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Quantitative vestibular assessment: The development and validation of a novel, remote video head impulse test against in-clinic measurements

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Abstract

Objectives: To develop a novel remote head impulse test (rHIT), and to provide preliminary data validating the rHIT vestibular-ocular reflex (VOR) gains against the in-clinic vHIT.

Methods: A convenience sample of 10 patients referred for vestibular assessment at our institution was recruited. In-clinic vHIT was used to quantify lateral VOR gains. Patients subsequently underwent an rHIT protocol, whereby patients performed active, lateral head rotations while their eyes and heads were recorded using a laptop camera and video-conferencing software. The vHIT and rHIT VOR gains were compared using paired *t*-tests, and a Pearson correlation coefficient between the gains was calculated. Absolute accuracy, sensitivity, and specificity of the rHIT were additionally calculated.

Results: Of the 10 patients recruited, 4 were male, and the average ± standard deviation (SD) age was 61.4 ± 15.3 years. As determined by the vHIT, 2 patients had normal bilateral VOR gains, 6 with unilateral vestibular hypofunction, and 2 with bilateral vestibular hypofunction. The correlation between the rHIT and vHIT gains was 0.73 ($p < .001$). The rHIT exhibited an absolute accuracy of 75.0%, sensitivity of 70.0%, and specificity of 80.0%. When ears had a vHIT VOR gain less than 0.40, the rHIT exhibited 100.0% accuracy. Conversely, 60.0% of deficient ears with vHIT VOR gains greater than 0.40 were incorrectly categorized by the rHIT.

Conclusion: The rHIT may be better suited for detecting more severe vestibular deficiencies. Future iterations of the rHIT should aim to increase the video frame-rate capabilities to detect subtler VOR impairments.

Level of Evidence: 4.

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KEYWORDS
remote, vestibular hypofunction, vestibular schwannoma, video head impulse test

1 | INTRODUCTION

The vestibular system is an important contributor to balance control. Comprised of three semicircular canals and two otolithic organs, the vestibular system provides continuous neural input regarding head position, orientation, and motion, and thereby helps drive compensatory eye, truncal, and lower limb movements to ensure maintenance of gaze and postural stability.[1–4] An estimated 69 million adults in the United States experience vestibular deficits, and the odds of developing vestibular loss have been shown to significantly increase with age.[5] Vestibular dysfunction typically manifests clinically as vertigo and postural imbalance, and in some cases, may result in catastrophic falls, which are associated with an increased risk for injury and shorter survival.[6–14] Furthermore, the costs associated with falls are immense, with the United States spending an estimated $50 billion and $754 million annually on healthcare associated with non-fatal and fatal falls, respectively.[15] Considering the rapidly aging population, the clinical and fiscal burden of vestibular loss can be readily appreciated as a particularly pressing public health concern.

Diagnosing vestibular dysfunction is challenging for several reasons. First, the clinical symptoms of vertigo and imbalance are non-specific, and may be attributable to many and potentially overlapping etiologies spanning visual, proprioceptive, musculoskeletal, and/or vestibular processes.[5,16–20] Second, accurately assessing the function of the peripheral vestibular organs presently necessitates in-clinic measurements using diagnostic tools such as the video head impulse test (vHIT), which quantifies the vestibular-ocular reflex (VOR). Among patients with vertigo and imbalance, however, ambulating to outpatient clinics may be challenging and may thereby preclude vestibular assessment in this patient population.

The development of a point-of-care, remote version of the vHIT may help expand access to vestibular assessment, may shorten the time to diagnosis, and may thereby result in earlier provision of appropriate therapies. In this pilot study, we describe a novel remote head impulse test (rHIT) and compare the VOR gains outputted by this remote platform against gold-standard, in-clinic vHIT measurements.

2 | MATERIALS AND METHODS

This study was approved by the Johns Hopkins Institutional Review Board. All participants provided informed consent, and all methods involving human participants were carried out in accordance with the ethical principles of the Declaration of Helsinki.

2.1 | Study design and participants

We performed a cross-sectional study designed to assess the accuracy of our novel rHIT platform against gold-standard, in-clinic vHIT measurements. We recruited a convenience sample of 10 participants presenting with dizziness who were seen at the neurotology clinics at the Johns Hopkins Outpatient Center, Green Spring Station, or Suburban Outpatient Center. A power analysis for sample size estimation was not performed for this initial pilot study.

2.2 | Study protocol

The in-clinic vHIT was first used to quantify the lateral semicircular canal VOR gains for all participants bilaterally. Twenty passive head rotations for each side were elicited by a trained study personnel while participants wore the EyeSeeCam (Interacoustics, Eden Prairie, MN) eye-tracking goggles. Patients subsequently underwent a novel rHIT protocol, whereby patients performed actively self-generated, horizontal head rotations while their eyes and heads were recorded using a standard laptop camera and Zoom software (Zoom Video Communications, San Jose, CA). Participants sat approximately one foot away from the study laptop with the camera lens at eye-level. Participants were instructed to maintain eye contact with the camera lens while rotating their heads as quickly as possible approximately 20 degrees to the right or left at the random command of a trained study personnel. Five head rotations were elicited for each side. The frame-by-frame positions of patients' eyes and heads were then manually tracked using the open-source Tracker software (Open Source Physics). Using this video-analysis software, digital position markers were placed in the center of the pupil and the lateral cusp of the eyelid for the side contralateral to the direction of each head rotation to track eye and head position, respectively. Figure 1 illustrates the eye and head tracking of one subject in our cohort.

The velocities of the eye and head rotations were individually calculated by dividing the change in position over one frame by the video frame-rate, which was 40 ms. The rHIT VOR gain for each head rotation was calculated as the ratio of eye to head velocity, and the final rHIT VOR gains was the average of the five gains calculated for each side.

2.3 | Statistical analysis

Each ear for all participants was considered independently. The vHIT and rHIT VOR gains were compared using paired

FIGURE 1 Demonstration of the manual tracking for the rHIT platform. Eye rotation was tracked using a marker placed in the center of the pupil. Head rotation was tracked using a marker placed at the lateral cusp of the eyelid.

Student's *t*-tests, and a Pearson correlation coefficient between the gains generated by each platform was calculated. The accuracy, sensitivity, and specificity of the rHIT was assessed using the standard vHIT gain diagnostic threshold of 0.80. Accuracy was defined as the proportion of ears correctly categorized by the rHIT. Sensitivity was defined as the proportion of deficient ears, as assessed by the vHIT, likewise categorized as deficient by the rHIT. Specificity was defined as the proportion of normal ears that too were classified as normal by the rHIT. Statistical significance was defined as $p < .05$.

3 | RESULTS

3.1 | Demographic and clinical characteristics

Of the 10 patients recruited, 4 (40.0%) were male, and the mean (±SD) age was 61.4 ± 15.3 years. While one patient identified as Black or African American and another as Asian, all other patients (80.0%) identified as non-Hispanic White. As determined by the vHIT, 2 (20.0%) patients exhibited normal bilateral VOR gains, 6 (60.0%) patients had unilateral vestibular hypofunction (UVH), and 2 (20.0%) patients had bilateral vestibular hypofunction (BVH). Of the 8 patients with vestibular hypofunction, 5 (62.5%) had previously undergone surgical resection of a vestibular schwannoma, and 3 (37.5%) had vestibular neuritis and/or labyrinthitis.

TABLE 1 Vestibular-ocular reflex gains outputted by the rHIT and vHIT platforms.

	rHIT		vHIT	
Patient #	Right	Left	Right	Left
1	0.62	0.94	0.40	1.00
2	0.99	1.00	1.10	0.93
3	0.78	0.83	0.76	0.52
4	0.88	0.93	0.57	0.98
5	0.99	0.47	0.89	0.37
6	0.72	0.31	0.75	0.30
7	0.53	0.55	0.38	0.81
8	0.93	1.38	1.01	0.92
9	0.77	0.63	0.86	0.29
10	1.05	1.10	0.91	0.73

TABLE 2 Average head and eye rotation velocities outputted by the rHIT for each participant.

	rHIT velocities (pixels/ms)		
		Eye	
Patient #	Head	Right	Left
1	0.37	0.24	0.28
2	0.04	0.03	0.06
3	0.20	0.10	0.22
4	0.10	0.07	0.10
5	0.09	0.09	0.04
6	0.09	0.05	0.03
7	0.33	0.40	0.12
8	0.22	0.26	0.25
9	0.26	0.17	0.22
10	0.23	0.31	0.16

3.2 | Comparison of rHIT and vHIT VOR gains

The rHIT and vHIT VOR gains for each patient are provided in Table 1. Eye and head velocities averaged across all trials are provided for each subject in Table 2. rHIT and vHIT gains were found to be statistically different using a paired Student's *t*-test ($p = .04$), with rHIT gains, on average, 0.10 greater than vHIT gains. The correlation between the rHIT and vHIT gains was 0.73 ($p < .001$). Using the standard vHIT gain threshold of 0.80, the rHIT exhibited an absolute accuracy of 75.0%, sensitivity of 70.0%, and specificity of 80.0%. A vHIT VOR gain less than or equal to 0.40 was exhibited by 5 ears, all of which were appropriately classified as deficient by the rHIT. In contrast, there were 5 ears with vHIT-assessed vestibular hypofunction but vHIT VOR gains greater than 0.40, 3 (60.0%) of which were incorrectly categorized as normal by the rHIT.

4 | DISCUSSION

The vHIT has been adopted as a critical vestibular assessment tool, but the in-clinic nature of the test may preclude assessment for patient populations that present with vertigo, imbalance, and/or other ambulatory challenges. In this pilot study, we developed a novel remote head impulse test and provide preliminary data comparing the VOR gains from the rHIT platform against gold-standard, in-clinic vHIT measurements.

Overall, the rHIT approximated the VOR gains outputted by the vHIT moderately well, with a correlation of 0.73 between the two platforms. The absolute accuracy of the rHIT, when using the standard vHIT gain threshold of 0.80, too was high at 75.0%, with sensitivity of 70.0% and specificity of 80.0%. In detecting disease, the rHIT performed best when patients had more severe vestibular impairments. In particular, the rHIT exhibited 100.0% accuracy for ears with a vHIT VOR gain less than or equal to 0.40, but only 40.0% accuracy for deficient ears with vHIT VOR gains greater than 0.40. Taken together, these results suggest that while the temporal resolution of a video recorded using a standard laptop camera and video-conferencing software may limit detection of subtle disease, the rHIT may be best applied in patients with more severe vestibular deficiencies, for example in patients who are being evaluated for vestibular neuritis. Additionally, the rHIT may be used as a preliminary screening tool for patients with a high pre-test probability for UVH. While a negative result on the rHIT should be subsequently confirmed using the in-clinic vHIT, a positive rHIT outcome may help expedite the provision of appropriate care to UVH patients.

Our study was subject to several limitations. First, the relatively slow frame-rate of 40 ms for a standard laptop camera and video-conferencing software limited the detection of subtle VOR deficiencies, although the rHIT performed well in detecting more obvious impairments. External cameras with higher frame-rate capabilities will be used in future studies to improve the diagnostic capabilities of the rHIT. As commercial video-oculography technologies exhibit recording frequencies of near 5 ms, future iterations of the rHIT should aim for similar capabilities. Second, the rHIT VOR gains depend upon the accuracy of the manual tracking of the patient's eyes and head from the recorded video. Video lighting and the speed of the head rotation may blur the frame-by-frame snapshots of the video, and increase the difficulty of manual tracking. Future studies may investigate machine learning approaches to automate eye-tracking and thereby decrease the potential subjectivity inherent in manual tracking. Finally, as the rHIT is designed as a remote vestibular assessment tool, vestibular function in this platform is assessed via active lateral head rotations, which could elicit pre-programmed eye movements originating from other oculomotor neural pathways that may compensate for poor VOR function.[21,22] Relatedly, the discrepancies in VOR between the rHIT and vHIT may arise either from the difference in head stimuli type (i.e., passive vs. active) or from the equipment itself, and future studies investigating the source of the VOR discrepancy should be performed. Additionally, it is known that the contralateral ear in patients with UVH may compensate for the deficient ear during slower head rotations. The maximum angular velocity of the head rotation during the rHIT may therefore be a limiting factor in properly isolating the VOR. Although the average velocities of the head rotations in our 6 patients with UVH were 0.37, 0.04, 0.20, 0.09, 0.33, and 0.22 pixels/ms, we were unable to standardize and scale these values, which thereby limited our capacity to interpret these velocities with respect to real space, although we did exclude rHIT trials with markedly slower head rotations. Future iterations of the rHIT will include a protocol to standardize object position, and only rHIT trials with sufficient head velocities will be included for analysis.

5 | CONCLUSION

Although the vHIT is a mainstay vestibular assessment tool, the in-clinic nature of the test limits its widespread application. In its current iteration, the rHIT is most suited for detecting more severe vestibular impairments, for example in patients who recently underwent vestibular schwannoma resection. The rHIT may be used as a screening tool for patients with a high pre-test probability for UVH. A negative result on the rHIT should be subsequently confirmed using the vHIT, but a positive rHIT outcome may help expedite the provision of care to this patient population.

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