Journal of Otology 19 (2024) 5–9

Contents lists available at ScienceDirect

Journal of Otology

journal homepage: www.journals.elsevier.com/journal-of-otology/

Comparative utility of vestibular function tests in patients with peripheral and central vestibular dysfunction

Cameron B. Fattahi[a,b], Christopher Zaro[a], Janice J. Chung[c], Richard F. Lewis[b,c,d], Divya A. Chari[a,b,c,*]

[a] *Department of Otolaryngology – Head and Neck Surgery, UMASS Memorial Medical Center, University of Massachusetts Chan Medical School, Worcester, MA, USA*
[b] *Jenks Vestibular Physiology Laboratory, Massachusetts Eye and Ear, Boston, MA, USA*
[c] *Department of Otolaryngology – Head and Neck Surgery, Massachusetts Eye and Ear, Harvard Medical School, Boston, MA, USA*
[d] *Department of Neurology, Harvard Medical School, Boston, MA, USA*

A B S T R A C T

Background: Bithermal caloric irrigation, video head impulse test (vHIT), and rotational testing are commonly used to assess peripheral vestibular function, but the relative clinical utility of each test in differentiating patients with peripheral vestibulopathy is debated.
Objectives: To determine whether (1) the combination of two or more vestibular tests enhances diagnostic utility over a single test; (2) abnormal test results on vestibular tests correlate with one another.
Methods: Retrospective analysis of data collected from multidisciplinary vestibular clinics at two academic medical centers from 2016 to 2022.
Results: 150 patients (54.10 ± 15.09 years, 88 females) were included. No individual test was significantly better at predicting the presence of peripheral vestibular damage ($p > 0.05$). vHIT test results improved significantly when combined with either the caloric test ($p = 0.007$) or rotary chair test ($p = 0.039$). Caloric and rotational testing had high sensitivity (74.65% and 76.06%, respectively) and specificity (83.54% and 78.48%, respectively). vHIT demonstrated excellent specificity (89.87%) but poor sensitivity (47.89%). Caloric, vHIT, and rotary chair tests results did not correlate with one another ($p > 0.05$).
Conclusions: Vestibular function tests have comparable diagnostic utility, yet each offers unique advantages. Caloric and rotational testing may be best suited for screening peripheral damage and vHIT may function ideally as a confirmatory test.

1. Introduction

Dizziness and imbalance affect almost 20% of adults and are major contributors to patient discomfort and disability (Agrawal et al., 2009). The diagnostic workup of dizzy symptoms relies on a combination of factors, including clinical history and physical examination (Sorathia et al., 2018). Vestibular testing has been used in the diagnostic process to determine whether the peripheral vestibular system is damaged. A complete vestibular test battery consists of an assessment of all five vestibular end organs of the inner ear – three semicircular canals that transduce angular acceleration and two otolith organs (utricle and saccule) that transduce linear acceleration. However, no single vestibular test can assess the entire labyrinth. Of all vestibular organs, the horizontal semicircular canal is the most amenable to evaluation because its function can be measured by three different vestibular tests: bithermal caloric irrigation, video head impulse test (vHIT), and rotational testing (Piker et al., 2016). Debate remains, however, over which of these tests is optimal due to conflicting test results and variability in test methodology. As a result, regional and institutional preferences often predominate (Adams et al., 2017, 2020).

The bithermal caloric test has been considered the gold standard technique for assessing vestibular function for the greater part of the 20th century (Bhansali and Honrubia 1999; Morrison et al., 2022). The widespread popularity of this test may be attributed to its reproducibility and relatively low cost of administration (van de Berg et al., 2018; Bush et al., 2013). However, this is a non-physiologic test as it provides an artificial, thermal-based low-frequency stimulus of approximately 0.003 Hz to stimulate the horizontal semicircular canal, well below the physiologic vestibular response range of 1.0–6.0 Hz (Shepard and Jacobson, 2016). In addition, caloric testing primarily assesses asymmetry between ears and is poor at assessing response amplitude, thus it may be within normal limits in the presence of relatively symmetric

Peer review under responsibility of PLA General Hospital Department of Otolaryngology Head and Neck Surgery.
* Corresponding author. Department of Otolaryngology – Head and Neck Surgery Massachusetts Eye and Ear Harvard Medical School, 243 Charles Street, Boston, MA, 02114, USA.
E-mail addresses: cameron.fattahi@umassmed.edu (C.B. Fattahi), chistopher.zaro@umassmed.edu (C. Zaro), janice_chung@hms.harvard.edu (J.J. Chung), divya_chari@meei.harvard.edu (D.A. Chari).

https://doi.org/10.1016/j.joto.2023.10.002
Received 15 August 2023; Accepted 31 October 2023
Available online 3 November 2023

bilateral vestibular damage.

In contrast to the caloric test, rotational testing and vHIT use physiologic stimuli to quantitatively assess the vestibulo-ocular (VOR) reflex of the semicircular canals, and vHIT can also assess the VOR produced by stimulation of each of the four vertical canals. Rotational testing uses a computer-controlled rotary stimulus of the head and body and employs low-frequency sinusoidal (typically 0.01–1.0 Hz) rotations or velocity steps (Wall, 1990). vHIT is performed by an examiner who rotates the patient's head on the body in the three canal planes and utilizes higher frequency motions, typically up to 5 Hz (Alhabib and Saliba, 2017). Limitations of rotational testing include the inability to assess each ear independently, expensive machinery, and its time consuming nature compared to the other vestibular tests (Zuniga and Adams, 2021). The main disadvantage of vHIT is that it requires an experienced operator as low head accelerations, large head overshoots, or extended excursion angles of head movement can lead to inaccurate results (Halmagyi et al., 2017). Furthermore, vHIT does not isolate vestibular afference like rotational testing because the motion of the head on the body activates cervico-ocular reflex responses, which are small in normal subjects but increase in magnitude in patients with vestibular damage.

This study was designed to investigate the comparative utility of caloric, vHIT, and rotational testing in differentiating between patients who had independent evidence supporting a diagnosis of peripheral vestibular damage and those patients with central vestibular dysfunction. We aimed to address the following questions:

1) Determine the sensitivity and specificity of individual vestibular tests in differentiating patients with peripheral and central vestibular dysfunction
2) Does the combination of two or more vestibular tests enhance diagnostic utility over a single test?
3) Is an abnormal test result on one vestibular test associated with an abnormal test result on other vestibular tests?

2. Materials and methods

2.1. Patient selection

A retrospective chart review was performed to identify patients presenting with dizziness, vertigo, and/or imbalance to multidisciplinary vestibular clinics at two academic tertiary care centers between January 1, 2016 and December 31, 2022. All patients had undergone a comprehensive otological and neurological examination. Only patients who had undergone a full vestibular test battery performed by a licensed audiologist or vestibular technician, including videonystagmography with bithermal caloric irrigation, video head impulse testing, and rotary chair testing, were included for study analysis. Patients with visual impairment, or an isolated diagnosis of benign paroxysmal positional vertigo or superior canal dehiscence were excluded since horizontal semicircular canal function is not commonly impaired in these conditions.

To obtain a "gold standard" clinical diagnosis, medical records of all patients were examined, including the clinical history, physical examination, audiologic evaluation, and radiologic studies. Using this information, patients were categorized as having or not having unilateral peripheral vestibular damage. Patients were classified as "peripheral vestibulopathy" if they: 1) demonstrated abnormal head thrust test or head-shaking nystagmus on clinical examination or spontaneous horizontal nystagmus, 2) met clinical diagnostic criteria for Meniere's disease, vestibular neuritis, or labyrinthitis, or 3) demonstrated evidence of a tumor affecting the vestibular nerve (e.g., vestibular schwannoma) on radiologic imaging. Patients were classified as "central" if they demonstrated no evidence of labyrinthine vestibular dysfunction on history or physical exam. Demographics, clinical characteristics, and diagnoses are summarized in Table 1.

Table 1
Demographic information for subjects.

Demographics	Peripheral Group (n = 71)	Central Group (n = 79)
Age (Mean ± SD), years	60.94 ± 10.87	48.90 ± 15.82
Gender (Female), n (%)	35 (49.30)	53 (67.09)
Cause of dizziness, n (%)	Vestibular neuritis, 36 (50.70)	Vestibular migraine, 51 (64.56)
	Meniere's disease, 22 (30.99)	[a]Central vestibular lesion, 12 (15.19)
	Labyrinthitis, 7 (9.86)	Persistent postural-perceptual dizziness, 9 (11.39)
	Vestibular schwannoma, 4 (5.63)	Mal de debarquement, 3 (3.80)
	Medication ototoxicity, 2 (2.82)	Traumatic brain injury/post-concussive syndrome, 4 (5.06)

[a] "Central vestibular lesion" includes malignant, ischemic, and/or inflammatory lesions of the brain (e.g., stroke, multiple sclerosis) leading to dizziness, vertigo, and/or imbalance.

2.2. Vestibular testing

Vestibular testing included vestibulo-ocular reflex (VOR) assessments of lateral semicircular canal function using caloric stimulation, impulsive head-on-body (vHIT) rotations, and sinusoidal en-bloc rotations (i.e., rotary chair).

2.2.1. Caloric stimulation

Caloric testing was performed as part of the standard videonystamogram (Neuro Kinetics, Inc., Pittsburg, PA and Interacoustics, Middelfart, Denmark). Standard bithermal irrigations of 30 °C and 44 °C were performed in the right and left ears. Caloric relative vestibular reduction (RVR) was calculated using the Jongkee's Index formula (Furman and Jacob, 1993). Since we were not concerned with the specific side of the unilateral vestibular impairment, we took the absolute value of the RVR to be the value used in statistical analysis. Abnormal results were defined as an RVR greater than or equal to 26%, based upon established clinical values in our laboratory.

2.2.2. Rotary stimulation

Sinusoidal earth-vertical rotational testing (Neuro Kinetics, Inc., Pittsburg, PA and Interacoustics, Middelfart, Denmark) was performed in the dark. Patients underwent yaw-axis rotations across the 0.01–1.0 Hz frequency range, with a peak velocity of 40 deg/s. From these data, the gain, time, and bias constants were calculated for each subject, using an approach previously described.[11] An age-adjusted time constant (TC) value of less than 12.7 s corresponds to peripheral vestibular damage, with a p value of 0.05, based on established clinical benchmarks in our laboratory (Dimitri et al., 1996).

2.2.3. Video head impulse testing (vHIT)

The video head impulse test (vHIT) was administered using an ICS Impulse 3-Dimensional vHIT unit (GN Otometrics, Taastrup, Denmark). Subjects wore tight-fitting videonystagmography goggles equipped with a high velocity camera and were seated 1-m from a fixation target mounted at eye level on the wall. Calibration was achieved via laser dots. The examiner delivered randomized (timing and direction) head impulses (100–250°/s peak head velocity) in the plane of the semicircular canals until approximately 10 acceptable head impulses were recorded from each semicircular canal. VOR gain was calculated with OTOsuite software (GN Otometrics, Taastrup, Denmark). Abnormal results were defined as a lateral canal VOR gain less than 0.7, based upon previously established clinical cutoffs (Alfarghal et al., 2022).

2.3. Statistical analysis

Statistical analysis was performed using R statistical software (Version, 2022.12.0, R Foundation for Statistical Computing, Vienna, Austria). Receiver operating characteristic (ROC) curves were calculated for each test parameter: absolute value of caloric RVR, vHIT VOR gain of the lateral canal, and rotary chair TC. Multinomial logistic regression analysis was then performed between combinations of individual test parameters, and an ROC curve was fit for each parameter combination. The area under the ROC curve (AUC) was compared across parameters using Delong's test. The sensitivity, specificity, positive predictive value (PPV), and negative predictive value (NPV) were also calculated for each individual test based upon the established clinical metrics. To compare consistency across vestibular tests, we implemented a Fisher's Exact test. Abnormal results from caloric RVR, vHIT gain, and rotary chair TC were compared in the peripheral and central vestibular dysfunction groups. The false discovery rate method was used to adjust all *p*-values. Statistical significance was defined as $p < 0.05$.

3. Results

3.1. Demographic data

A total of 150 subjects met inclusion criteria. Table 1 describes the demographic characteristics of subjects according to their clinical classification into groups with and without evidence of peripheral vestibular damage. The mean age for the entire cohort was 54.10 years with a range of 13–84. The mean ages of patients in the peripheral and central vestibular dysfunction groups were 60.94 ± 10.87 years and 48.90 ± 15.82 years, respectively. A total of 88 (58.67%) females were included in the analysis, with 35 (49.30%) in the peripheral vestibulopathy group and 53 (67.09%) in the central vestibular dysfunction group. The most common causes of dizziness in the peripheral vestibulopathy group (n = 71) were vestibular neuritis (50.70%) followed by definite Meniere's disease (30.99%). In the central vestibular dysfunction group (n = 79), vestibular migraine patients comprised the largest cohort (64.56%) followed by central lesions causing dizziness, vertigo, and/or imbalance (15.19%).

The ROC curves for all test parameters are shown in Fig. 1. AUC values corresponding to each ROC parameter are listed in Table 2. The

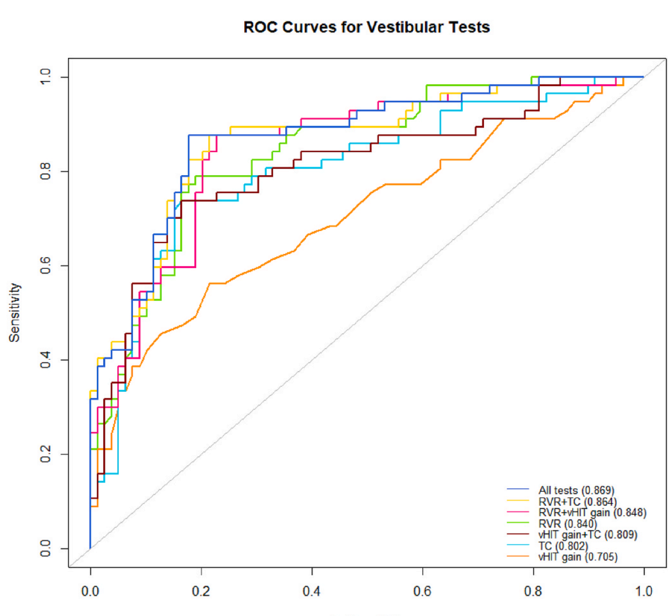

Fig. 1. Receiver operating characteristic curves for vestibular tests in isolation and in combination.

Table 2
Area under the receiver operating characteristic curve (AUC) for vestibular tests in isolation and in combination.

	AUC	Confidence Interval (95%)
All tests	0.869	0.808–0.931
RVR + TC	0.864	0.773–0.907
RVR + vHIT gain	0.848	0.782–0.915
RVR	0.840	0.773–0.907
VHIT gain + TC	0.809	0.731–0.886
TC	0.802	0.724–0.880
VHIT gain	0.704	0.612–0.795

best overall single predictive parameter based on AUC was the caloric test (AUC 0.840, 95% confidence interval [CI] 0.773–0.907), while vHIT gain had the lowest AUC of any single test (AUC 0.704, 95% CI 0.612–0.795). The nonparametric Delong's test was used to compare the AUC of ROC curves from individual tests and combinations of test batteries (Table 3). AUC values were not significantly different among the three tests; thus, no individual test was significantly better at predicting the presence or absence of peripheral vestibular damage compared to other tests. However, vHIT test results improved significantly when the vHIT test was combined with either the caloric test (AUC 0.704 vs 0.848, $p = 0.007$) or the rotary chair test (AUC 0.704 vs 0.809, $p = 0.039$). The combination of the rotary chair and caloric tests had significantly greater predictive power compared to the rotary chair test alone (AUC 0.840 vs 0.864, $p = 0.039$). The combined predictive power of all three tests was greater than either the vHIT in isolation (AUC 0.704 vs 0.869, $p = 0.006$).

The sensitivity, specificity, PPV, and NPV for each test based upon established clinical cutoffs are shown in Table 4. Caloric testing had the highest sensitivity (74.65%) of any single test. vHIT testing had the highest specificity of any single test (89.87%) but had relatively poor sensitivity (47.89%). Rotary chair testing demonstrated relatively equivalent sensitivity to caloric testing (76.06%) but lower specificity

Table 3
Results of Delong's test for difference in area under the receiver operating characteristic curve (AUC) between vestibular tests.

	AUC of Baseline Test	AUC of Comparison Test	Difference in AUC	*P* Value * ($\alpha < 0.05$)
RVR vs vHIT gain	0.840	0.704	0.136	0.039*
RVR vs TC	0.840	0.802	0.038	0.524
RVR vs RVR + vHIT gain	0.840	0.848	−0.008	0.702
RVR vs RVR + TC	0.840	0.864	−0.024	0.505
RVR vs vHIT gain + TC	0.840	0.809	0.031	0.579
RVR vs All tests	0.840	0.869	−0.029	0.447
TC vs RVR + TC	0.802	0.864	−0.062	0.039*
TC vs RVR + vHIT gain	0.802	0.848	−0.046	0.447
TC vs vHIT gain + TC	0.802	0.809	−0.007	0.713
TC vs All tests	0.802	0.869	−0.067	0.059
VHIT gain vs TC	0.704	0.802	−0.097	0.150
VHIT gain vs RVR + TC	0.704	0.864	−0.159	0.012*
VHIT gain vs RVR + vHIT gain	0.704	0.848	−0.143	0.007*
VHIT gain vs vHIT + TC	0.704	0.809	−0.104	0.039*
VHIT gain vs All tests	0.704	0.869	−0.164	0.006*

Table 4
Sensitivity, specificity, positive predictive value, and negative predictive value for vestibular tests.

	Sensitivity (%)	Specificity (%)	PPV (%)	NPV (%)
RVR	74.65	83.54	80.30	78.57
TC	76.06	78.48	76.06	78.48
vHIT Gain	47.89	89.87	80.95	65.74
All tests	33.80	98.73	96.00	62.40

(78.48% compared to 83.54%).

To determine whether the vestibular test battery demonstrated consistent results across the three tests compared to clinical assessments, a Fisher's Exact test was used. Discordancy rates were high in both the peripheral and central vestibular dysfunction groups (Table 5). Overall, for both the peripheral and central vestibular dysfunction groups, there are no statistically significant associations in caloric, vHIT, and rotary chair tests ($p > 0.05$).

4. Discussion

Our primary finding is that caloric, vHIT, and rotational testing demonstrate similar clinical utility in detecting peripheral vestibulopathy. Although the caloric test had the highest absolute AUC value indicating that it is the single best predictive parameter, it was not found to be significantly better than either vHIT or rotational testing. In our dataset, vHIT performed in combination with either caloric or rotation testing appeared to have greater clinical utility compared to vHIT alone. Similarly, the combination of rotational testing and caloric testing increased the diagnostic yield compared to rotational testing alone. Our study findings suggest that while no single functional assessment of the horizontal semicircular canal is significantly more useful compared to another vestibular test, there may be clinical circumstances in which the combination of two or more tests may enhance the overall clinical diagnostic utility of vestibular function tests.

Our study extends prior observations that vestibular tests provide complementary information and should be used in conjunction with one another to maximize clinical utility (Eza-Nuñez, et al., 2016; Vallim et al., 2021; Ahmed et al., 2009; Maes et al., 2011). Consistent with prior studies, our results suggest that the correlation among vestibular tests is relatively poor – that is, an abnormal result indicative of peripheral vestibular damage on one vestibular test is not significantly associated with abnormal results on other tests (Eza-Nuñez et al., 2016; Priesol et al., 2015; Zellhuber et al., 2014; Mahringer and Rambold 2014). Notably, in our study population, approximately 30% of patients within the peripheral vestibulopathy group were diagnosed with Meniere's disease. A well-known dissociation exists between caloric and vHIT results in patients with Meniere's disease: caloric testing is more likely to be abnormal, particularly in patients with end-stage Meniere's disease, while vHIT of the horizontal semicircular canal remains in the normal range in the majority of patients with Meniere's disease (Leng and Liu 2020; McGarvie et al., 2015; Maire and van Melle 2008; Hannigan et al., 2021). The mechanism for this dissociation is not well understood, but one hypothesis suggests that pathologic herniation of vestibular structures into the horizontal semicircular canal may lead to diminished caloric responses (Shen, et al., 2023). Regardless of the underlying etiology of this phenomenon, the large portion of patients with Meniere's disease in our study may partly account for the weak association among test modalities.

The current study is different from several previous studies which were limited by small sample sizes and based on predetermined normative cutoff criteria (Eza-Nuñez et al., 2016; Maes et al., 2011; Arriaga et al., 2005). In the present study, ROC curves for individual parameters and combinations of tests yielded the AUC-ROC which were statistically compared to determine which tests or combinations demonstrated greater clinical utility. AUC was used as a predictive parameter of diagnostic potential, unconstrained by predetermined cutoff values that differentiate normal from abnormal results. To standardize our findings, we also calculated sensitivity and specificity of each test using standard cutoff values (caloric RVR >26%, vHIT VOR gain <0.8, rotatory chair TC < 12.7 s) (Priesol et al., 2015). Based on these predetermined values, our results suggest that caloric and rotational testing demonstrate similarly high levels of sensitivity and specificity (caloric testing: 74.7% and 83.5%; rotational testing: 76.1% and 78.5%, respectively). In contrast, however, vHIT demonstrated excellent specificity (89.9%) but poor sensitivity (47.9%). Taken together, these results suggest that vHIT may underperform when used as a first-line screening tool.

Our study also highlights important differences in the function of each vestibular test. Although caloric, rotational, and lateral semicircular canal vHIT testing are all designed to assess the same vestibular end-organs, the range of stimulation frequencies vary widely. It is perhaps not surprising, therefore, that these tests produce discordant results across an entire study population. Given unlimited time and resources, it may be beneficial to perform all three tests in patients. Unfortunately, vestibular function testing, notably rotational testing, can be rather costly and remains inaccessible to many patients (Adams et al., 2020). Based on our study findings, caloric and rotational testing are likely to be useful as a first-line screening assessment for peripheral vestibular damage. As vHIT has been shown to have superior specificity at established clinical cutoffs, we propose that it be used as a confirmatory test rather than as a standalone test.

There are several limitations to our study. Due to the retrospective nature of the study, we were limited to chart documentation for clinical history, physical examination, and diagnosis, which may not accurately or completely reflect the full range of clinical findings. No longitudinal data were obtained and thus, this study represents a cross-sectional analysis of data collected at a given time. Although the gold standard clinical diagnosis was made based on history and physical examination findings (not vestibular test results), imaging and audiograms, it is possible that the clinical documentation was inherently biased and may have included knowledge of vestibular test results. This study consists of data compiled from two large academic medical centers with some minor differences in vestibular test equipment and protocols, though it may be argued that this represents a strength of the study as it contributes to generalizability of our study findings. Finally, this study represents a review of vestibular function testing of the horizontal semicircular canal. Many of the patients included in the study also underwent vestibular testing of other vestibular end-organs (e.g., assessment of vertical semicircular canals with vHIT and/or otolith organs with cervical or ocular vestibular evoked myogenic potentials). Results from these tests were not included or analyzed in the present study.

Table 5
Results of Fisher's exact test for vestibular tests, sorted by group.

		P Value (α < 0.05)
Central Group (n = 79)	RVR vs vHIT gain	1.000
	RVR vs TC	1.000
	vHIT gain vs TC	1.000
Peripheral Group (n = 71)	RVR vs vHIT gain	0.773
	RVR vs TC	0.488
	vHIT gain vs TC	0.437

5. Conclusion

The diagnostic evaluation of a patients with suspected peripheral vestibular disorders can be challenging and vestibular function testing may be a useful adjunct. Our results suggest that caloric testing, rotational testing, and vHIT have comparable clinical utility. Based on our study results, caloric and rotational testing may be effective screening tools, while vHIT, with a high specificity, serves as an excellent confirmatory assessment. Future research avenues may include cost-benefit analyses of these vestibular tests to guide patient care more accurately.

Declaration of Competing interest

The authors have no conflicts of interest to disclose.

Acknowledgements

We would like to thank Yan Zhao for her gracious support with and contributions to the statistical analysis used in this study.

References

Adams, M.E., Marmor, S., Yueh, B., Kane, R.L., 2017. Geographic variation in use of vestibular testing among medicare beneficiaries. Otolaryngol. Head Neck Surg. 156, 312–320. https://doi.org/10.1177/0194599816676450.

Adams, M.E., Yueh, B., Marmor, S., 2020. Clinician use and payments by medical specialty for audiometric and vestibular testing among US medicare beneficiaries. JAMA Otolaryngol. Head Neck Surg 146, 143–149. https://doi.org/10.1001/jamaoto.2019.3924.

Agrawal, Y., Carey, J.P., Della Santina, C.C., Schubert, M.C., Minor, L.B., 2009. Disorders of balance and vestibular function in US adults: data from the National Health and Nutrition Examination Survey, 2001-2004. Arch. Intern. Med. 169, 938–944. https://doi.org/10.1001/archinternmed.2009.66.

Ahmed, M.F., Goebel, J.A., Sinks, B.C., 2009. Caloric test versus rotational sinusoidal harmonic acceleration and step-velocity tests in patients with and without suspected peripheral vestibulopathy. Otol. Neurotol. 30, 800–805. https://doi.org/10.1097/MAO.0b013e3181b0d02d.

Alfarghal, M., Algarni, M.A., Sinha, S.K., Nagarajan, A., 2022. VOR gain of lateral semicircular canal using video head impulse test in acute unilateral vestibular hypofunction: a systematic review. Front. Neurol. 13, 948462 https://doi.org/10.3389/fneur.2022.948462.

Alhabib, S.F., Saliba, I., 2017. Video head impulse test: a review of the literature. Eur. Arch. Oto-Rhino-Laryngol. 274, 1215–1222. https://doi.org/10.1007/s00405-016-4157-4.

Arriaga, M.A., Chen, D.A., Cenci, K.A., 2005. Rotational chair (ROTO) instead of electronystagmography (ENG) as the primary vestibular test. Otolaryngol. Head Neck Surg. 133, 329–333. https://doi.org/10.1016/j.otohns.2005.05.002.

Bhansali, S.A., Honrubia, V., 1999. Current status of electronystagmography testing. Otolaryngol. Head Neck Surg. 120, 419–426. https://doi.org/10.1016/S0194-5998(99)70286-X.

Bush, M.L., Bingcang, C.M., Chang, E.T., Fornwalt, B., Rayle, C., Gal, T.J., Jones, R.O., Shinn, J.B., 2013. Hot or cold? Is monothermal caloric testing useful and cost-effective? Ann. Otol. Rhinol. Laryngol. 122, 412–416. https://doi.org/10.1177/000348941312200611.

Dimitri, P.S., Wall, C., Oas, J.G., 1996. Classification of human rotation test results using parametric modeling and multivariate statistics. Acta Otolaryngol. 116, 497–506. https://doi.org/10.3109/00016489609137880.

Eza-Nuñez, P., Fariñas-Alvarez, C., Fernandez, N.P., 2016. Comparison of three diagnostic tests in detecting vestibular deficit in patients with peripheral vestibulopathy. J. Laryngol. Otol. 130, 145–150. https://doi.org/10.1017/S0022215115003114.

Furman, J.M., Jacob, R.G., 1993. Jongkees' formula re-evaluated: order effects in the response to alternate binaural bithermal caloric stimulation using closed-loop irrigation. Acta Otolaryngol. 113, 3–10. https://doi.org/10.3109/00016489309135759.

Halmagyi, G.M., Chen, L., MacDougall, H.G., Weber, K.P., McGarvie, L.A., Curthoys, I.S., 2017. The video head impulse test. Front. Neurol. 8, 258. https://doi.org/10.3389/fneur.2017.00258.

Hannigan, I.P., Welgampola, M.S., Watson, S.R.D., 2021. Dissociation of caloric and head impulse tests: a marker of Meniere's disease. J. Neurol. 268, 431–439. https://doi.org/10.1007/s00415-019-09431-9.

Leng, Y., Liu, B., 2020. Dissociation of caloric and video head impulse tests in patients with delayed endolymphatic hydrops. Front. Neurol. 11, 362. https://doi.org/10.3389/fneur.2020.00362.

Maes, L., Vinck, B.M., Wuyts, F., D'haenens, W., Bockstael, A., Keppler, H., Philips, B., Swinnen, F., Dhooge, I., 2011. Clinical usefulness of the rotatory, caloric, and vestibular evoked myogenic potential test in unilateral peripheral vestibular pathologies. Int. J. Audiol. 50, 566–576. https://doi.org/10.3109/14992027.2011.576706.

Mahringer, A., Rambold, H.A., 2014. Caloric test and video-head-impulse: a study of vertigo/dizziness patients in a community hospital. Eur. Arch. Oto-Rhino-Laryngol. 271, 463–472. https://doi.org/10.1007/s00405-013-2376-5.

Maire, R., van Melle, G., 2008. Vestibulo-ocular reflex characteristics in patients with unilateral Ménière's disease. Otol. Neurotol. 29, 693–698. https://doi.org/10.1097/MAO.0b013e3181776703.

McGarvie, L.A., Curthoys, I.S., MacDougall, H.G., Halmagyi, G.M., 2015. What does the head impulse test versus caloric dissociation reveal about vestibular dysfunction in Ménière's disease? Ann. N. Y. Acad. Sci. 1343, 58–62. https://doi.org/10.1111/nyas.12687.

Morrison, M., Korda, A., Zamaro, E., Wagner, F., Caversaccio, M.D., Sauter, T.C., Kalla, R., Mantokoudis, G., 2022. Paradigm shift in acute dizziness: is caloric testing obsolete? J. Neurol. 269, 853–860. https://doi.org/10.1007/s00415-021-10667-7.

Piker, E.G., Schulz, K., Parham, K., Vambutas, A., Witsell, D., Tucci, D., Shin, J.J., Pynnonen, M.A., Nguyen-Huynh, A., Crowson, M., Ryan, S.E., Langman, A., Roberts, R., Wolfley, A., Lee, W.T., 2016. Variation in the use of vestibular diagnostic testing for patients presenting to otolaryngology clinics with dizziness. Otolaryngol. Head Neck Surg. 155, 42–47. https://doi.org/10.1177/0194599816650173.

Priesol, A.J., Cao, M., Brodley, C.E., Lewis, R.F., 2015. Clinical vestibular testing assessed with machine-learning algorithms. JAMA Otolaryngol. Head Neck Surg. 141, 364–372. https://doi.org/10.1001/jamaoto.2014.3519.

Shen, L.S., Andresen, N.S., Chari, D.A., Pogson, J.M., Lauer, A.M., Rabbitt, R.D., Carey, J. D., Santos, F., Ward, B.K., 2023. Otolith membrane herniation, not semicircular canal duct dilation, is associated with decreased caloric responses in Meniere's disease. J. Assoc Res. Otolaryngol. 24, 95–106.

Shepard, N.T., Jacobson, G.P., 2016. The caloric irrigation test. Handb. Clin. Neurol. 137, 119–131. https://doi.org/10.1016/B978-0-444-63437-5.00009-1.

Sorathia, S., Agrawal, Y., Schubert, M.C., 2018. Dizziness and the otolaryngology point of view. Med. Clin. North Am. 102, 1001–1012. https://doi.org/10.1016/j.mcna.2018.06.004.

Vallim, M.G.B., Gabriel, G.P., Mezzalira, R., Stoler, G., Chone, C.T., 2021. Does the video head impulse test replace caloric testing in the assessment of patients with chronic dizziness? A systematic review and meta-analysis. Braz J. Otorhinol. 87, 733–741. https://doi.org/10.1016/j.bjorl.2021.01.002.

van de Berg, R., Rosengren, S., Kingma, H., 2018. Laboratory examinations for the vestibular system. Curr. Opin. Neurol. 31, 111–116. https://doi.org/10.1097/WCO.0000000000000526.

Wall, C., 1990. The sinusoidal harmonic acceleration rotary chair test. Theoretical and clinical basis. Neurol. Clin. 8, 269–285.

Zellhuber, S., Mahringer, A., Rambold, H.A., 2014. Relation of video-head-impulse test and caloric irrigation: a study on the recovery in unilateral vestibular neuritis. Eur. Arch. Oto-Rhino-Laryngol. 271, 2375–2383. https://doi.org/10.1007/s00405-013-2723-6.

Zuniga, S.A., Adams, M.E., 2021. Efficient use of vestibular testing. Otolaryngol. Clin. 54, 875–891. https://doi.org/10.1016/j.otc.2021.05.011.