair test is expensive to operate
Blodow et al.[18] (2013)	• vHIT against previously performed Caloric test, cranial MRI, and bHIT	• 117 patients diagnosed with 4 types of peripheral vestibular dysfunction, against 20 healthy subjects • 65 women, 52 men, mean age 52.8 years, range 24–78 years	• All participants underwent a vHIT assessment with video-ocular goggles • Participants instructed to fixate gaze on a dot located 1.2 meters on a wall in front of them, while 10 manual, randomized head thrusts in the left and right horizontal planes were delivered by examiner • Software program recorded and analyzed VOR vestibular gain and overt and/or covert corrective saccades	• Abnormal vHIT: VOR vestibular gain below 0.79 value, and presence of overt and/or covert corrective saccades	• Healthy subjects had a high VOR vestibular gain of 0.96 for left and right lateral semicircular canal • Patients with 4 varying types of peripheral vestibular dysfunction had a low overall mean VOR vestibular gain of 0.44 for left and right lateral semicircular canals	• vHIT assessment tool can accurately detect abnormal VOR responses and record the covert saccades that are missed by exclusive visual examination of the bHIT tool, making diagnosis of peripheral vestibular dysfunction more definitive
MacDougall et al.[16] (2009)	• vHIT versus Scleral Search Coil technique	• Prospective, cross-sectional comparison study that enrolled 16 participants ranging from 25 – 72 years old ○ 8 as patients with	• Both groups had on the video-oculographic goggle and the scleral search coil contact lens in the right eye for simultaneous recording of both tests	• Abnormal vHIT and scleral search coil: VOR vestibular gain below 0.68 value	• Simultaneous recordings of VOR and saccadic eye movement from vHIT and scleral search coil technique were closely comparable	• vHIT and the gold standard scleral search coil technique produced equal results in both healthy subjects and patients with pre-diagnosed impaired

		confirmed peripheral vestibular dysfunction (ranging from 5 months to 27 years of symptoms) ○ 8 as healthy control group	• All participants were instructed to fixate on a laser dot on a screen 91 cm in front of them in dim light while approximately 50 horizontal manual head thrusts were delivered to them at random velocity, amplitude, and frequency, by the same examiner • Recordings were performed twice for test-retest reliability		• No significant differences between the normal control and patient groups • Sensitivity and specificity of both tests were 1.0 (95% confidence interval 0.69–1.0)	peripheral vestibular function • vHIT is an accurate and valid peripheral vestibular function assessment tool • Scleral search coil technique is invasive , uncomfortable, expensive, and non-portable, unlike vHIT
Mahringer et al.[25] (2014)	• vHIT versus Caloric test	• Enrolled 788 patients from a vertigo/dizzy clinic • Analyzed only 172 patients (102 males, 70 females, age • 59 ± 15 years) with inclusion criteria of ≥25% pathological caloric response	• All 172 patients underwent a vHIT assessment with video-ocular goggles by the same examiner, on the same day as caloric test *Caloric test:* • Caloric irrigation was performed for 1 min separately for each ear with water at a temperature of 30 and 44◦C • 5 minute intervals between each individual irrigation • Responses recorded for eye nystagmus movement *vHIT method:* • Participants instructed to fixate gaze on a dot located 1 meter on a wall in front of them, while 20 manual, randomized head thrusts in the left and right horizontal plane were delivered by one examiner	*Pathological caloric response:* • ≥25% left to right ear caloric difference from Jonkees formula and normative data calculations *Pathological vHIT:* • VOR vestibular gain below 0.8 value, and presence of overt and/or covert corrective saccades	• vHIT produced a low sensitivity of 41% and a high specificity of 92% when compared to the caloric test	• Caloric irrigation and vHIT assessment tools are complementary to identify vestibular hypofunction of the lateral semicircular canals • To save time clinically, vHIT should be performed first, if unremarkable, caloric test should be second • Caloric test can only achieve low 0.003Hz head rotation frequencies; vHIT high 5Hz frequencies • Caloric test lacks physiologic endolymphatic flow from rapid head thrusts as vHIT can

			• Sensitivity and specificity of vHIT against caloric test was analyzed for lateral semicircular canal dysfunction			

McCaslin et al.[9] (2014)	• vHIT versus Caloric test
	• Dizziness Handicap Inventory outcome measure
		• 115 adults presenting to a tertiary medical care center with symptoms of dizziness and negative MRI
		• Under 65 years (mean 45.63 years, SD 14.91), 58 males
			• All 115 patients underwent both caloric testing and vHIT assessment at the same appointment, after answering Dizziness Handicap Inventory outcome measure
			Dizziness Handicap Inventory outcome measure:
			• 0 to 100 point scale which represents self-reported dizziness handicap
			  ○ 0 is minimum handicap
			  ○ 100 is maximum handicap
			• Administered in face-to-face format to all subjects prior to vHIT and caloric test
			Caloric test:
			• 250mL of warm water (44°C), and cool water (30°C) irrigated in each ear for 25 seconds
			• Responses recorded for eye nystagmus movement
			vHIT method:
			• Use of video-ocular goggles
			• Patients instructed to fixate gaze on a dot located on a wall 5ft in front of them while 10-20 manual, randomized
				Pathological caloric response:
				• ≥25% left to right ear caloric difference from Jonkees formula and normative data calculations
				• Patients placed into 4 groups based on left to right ear caloric asymmetry: 0–25%, 26–50%, 51–75%, and 76–100%
				Pathological vHIT:
				• VOR vestibular gain below 0.7 value, and presence of overt and/or covert corrective saccades in >50% of head thrust trials
					• More severe the caloric asymmetry from the 4 groups, the further reduction in VOR vestibular gain, and the increased presence of overt and/or covert corrective saccades
					• Result suggestive of impaired lateral semicircular canal function
					• vHIT produced a sensitivity of 78% and a high specificity of 95% when compared to the caloric test at cutoff point of 39.50% caloric asymmetry
					• No significant correlations between vHIT and caloric test to the Dizziness Handicap Inventory outcome measure
						• vHIT and caloric test findings are not redundant
						• Recommend vHIT should not replace caloric test as the gold standard, instead should be complementary
						• vHIT is a quicker, non-invasive method unlike caloric test
						• Caloric test lacks ability to test vertical semicircular canal unlike vHIT
						• Caloric test can only achieve low 0.003Hz head rotation frequencies; vHIT high 5Hz frequencies
						• Caloric test lacks physiologic endolymphatic flow from rapid head thrusts as vHIT can

			head thrusts were delivered in the left and right horizontal directions • Software program recorded and analyzed VOR vestibular gain and overt and/or corrective saccades • Researchers blinded of caloric test results during interpretation of vHIT data			
Perez-Fernandez et al.[20] (2012)	vHIT versus bHIT	• Broad population of 179 patients with various types of balance and dizziness peripheral vestibular disorders • 69 (38.5%) males, 110 (61.5%) females	*bHIT method:* • Performed on all patients • 3 manual, randomized head thrusts in the left and right horizontal directions • visual examination by the examiner to determine presence/absence of overt saccades *vHIT method:* • Performed on same patients • Use of video-ocular goggles with 20 manual, randomized head thrusts delivered in the left and right horizontal directions • Software program recorded and analyzed VOR vestibular gain and overt and/or covert corrective saccades	*bHIT method:* • *Normal:* absence of overt corrective saccades at end of the head movement in at least two head thrusts • *Abnormal:* presence of overt saccades *vHIT method:* • *Abnormal:* VOR vestibular gain below 0.6 value, and presence of overt and/or covert corrective saccades	• Variances in normal and abnormal bHIT and vHIT findings, with an overlap of only 67.9% of head thrusts performed • Majority showed the bHIT as normal while the vHIT as abnormal	• vHIT device provide the necessary objective data in a simplistic, time-sensitive, and versatile manner which can allow it to be as clinically applicable as the bHIT method • bHIT method only used 3 head thrusts; vHIT method used 20 • bHIT lacks quantifiable measure of the head movement velocity; vHIT able to record instantly as head thrusts are delivered • bHIT lacks detection ability of covert saccades as vHIT can→leads to false negative diagnosis of “normal” peripheral vestibular function

SECTION 4: Discussion & Conclusion

Discussion

The vestibulo-ocular reflex (VOR) response is a coaction between the six semicircular canals and the twelve extraocular muscles to stabilize gaze on a target, such that head movements in one direction trigger the eyes to move with equal speed and distance to the opposite direction.[1-3,24] The ability to maintain a clear vision of a target during natural rapid head movements is a vital automatic reflex that allows humans to be mobile without blurred vision, dizziness, nausea, loss of postural control, and spatial disorientation.[1]

In contrast, a deficient VOR response lacks signals from head movements to stimulate eye movements, such that the eyes have to perform a quick, compensatory, catch-up movement, known as a corrective saccade, to relocate the target back onto the visual field.[1-3] These saccades occur either during the head movements (covert saccades), or at the end of the head movements (overt saccades).[1-3] The presence of any saccades indicates dysfunction of the semicircular canal.[1,4] Thus, the integrity of the VOR response and saccadic eye movement is not only crucial in understanding but central to determining normal versus abnormal semicircular canal functionality of the peripheral vestibular system. Determining this specific functionality requires appropriate assessment tools which provide accurate, objective, and reliable measurements of head rotations and eye movements.

Clinicians and researchers since early 20th century have designed several functional assessment tools to specifically measure the VOR response and saccadic eye movement, five of which are currently still widely used in practice: the caloric test, rotary chair test, bedside head impulse test (bHIT), scleral search coil technique, and video head impulse test (vHIT). With the advent of new technology, evidence-based medicine, and patient-driven and cost-effective clinical care, some of these traditionally used functional assessment tools lack validity and reliability.[14] The newest assessment tool, the vHIT, has been purported by many clinicians and researchers to have potential to be the next "gold standard."[9,14,20,23]

It should be noted that these functional assessment tools are not to be considered diagnostic, but rather demonstrative in quantifying peripheral vestibular function, as neurotologists would argue "vestibular function represents a complex interaction between peripheral and central vestibular physiology with changes in each of the system's components during disease."[14, p332] Arriaga et al.[14] convey the challenges in medicine of establishing a test as a "gold standard" since the specificity and sensitivity characteristics of any assessment tool rely on the parameters set by researchers for "normal" and "abnormal." Thus they suggest utilizing the "best available"[14, p332] standard instead, in which the clinician decides on which assessment tool to perform on patients to provide the most valid and reliable results.

In the current literature, the vHIT was consistently found to provide accurate objective data in identifying peripheral vestibular dysfunction of the semicircular canals.[3,9,14,16,18,20,23,25] When the vHIT tool is compared against the age-tested caloric test, the high sensitivity and specificity characteristics suggest the vHIT is adequately capable of detecting unilateral semicircular dysfunction in patients with abnormal results, as well as detecting patients without the dysfunction with normal test results, respectively.[9,25]

Despite the lack of evidence for a comparison to the vHIT tool, the rotary chair test in itself has been found to be an ineffective tool clinically and has questionable reliability and validity.[12,13] The rotary chair test thus falls short of what the vHIT tool has developed into clinically and objectively.

Comparison of the objective vHIT tool against the subjective bHIT method (from which the basis of the vHIT tool derives from), the vHIT surpasses the known limitations of the bHIT method by being quantitative and more accurate at identifying peripheral vestibular dysfunction of the semicircular canals.[18,20]

Finally, when the vHIT tool is compared against the current gold standard scleral search coil technique, the vHIT stands to be as accurate and sensitive in identifying peripheral vestibular dysfunction of the semicircular canals as the scleral search coil technique in both middle-aged and older healthy controls as well as in patients in an acute and non-acute peripheral vestibular disease stage.[16,23] Two highly acclaimed studies performed simultaneous vHIT and scleral search coil testing of the VOR response and saccadic eye movement. A high and equal sensitivity and specificity of 1.0 was produced in both assessment tools, concluding that the vHIT can provide the same reliability and validity as the gold standard scleral search coil technique.[16,23]

The major limitation shared by the vHIT, the bHIT method, and the scleral search coil technique is the general clinical precaution or contraindication for a patient with a neck injury or limitations in cervical range of motion.[10] In such cases, the clinician can refer to the caloric test, rotary chair test, or other functional assessment tests which limit or avoid head and neck movements. A minor limitation of the vHIT is the minimal slippage of the goggles usually from lack of a snug fit of the video-ocular goggles which can be easily fixed by readjustment.[3,10,16,21,23]

It is worthy to note that given the recent development of the vHIT tool, a standard protocol has not yet been established of how many head thrusts to perform, or the distance of the patient from the fixation point, as there are only a few manufacturers that have developed the vHIT device to date. However, most recent studies testing the vHIT tool have taken the methodology from studies on the gold standard scleral search coil technique and incorporated into their vHIT research design.

Considering the consistent favorable results from the studies on the benefits of the vHIT tool, and the added value of its portability, simplicity, affordability, quickness, non-invasiveness, and widespread clinical applicability over its counterpart assessment tools,[9,16,18,20,23,25] the implications of this new assessment tool solidify the message of vHIT being the "best available" reference standard.[14, p332] The vHIT has enhanced the clinical ease of detecting VOR response and saccadic eye movement by eliminating various limitations from traditional assessment tools, yet remaining accurate, reliable, and valid at identifying peripheral vestibular dysfunction of the semicircular canals.

<u>Conclusion:</u>

"Eyes provide [the] most accessible window for exploring vestibular function" (Goebel et al.[11, p401]). The findings of this comparative literature search suggest the newest assessment tool, the vHIT, can be considered objective, valid, complementary, and statistically equivalent to the traditional assessment tools: the caloric test, rotary chair test, bHIT, and scleral search coil technique. To save time, be more cost-effective, prevent patient discomfort, and deliver ease of clinical use, the vHIT stands to provide the "best available" reference standard for an assessment tool in identifying peripheral vestibular dysfunction of the semicircular canals. Given the strong validity and clinical applicability already available, the vHIT can provide even more impact on further clinical research for the functionality of the entire vestibular system. There are widespread clinical research opportunities to assess the theoretical effects of vHIT on broader topics such as imaging, pharmacological agents, or vestibular rehabilitation.

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