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Normative Data and Test-Retest Reliability of the SYNAPSYS Video Head Impulse Test

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Abstract

Background: The observation or measurement of eye movement can aid in the detection and localization of vestibular pathology due to the relationship between the function of the vestibular sensory receptors in the inner ear and the eye movements produced by the vestibulo-ocular reflex (VOR). The majority of bedside and laboratory tests of vestibular function involve the observation or measurement of horizontal eye movements (i.e., horizontal VOR) produced by stimuli that activate the horizontal semicircular canals (SCCs) and the superior vestibular nerve. The video head impulse test (vHIT) is a new clinical test of dynamic SCC function that uses a high-speed digital video camera to record head and eye movement during and immediately after passive head rotations. The SYNAPSYS Inc. vHIT device measures the "canal deficit" (deviation in gaze) during passive head impulses in the horizontal and diagonal (vertical) planes. There is, however, a paucity of data that has been reported using this device.

Purpose: The purpose of this study was to obtain normative data and assess the test-retest reliability of the SYNAPSYS vHIT (version 2.0).

Research Design: A prospective repeated measures design was utilized.

Study Sample: Thirty young adults with normal hearing, normal caloric test results, and a negative history of vestibular disorder, neurological disease, open or closed head injury, or cervical spine injury participated in the study.

Data Collection and Analysis: A single examiner manually rotated each participant's head in the horizontal and diagonal planes in two directions (left and right in the horizontal plane; downward and upward in each diagonal plane) resulting in the stimulation of each of the six SCCs. Each participant returned for repeat testing to assess test-retest reliability. The effects of ear, session, and semicircular canal (horizontal, anterior, posterior) on the magnitude of canal deficit during the vHIT were assessed using repeated measures analysis of variance.

Results: The mean canal deficit of the horizontal canals (8.3%) was significantly lower than the mean canal deficit of the anterior canals (16.5%) and the posterior canals (15.2%); there was no significant difference between the mean canal deficits of the anterior and posterior canals. The main effects of session and ear on canal deficit were not significant, and there were no significant interaction effects. There was no significant difference between the mean canal deficit for session 1 and session 2 for the horizontal, anterior, and posterior canals. The 95th percentiles for canal deficit were 19, 26, and 22% for the horizontal, anterior, and posterior SCCs, respectively.

Conclusions: Testing of all six SCCs was completed in most participants in $\sim$10 min and was well-tolerated. The vHIT has some important advantages relative to more established laboratory tests of horizontal SCC function including the ability to assess the vertical SCCs, lower cost, shorter test time, greater

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portability, minimal space requirements, and increased patient comfort. Additional data, however, should be obtained from older participants with normal vestibular function and from patients with vestibular disorders. Within-subject comparisons between the results of the vHIT and the caloric and rotary chair tests will be important in determining the role of the vHIT in the vestibular test battery.

Key Words: Head impulse test, semicircular canal, vestibulo-ocular reflex, video head impulse test

Abbreviations: HIT = head impulse test; LARP = left anterior and right posterior SCCs; RALP = right anterior and left posterior SCCs; RMANOVA = repeated measures analysis of variance; SCC = semicircular canal; SVN = superior vestibular nerve; vHIT = video head impulse test; VOR = vestibulo-ocular reflex

The angular vestibulo-ocular reflex (VOR) ensures gaze stability during head rotations by generating eye movements that are equal and opposite to head rotation. The gain of the VOR (eye velocity/head velocity) for natural head movements, therefore, approaches unity in healthy individuals. The VOR has three main anatomic components: the semicircular canals in the peripheral vestibular system, the vestibular and ocular motor nuclei in the brainstem, and the extraocular muscles. The semicircular canals (SCCs) are positioned in three nearly orthogonal planes within the head allowing for the detection of head rotation in three-dimensional axes. The SCCs function as angular accelerometers in a push-pull fashion with two coplanar canals on each side of the head working together, that is, left and right horizontal SCCs, the right anterior and left posterior SCCs or RALP, and the left anterior and right posterior SCCs or LARP. For example, during rightward head rotation in the horizontal plane, the discharge rate of the right horizontal SCC afferents increases, and, at the same time, the discharge rate of the left horizontal SCC afferents decreases relative to the resting discharge rate. The difference in output between the right and left horizontal SCCs drives the leftward compensatory eye movement of the VOR so that the eyes remain still in space during head rotation and enable stable vision. The observation or measurement of eye movement, therefore, can aid in the detection and localization of vestibular pathology due to the relationship between the function of the vestibular sensory receptors in the inner ear and the compensatory eye movements produced by the VOR. The majority of bedside and laboratory tests of vestibular function involve the observation or measurement of horizontal eye movements (i.e., horizontal VOR) produced by stimuli that activate the horizontal SCCs and the superior vestibular nerve (SVN).

The video head impulse test (vHIT) is a new clinical test of dynamic SCC function that uses a high-speed digital video camera to record head and eye movement during and immediately after passive head rotations and is based on the bedside head impulse test first described by Halmagyi and Curthoys (1988). The head impulse test is based on two principles in vestibular physiology: (1) eye movements evoked by stimulation of a single semicircular canal occur in the plane of that canal, and (2) excitatory responses have a larger dynamic range than inhibitory responses (Ewald, 1892; Goldberg and Fernandez, 1971; Estes et al, 1975; Baloh et al, 1977; Böhmer et al, 1985). Specifically, because the three SCC pairs (horizontal, RALP, and LARP) are nearly orthogonal to each other, a head impulse delivered in the plane of one pair will stimulate mainly that pair and not the other two SCC pairs. In addition, the VOR during a canal-plane impulse toward a particular SCC is driven largely by that SCC and not by its coplanar counterpart due to the asymmetric response of primary vestibular afferents. The head impulse test, therefore, can assess the function of each SCC separately and, in the case of unilateral vestibular hypofunction, the gain of the VOR during ipsilesional head impulses will be lower than the gain during contralesional head impulses.

To perform the vHIT, patients are seated and instructed to maintain their gaze on an earth-fixed visual target. The clinician stands behind the patient and manually rotates the head abruptly and unpredictably to the left or right through a small angle (10–20°) in the horizontal plane to stimulate the left and right horizontal SCCs. To test either of the coplanar vertical canal pairs (RALP or LARP), the head is turned ~30–45° relative to the trunk (aligns the vertical canal pair with the trunk's sagittal plane) prior to rotating the head either downward (stimulates the anterior canal) or upward (stimulates the posterior canal) (see Fig. 1). A high-speed digital infrared video camera uses pupil detection methods to record two-dimensional eye movement during and immediately after the head rotation. Depending on the vHIT device, the camera is either embedded in head-worn goggles or mounted on a tripod facing the patient. Head movement is recorded by an inertial measurement unit (triaxial linear accelerometer and gyroscopes) mounted on the head-worn goggles, or the change in the angle of head position during the head impulse is recorded by an external camera.

The SYNAPSYS Inc. vHIT device measures the deviation in gaze during passive head impulses in the horizontal and diagonal planes using an external camera (Ulmer and Chays, 2005). There is, however, a paucity of data that has been reported using this device (Ulmer et al, 2011). The purpose of this study was to obtain normative data and assess the test-retest

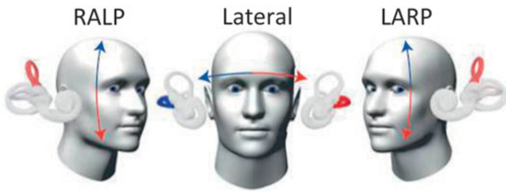

Figure 1. Initial head position and head impulse directions (arrows) for RALP (right anterior and left posterior), LARP (left anterior and right posterior), and lateral canal stimulation as viewed from the earth-fixed visual target. Prior to testing the vertical canals, the head is rotated ~45° relative to the trunk, and the head impulse is a pitch movement either downward (red vertical arrows) to stimulate the anterior canals or upward (blue vertical arrows) to stimulate the posterior canals. For testing the lateral (horizontal) canals, the head impulse is a rotation of the head in the horizontal plane either to the right (red horizontal arrow) to stimulate the right horizontal canal or to the left (blue horizontal arrow) to stimulate the left horizontal canal. The desired amplitude of head rotation used to stimulate each canal is 10–20°. These images were modified from the free iPhone application (aVOR) developed by Hamish G. MacDougall, PhD (Vestibular Research Laboratory, School of Psychology, University of Sydney, Sydney, NSW, Australia).

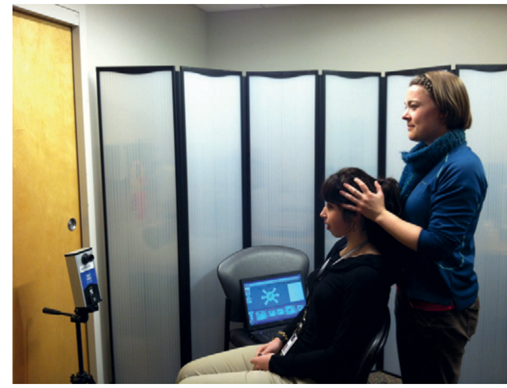

Figure 2. The SYNAPSYS video head impulse test (vHIT) system. The system consists of a high-speed infrared digital video camera mounted on an adjustable tripod, a computer, and the vHIT software. The camera is located at a distance of 90 cm from the patient's eyes and is connected to the computer via a USB cable. The patient is seated in an immovable chair facing the camera and is instructed to maintain their gaze on an earth-fixed target located beyond the camera at a distance of at least 2 m at eye level. The clinician stands behind the patient when performing the head impulses. The vHIT software provides the clinician with real-time visual feedback re the adequacy of the head impulses and auditory feedback re the direction (right versus left) and the plane (horizontal, LARP, or RALP) of stimulation.

reliability of the SYNAPSYS vHIT (version 2.0) in young healthy adult participants.

METHODS

Participants

Thirty participants (age range = 18 to 30 yr; mean = 23.5 yr; 26 females) with normal hearing, a negative history of vestibular or neurological disease, a negative history of cervical spine injury, and normal caloric test results were recruited for this study. Normal caloric test results were defined as either a unilateral weakness <25% for the alternate binaural bithermal caloric test or an interear difference ≤10% for the monothermal warm caloric screening test (slow phase eye velocity of >7°/sec for each of the warm caloric irrigations) (Murnane et al, 2009).

Procedures

The SYNAPSYS vHIT system was used to record head and eye position in response to passive, unpredictable, low-amplitude (~10–20°), high-acceleration head impulses. The system consists of a high-speed (250 Hz) infrared digital video camera mounted on an adjustable tripod, a computer, and the vHIT software (version 2.0). Participants were seated facing the camera at a distance of 90 cm and were instructed to maintain their gaze on an earth-fixed visual target located at eye level beyond the camera at a distance of 2 m straight ahead (see Fig. 2). The examiner stood behind each participant and rotated the head in the horizontal and diagonal planes in two directions (left and right in the horizontal plane; downward and upward in each diagonal plane) (see Fig. 1) resulting in the stimulation of each of the six SCCs (right horizontal and left horizontal; right anterior and left posterior; left anterior and right posterior). A single examiner administered the head impulses for this study.

Participants underwent a minimum of six head impulses in each plane and in each direction; the order of the plane of head impulse was randomized. The camera recorded eye and head position before and during head rotation. If the following conditions were met, then a computer algorithm calculated the percentage of canal deficit at t = 120 msec post–head impulse onset:

1. Head acceleration exceeded the preset manufacturer-recommended thresholds (2500°/sec^2 for horizontal head impulses and 2000°/sec^2 for vertical head impulses).
2. Camera detected pupil at t = 0 msec and at t = 120 msec post–head impulse onset (see Fig. 3).

Canal deficit was measured at 120 msec and defined as 100*G/H, where *H* was the angle of head rotation (in angular degrees relative to t = 0 msec) and *G* was the angle of gaze deviation (in angular degrees relative to t = 0 msec).

In general, low values of canal deficit (little or no deviation in gaze during the head impulse) indicated normal SCC function, whereas high values of canal deficit (gaze

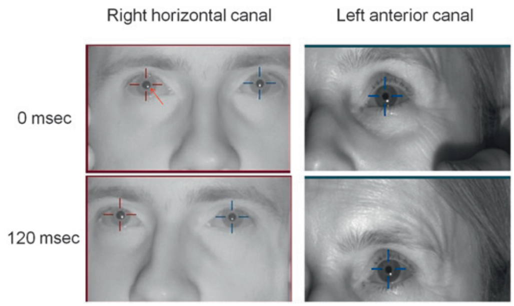

Figure 3. Corneal reflection and gaze deviation during a right horizontal canal head impulse (left column) and during a left anterior canal head impulse (right column) for two normal subjects. The video images in the top row show the position of the corneal reflection (small white circle near the pupil indicated by red arrow) at 0 msec relative to the onset of head impulse, and the video images in the bottom row show the position of the corneal reflection at 120 msec post–head impulse onset. Note that there is little or no change in the position of the corneal reflection at t = 120 msec relative to t = 0 msec (i.e., little or no deviation in gaze during the head impulse).

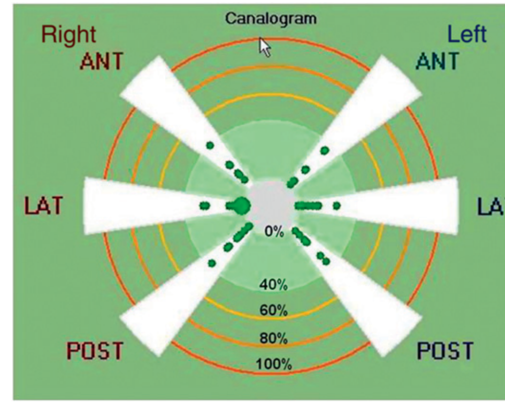

Figure 4. Representative canalogram for a normal participant. The semicircular canals (SCCs) are represented by the six white branches, and the concentric circles around the six branches represent different intervals for canal deficit (range = 0–100%). The canal deficit value obtained for each head impulse is represented by a solid green circle plotted on the canalogram. The central light-green shaded area represents the manufacturer's normal range for canal deficit (0–40%). ANT = anterior SCC; LAT = lateral (horizontal) SCC; POST = posterior SCC.

shifts with the head in the direction of the head impulse) indicated impaired function in the SCC toward which the head was rotated. The canal deficit for each subject was calculated as the mean of the six accepted head impulses for each of the six SCCs. Each subject returned for repeat testing within 1 to 14 days of the first session to assess test-retest reliability.

Data Analysis

A three-way repeated measures analysis of variance (RMANOVA) was conducted to assess the effect of ear (right versus left), session (session 1 versus session 2), and SCC (horizontal, anterior, posterior) on canal deficit (D%). The degrees of freedom for main effects were corrected using Greenhouse-Geisser estimates of sphericity whenever Mauchly's test indicated that the assumption of sphericity had been violated. Post hoc tests consisted of paired comparisons, and the p-values were adjusted using the Bonferroni procedure to correct for experiment-wise error. The difference between the mean canal deficit for session 1 and session 2 for each SCC was assessed using the paired-sample *t*-test. We considered p-values <0.05 as significant. SPSS statistical software (Version 14.0, SPSS Inc., Chicago, IL) was used for all analyses.

This study was approved by the institutional review board at East Tennessee State University/Mountain Home VAMC, and all participants signed an informed consent form prior to participation in the study. The study participants were given nominal payment for their time.

RESULTS

The SYNAPSYS software displays the results of the vHIT via a canalogram, and Figure 4 shows a representative canalogram for a normal participant. In the canalogram, the SCCs are represented by the six white branches, and the concentric circles around the six branches represent different intervals for canal deficit (%). The canal deficit value obtained for each head impulse is represented by a solid green circle that is plotted in real time within the branch of the canalogram that corresponds to the stimulated SCC. The central light-green shaded area represents the manufacturer's suggested normal range for canal deficit (0–40%), and the results obtained for the normal participant in Figure 4 indicate that each value of canal deficit for each SCC was within the normal range.

The means and standard deviations for canal deficit for session 1 and session 2 are shown for each SCC in Figure 5. The red bars represent the data obtained in session 1, and the green bars represent the data obtained in session 2. In general, the mean canal deficits obtained for each SCC were similar for sessions 1 and 2 and for the right and left ears. The mean canal deficits obtained for the horizontal canals were smaller than the mean canal deficits for the two vertical canals, and the mean canal deficits for the two vertical canals were similar. The magnitude of the standard deviation for each SCC appears to be similar both within and between sessions. The descriptive statistics for canal deficit are listed in Table 1. For comparison, the results of the only published study using the SYNAPSYS vHIT device (Ulmer et al, 2011) are also included in the bottom row of Table 1.

The RMANOVA indicated that the main effect of SCC on canal deficit was significant ($F_{(2,\ 58)} = 98.7$, $p = .0001$), and post hoc paired comparisons revealed

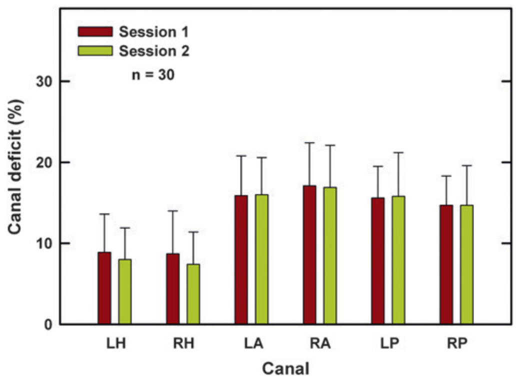

Figure 5. Means and standard deviations for canal deficit (%) for sessions 1 and 2 for each semicircular canal. The red bars represent the mean data obtained in session 1, and the green bars represent the mean data obtained in session 2. Error bars indicate 1 standard deviation. L = left; R = right; H = horizontal canal; A = anterior canal; P = posterior canal.

that the mean canal deficit of the horizontal canals (8.3%) was significantly lower than the mean canal deficit of the anterior (16.5%) and the posterior (15.2%) canals ($p = .0001$); there was no significant difference between the mean canal deficits of the anterior and posterior canals ($p = .073$). The main effects of session (session 1 versus session 2) and ear (right versus left) on canal deficit were not significant ($p \geq .542$); there were no significant interaction effects among canal, session, and ear ($p \geq .198$).

Figure 6 shows bivariate plots of the canal deficits obtained from each ear in session 1 as a function of the canal deficits obtained from each ear in session 2 for the horizontal canals (top panel), the anterior canals (middle panel), and the posterior canals (bottom panel). The diagonal line within each panel is the line of equality. For the paired-sample *t*-test, the data for the left and right ears for each SCC were pooled as the RMANOVA indicated no significant effect of ear on canal deficit. The results of the paired-sample *t*-tests are shown in the upper-left portion of each panel in Figure 6 and indicated no significant difference between the mean canal deficit for session 1 and session 2 for the horizontal ($t_{(59)} = 1.64$, $p = .107$), anterior ($t_{(59)} = .08$, $p = .937$), and posterior SCCs ($t_{(59)} = -.17$, $p = .862$).

DISCUSSION

The purpose of this study was to obtain normative data and assess the test-retest reliability of the SYNAPSYS vHIT (version 2.0) in young healthy adult participants. The mean canal deficit for the horizontal canal (8.3%) was significantly lower than the mean canal deficit of either the anterior canal (16.5%) or the posterior canals (15.2%); there was no significant difference between the mean canal deficits of the anterior and posterior canals. The larger canal deficits obtained for the vertical canals may be related to a number of factors including the smaller amplitude of eye movement in the vertical plane than in the horizontal plane, the camera's smaller field of vision in the vertical plane (3.8°) than in the horizontal plane (7.1°), and the smaller number of pixels in the vertical plane than in the horizontal plane (i.e., camera resolution is poorer by a factor of 1.57 in the vertical plane). There was no significant difference between the mean canal deficit for session 1 and session 2 for each SCC, suggesting good test-retest reliability. Testing of all six SCCs was completed in most participants in ~10 min and was well tolerated in this sample of young adults.

The mean canal deficits obtained in the present study were nearly identical to those of Ulmer et al (2011) (see Table 1), although the standard deviations for the current study are smaller than those obtained by Ulmer and colleagues, especially for the vertical canals. One possible source of the increased variability in canal deficit reported by Ulmer et al (2011) may be their older participant sample; the mean age of the participants in the current study was 23.5 yr (n = 30; range = 18–30 yr) compared to a mean age of 40 yr (n = 49; range = 21–64 yr) in the Ulmer et al (2011) study. Although Ulmer and colleagues did not report a statistically significant effect of age on canal deficit, they did observe a trend for larger canal deficits for older participants (>60 yr of age) compared to younger participants (<25 yr of age).

Table 1. Mean ±SD (95% CI for mean) for Canal Deficit (%) for Session 1 (S1) and Session 2 (S2) of the Current Study and the Mean ±SD for Ulmer et al (2011)

Canal	Horizontal		Anterior		Posterior	
Ear	Left	Right	Left	Right	Left	Right
S1	8.9 ± 4.7 (7.1–10.7)	8.7 ± 5.3 (6.7–10.7)	15.9 ± 4.9 (14.1–17.8)	17.1 ± 5.3 (15.1–19.0)	15.6 ± 4.0 (14.2–17.1)	14.7 ± 3.6 (13.3–16.0)
S2	8.0 ± 3.9 (6.6–9.5)	7.5 ± 4.0 (5.9–8.9)	16.0 ± 4.6 (14.3–17.7)	16.9 ± 5.2 (14.9–18.8)	15.8 ± 5.4 (13.8–17.9)	14.7 ± 4.9 (12.9–16.6)
Ulmer et al (2011)	8.4 ± 7.4	7.8 ± 6.8	16.3 ± 10.7	16.3 ± 10.7	16.0 ± 10.7	16.4 ± 10.6

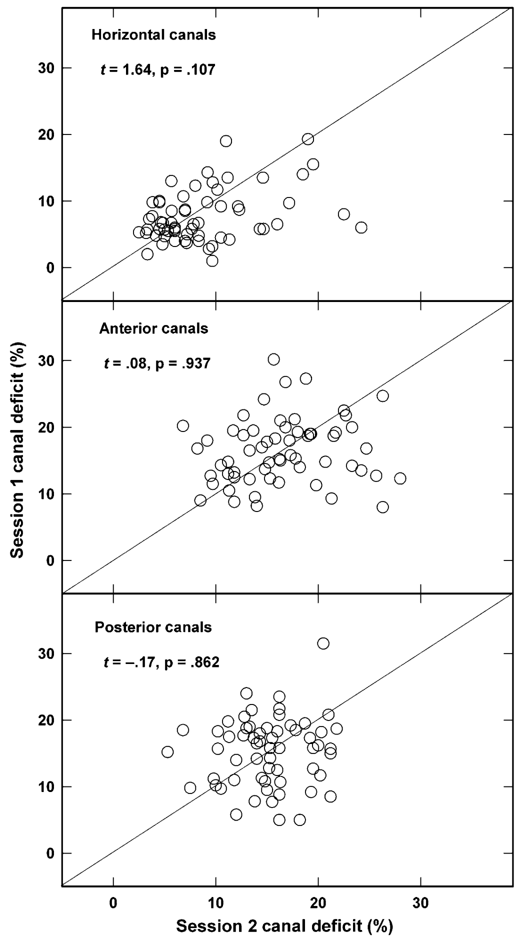

Figure 6. Bivariate scatterplots of the canal deficits from each ear obtained in session 1 as a function of the canal deficits obtained from each ear in session 2 for the horizontal canals (top panel), the anterior canals (middle panel), and the posterior canals (bottom panel). The diagonal line in each panel is the line of equality. The results of the paired-sample *t*-tests comparing the difference between the mean canal deficit for session 1 and session 2 are shown in the upper-left portion of each panel.

Presently, the manufacturer recommends a single normal cutoff value (40%) for canal deficit for the horizontal and vertical canals. The 40% cutoff value is based on the clinical experience of Dr. Erik Ulmer (Stéphane Curcio, SYNAPSYS, pers. comm., March 11, 2013). The results of the current study, however, suggest that the use of a lower normal cutoff value may be warranted, at least for young adults. It is common practice for the upper bound of a normal reference range to be set at two standard deviations above the mean, which approximates the 95th percentile of the normal distribution (e.g., Kirkwood and Sterne, 2003). The 95th percentiles for canal deficit (collapsed across ear and session) obtained in the current study were 19, 26, and 22% for the horizontal, anterior, and posterior SCCs, respectively. In comparison, the 95th percentiles for canal deficit (averaged across ears) obtained by Ulmer et al (2011) were 20% for the horizontal canals and 34% for both the anterior and posterior canals. The lower 95th percentiles for the vertical canal deficits obtained in the current study are due to the smaller standard deviations (half the magnitude of those obtained by Ulmer et al, 2011), which, as noted above, may be related to our younger participant sample. The only published patient data using the SYNAPSYS vHIT device were obtained from 10 patients following surgical removal of a unilateral vestibular schwannoma, and the average canal deficits were 97, 89, and 92% for the horizontal, anterior, and posterior canals, respectively (Ulmer et al, 2011).

The vHIT has several advantages over the bedside head impulse test (HIT) first described by Halmagyi and Curthoys (1988). The bedside HIT is a subjective test, and there is no objective measure of the eye movement response; the outcome of the bedside HIT is based on the clinician's subjective visual observation of the presence or absence of overt saccades (large fast changes in eye position also referred to as corrective or catch-up saccades) that occur at the *cessation* of head rotation. If the corrective saccades occur *during* the head rotation, then it is likely that they will not be observed by the clinician (covert saccades) and thereby increase the likelihood of a false-negative result (Weber et al, 2008, 2009). In contrast to the bedside HIT, the vHIT records eye movement and, depending on the device, provides objective measures of either gaze deviation (Ulmer and Chays, 2005; Ulmer et al, 2011) or VOR gain (Bartl et al, 2009; MacDougall et al, 2009; Weber et al, 2009; Blödow et al, 2013; Pérez-Fernández et al, 2012). Importantly, at least two vHIT devices also detect and record both covert and overt saccades (MacDougall et al, 2009; Weber et al, 2009; Blödow et al, 2013; Pérez-Fernández et al, 2012). The false-negative rate of the bedside HIT in patients with peripheral vestibular disorders has recently been estimated at 14% based on the rate of occurrence of isolated covert saccades detected with the vHIT (Blödow et al, 2013). Similarly, a disassociation between the outcomes of the horizontal vHIT and the bedside HIT was observed in 32% of patients with peripheral vestibular disorders (Pérez-Fernández et al, 2012). The most frequently occurring disassociation was the finding of a normal bedside HIT in combination with normal VOR gain and the presence of covert saccades on the vHIT. These results underscore the importance of recording corrective saccades and of considering the presence/absence of corrective saccades, in addition to VOR gain or gaze deviation, in the determination of the outcome of the vHIT. Although the vHIT software version (2.0) used in the present study did not have the capability of recording covert saccades, the current version (SYNAPSYS vHIT Evolution) provides a recording of both the angular head position and the angular gaze deviation during the head impulse and, therefore, is able to record covert saccades (Stéphane Curcio, SYNAPSYS, pers. comm., March 11, 2013).

Currently, it is not clear how the vHIT will be incorporated in the vestibular test battery. The two most widely used clinical laboratory tests of vestibular function are the caloric test and the rotary chair test. The main advantage of the caloric test is the ability to lateralize a vestibular deficit by stimulating each ear independently, and it is generally considered the gold standard test of horizontal SCC function, especially for the identification of unilateral vestibular losses (e.g., Herdman et al, 1998). The caloric test, however, is limited to the assessment of the horizontal SCCs and generates an extremely low-acceleration, low-frequency (~0.003 Hz) stimulus that is well below the optimal operating range of the sensory receptors of the SCCs (Hamid et al, 1987; Minor et al, 1999). Similar to the caloric test, the rotary chair test is limited to the assessment of horizontal SCC function. Although the VOR response can be measured over a wider frequency range for the rotary chair test (sinusoidal harmonic acceleration test) than the caloric test, the frequencies of natural head rotations largely exceed the frequencies typically used for the rotary chair test (0.01 to 0.64 Hz). For example, the fundamental frequencies of rotational head perturbations during locomotion are in the range of 0.5 to 6.0 Hz with significant harmonics up to 20 Hz (Grossman et al, 1988). An additional major limitation of the rotary chair test is that it frequently fails to lateralize a unilateral vestibular loss since both labyrinths are stimulated simultaneously. Although the test can show asymmetries toward the side of lesion in some patients with acute (uncompensated) unilateral vestibular losses (Hamid, 1991), it usually provides no evidence of the side of lesion in patients with chronic (compensated) unilateral vestibular losses (Barin, 2008).

In contrast to the caloric and rotary chair tests, the vHIT also evaluates the function of each vertical SCC and assesses the vestibular system using a stimulus that is more physiologically relevant and more representative of the head movements that occur during activities of daily living. Other important advantages of the vHIT relative to the caloric and rotary chair tests include lower cost, shorter test time, greater portability, minimal space requirements, and increased patient comfort. The bedside HIT, the horizontal vHIT, and the caloric test are all measures of horizontal SCC/SVN function, and each test can lateralize a unilateral vestibular loss. As the caloric test is considered the gold standard test of horizontal SCC function, especially for the identification of unilateral vestibular losses, it has been used as the reference standard to evaluate the performance of the HIT. The bedside HIT has been shown to have a sensitivity of 100% and specificity ranging from 97 to 100% in cases of vestibular nerve sections (Foster et al, 1994; Lehnen et al, 2004; Cremer et al, 1998; Halmagyi and Curthoys, 1988). In less severe cases of vestibular loss, however, the sensitivity and specificity are reduced with sensitivity ranging from 34 to 75% (average = 51%) and specificity ranging from 82 to 97% (average 91%) (Harvey and Wood, 1996; Harvey et al, 1997; Beynon et al, 1998; Pérez and Rama-Lopez, 2003; Schubert, et al, 2004).

Several recent studies have evaluated the test performance of the horizontal SCC vHIT using the caloric test as the reference test (Bartolomeo et al, 2014; Mahringer and Rambold, 2014; McCaslin et al, forthcoming). The false-positive rates (normal caloric response [UW <30% or UW <25%] and an abnormal vHIT) were low (0% and 1%). In contrast, the false negative findings (abnormal caloric [UW ≥30% or UW ≥25%] and a normal vHIT) were 31% and 59% (Bartolomeo et al, 2014; Mahringer and Rambold, 2014). Using receiver operating characteristic (ROC) curve analysis, the best compromise between optimizing both specificity and sensitivity of the vHIT was obtained at a unilateral caloric weakness of 52% (Bartolomeo et al, 2014) and 39.5% (McCaslin et al, forthcoming). The authors (Bartolomeo et al, 2014; Mahringer and Rambold, 2014) recommended a test protocol in which vHIT is performed first followed by caloric testing only for patients with normal vHIT findings. The use of this protocol in the two studies would have reduced the number of caloric tests by 13% and 20%. The results of these studies suggest that the inclusion of the vHIT in the vestibular assessment protocol and the performance of the vHIT prior to caloric testing will result in decreased test time, decreased costs, increased patient comfort, and a decrease in the overall testing burden imposed on a relatively substantial proportion of patients referred for vestibular assessment. Disassociations between the results of the caloric test and the vHIT may be due, at least in part, to the substantial difference between the acceleration/frequency profiles of the stimuli used to activate the horizontal SCC for each test. The results of the two tests, therefore, may provide complementary information concerning low-acceleration/low-frequency versus high-acceleration/high-frequency horizontal SCC function in some proportion of patients referred for vestibular assessment (Halmagyi et al, 1990; Prepageran et al, 2005; Kessler et al, 2008).

CONCLUSION

The mean canal deficits obtained from normal young adults with the SYNAPSYS vHIT (version 2.0) were 8.3, 16.5, and 15.2% for the horizontal, anterior, and posterior SCCs, respectively. Test-retest reliability was good, and the 95th percentiles for canal deficit were 19, 26, and 22% for the horizontal, anterior, and posterior SCCs, respectively. These percentiles can be used as normal cutoff values for young adults. The vHIT has some important advantages relative to more established laboratory tests of horizontal SCC function including the ability to assess the vertical SCCs, lower cost, shorter test time, greater portability, minimal space requirements, and increased patient comfort. Additional data, however, should be obtained from older participants with normal vestibular function and from patients with vestibular disorders. Additional within-subject comparisons between the results of the vHIT and the caloric and rotary chair tests will be important in determining the role of the vHIT in the vestibular test battery.

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REFERENCES

Baloh RW, Honrubia V, Konrad HR. (1977) Ewald's second law reevaluated. *Acta Otolaryngol* 83(5–6):475–479.

Barin K. (2008) Interpretation and usefulness of caloric testing. In: Jacobson GP, Shepard NT, eds. *Balance Function Assessment and Management*. San Diego: Plural Publishing, 229–252.

Bartl K, Lehnen N, Kohlbecher S, Schneider E. (2009) Head impulse testing using video-oculography. *Ann N Y Acad Sci* 1164:331–333.

Bartolomeo M, Biboulet R, Pierre G, Mondain M, Uziel A, Venail F. (2014) Value of the video head impulse test in assessing vestibular deficits following vestibular neuritis. *Eur Arch Otorhinolaryngol* 271(4):681–688.

Beynon GJ, Jani P, Baguley DM. (1998) A clinical evaluation of head impulse testing. *Clin Otolaryngol Allied Sci* 23(2):117–122.

Blödow A, Pannasch S, Walther LE. (2013) Detection of isolated covert saccades with the video head impulse test in peripheral vestibular disorders. *Auris Nasus Larynx* 40(4):348–351.

Böhmer A, Henn V, Suzuki JI. (1985) Vestibulo-ocular reflexes after selective plugging of the semicircular canals in the monkey—response plane determinations. *Brain Res* 326(2):291–298.

Cremer PD, Halmagyi GM, Aw ST, et al. (1998) Semicircular canal plane head impulses detect absent function of individual semicircular canals. *Brain* 121(Pt. 4):699–716.

Estes MS, Blanks RH, Markham CH. (1975) Physiologic characteristics of vestibular first-order canal neurons in the cat. I. Response plane determination and resting discharge characteristics. *J Neurophysiol* 38(5):1232–1249.

Ewald EJR. (1892) *Physiologische Untersuchungen üeber das Endorgan des Nervus octavus*. Wiesbaden: Bergmann.

Foster CA, Foster BD, Spindler J, Harris JP. (1994) Functional loss of the horizontal doll's eye reflex following unilateral vestibular lesions. *Laryngoscope* 104(4):473–478.

Goldberg JM, Fernandez C. (1971) Physiology of peripheral neurons innervating semicircular canals of the squirrel monkey. I. Resting discharge and response to constant angular accelerations. *J Neurophysiol* 34(4):635–660.

Grossman GE, Leigh RJ, Abel LA, Lanska DJ, Thurston SE. (1988) Frequency and velocity of rotational head perturbations during locomotion. *Exp Brain Res* 70(3):470–476.

Halmagyi GM, Curthoys IS. (1988) A clinical sign of canal paresis. *Arch Neurol* 45(7):737–739.

Halmagyi GM, Curthoys IS, Cremer PD, Henderson CJ, Todd MJ, Staples MJ, D'Cruz DM. (1990) The human horizontal vestibulo-ocular reflex in response to high-acceleration stimulation before and after unilateral vestibular neurectomy. *Exp Brain Res* 81: 479–490.

Hamid MA. (1991) Determining side of vestibular dysfunction with rotatory chair testing. *Otolaryngol Head Neck Surg* 105(1): 40–43.

Hamid MA, Hughes GB, Kinney SE. (1987) Criteria for diagnosing bilateral vestibular dysfunction. In: Graham MD, Kemink JL, eds. *The Vestibular System: Neurophysiologic and Clinical Research*. New York: Raven Press, 115–118.

Harvey SA, Wood DJ. (1996) The oculocephalic response in the evaluation of the dizzy patient. *Laryngoscope* 106(1, Pt. 1):6–9.

Harvey SA, Wood DJ, Feroah TR. (1997) Relationship of the head impulse test and head-shake nystagmus in reference to caloric testing. *Am J Otol* 18(2):207–213.

Herdman SJ, Tusa RJ, Blatt P, Suzuki A, Venuto PJ, Roberts D. (1998) Computerized dynamic visual acuity test in the assessment of vestibular deficits. *Am J Otol* 19(6):790–796.

Kessler P, Zarandy MM, Hajioff D, Tomlinson D, Ranalli P, Rutka J. (2008) The clinical utility of search coil horizontal vestibulo-ocular reflex testing. *Acta Otolaryngol* 128(1):29–37.

Kirkwood B, Sterne J. (2003) *Essentials of Medical Statistics*. Malden: Wiley-Blackwell.

Lehnen N, Aw ST, Todd MJ, Halmagyi GM. (2004) Head impulse test reveals residual semicircular canal function after vestibular neurectomy. *Neurology* 62(12):2294–2296.

MacDougall HG, Weber KP, McGarvie LA, Halmagyi GM, Curthoys IS. (2009) The video head impulse test: diagnostic accuracy in peripheral vestibulopathy. *Neurology* 73(14):1134–1141.

Mahringer A, Rambold HA. (2014) Caloric test and video-head-impulse: a study of vertigo/dizziness patients in a community hospital. *Eur Arch Otorhinolaryngol* 271(3):463–472.

McCaslin DL, Jacobson GP, Bennett ML, Gruenwald JM, Green AP. (Forthcoming) Predictive properties of the video head impulse test (vHIT): measures of caloric symmetry and self-report dizziness handicap. *Ear Hear*.

Minor LB, Lasker DM, Backous DD, Hullar TE. (1999) Horizontal vestibuloocular reflex evoked by high-acceleration rotations in the squirrel monkey. I. Normal responses. *J Neurophysiol* 82(3): 1254–1270.

Murnane OD, Akin FW, Lynn SG, Cyr DG. (2009) Monothermal caloric screening test performance: a relative operating characteristic curve analysis. *Ear Hear* 30(3):313–319.

Pérez N, Rama-Lopez J. (2003) Head-impulse and caloric tests in patients with dizziness. *Otol Neurotol* 24(6):913–917.

Pérez-Fernández N, Gallegos-Constantino V, Barona-Lleo L, Manrique-Huarte R. (2012) Clinical and video-assisted examination of the vestibulo-ocular reflex: a comparative study. *Acta Otorrinolaringol Esp* 63(6):429–435.

Prepageran N, Kisilevsky V, Tomlinson D, Ranalli P, Rutka J. (2005) Symptomatic high frequency/acceleration vestibular loss: consideration of a new clinical syndrome of vestibular dysfunction. *Acta Otolaryngol* 125(1):48–54.

Schubert MC, Tusa RJ, Grine LE, Herdman SJ. (2004) Optimizing the sensitivity of the head thrust test for identifying vestibular hypofunction. *Phys Ther* 84(2):151–158.

Ulmer E, Bernard-Demanze L, Lacour M. (2011) Statistical study of normal canal deficit variation range. Measurement using the Head Impulse Test video system. *Eur Ann Otorhinolaryngol Head Neck Dis* 128(5):278–282.

Ulmer E, Chays A. (2005) “Head Impulse test de Curthoys & Halmagyi”. Un dispositif d’analyse. [Curthoys and Halmagyi Head Impulse test: an analytical device.] *Ann Otolaryngol Chir Cervicofac* 122(2):84–90.

Weber KP, Aw ST, Todd MJ, McGarvie LA, Curthoys IS, Halmagyi GM. (2008) Head impulse test in unilateral vestibular loss: vestibulo-ocular reflex and catch-up saccades. *Neurology* 70(6):454–463.

Weber KP, MacDougall HG, Halmagyi GM, Curthoys IS. (2009) Impulsive testing of semicircular-canal function using video-oculography. *Ann N Y Acad Sci* 1164:486–491.