Department of Otorhinolaryngology, Head and Neck Surgery

The Video Head Impulse Test and Predictability of Vestibular Disorders

Master's thesis

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Abstract

Introduction

Vestibular disorder (VD) is a prominent socioeconomic burden due to its high prevalence and diagnostic difficulty. A rather new tool, the video head impulse test (vHIT), might act as a screening tool for VD by separate evaluation of the vestibulo-ocular reflex (VOR) involving all six semicircular canals (SCCs) and thereby also both the superior and inferior vestibular nerves bilaterally.

Methods

All subjects included presented with vertigo and/or dizziness and underwent a vHIT examination of the horizontal semicircular canals. This study had rather strict inclusion and exclusion criteria, standardized vHIT quality requirements, and clear definitions of pathological gain and saccades. A potential diagnosis related to VD was placed either on the day of the vHIT examination or following more extensive vestibular testing. All vHIT reports were assessed thoroughly. Poor-quality markers and artifacts were recorded for each subject excluded due to the low quality of the vHIT results.

Results

A total of 1119 subjects met the inclusion criteria. The subjects had a mean age of 59.2 years, and 42.4% were males. The subjects were divided into two subgroups: VD (52.0%) and non-VD (48.0%). For the main analyses, the following three criteria were used: 1) low mean VOR gain and pathological saccades, 2) low mean VOR gain only, and 3) pathological saccades only with the following results: sensitivity (43.5%, 47.2%, and 54.3%), specificity (96.1%, 94.0% and 84.0%), positive predictive value (92.3%, 89.6% and 78.6%), negative predictive value (61.1%, 62.2% and 62.9%), overall agreement ranged from 68.5% to 69.7%, and Cohen's kappa indicated fair agreement. Sub-analyses showed substantial variation between individual VDs.

Conclusion

Results of the main analyses implied a combination of parameters gain and saccades as the rational choice for vHIT when predicting VD. Gain proved a viable standalone parameter when encountering a pathological mean VOR gain value and doubtful saccades. Based upon the results of this study, vHIT should not act as a screening tool for VD but rather as a first-line vestibular test among others.

vHIT was a poor screening tool for benign paroxysmal positional vertigo, Ménière's disease, and vestibular schwannoma. However, vHIT showed great potential as a screening tool for vestibular neuritis. Notably, this study found 40.5% of all vHIT examinations to be of poor quality, emphasizing the need for implementation of some kind of universal quality markers with this test.

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1. Introduction

1.1. Vertigo, Dizziness, and Vestibular Disorder

Vertigo and dizziness are common symptoms with a reported lifetime prevalence of 30% with vestibular disorders accounting for approximately one third to half of all vertiginous patients[1–5]. Patients often have difficulty explaining their vertiginous symptoms adequately[6], and physicians, who rely on a precise anamnesis, may therefore be prone to high-risk diagnostic reasoning[7].

The cost of assessing patients reporting dizziness was investigated in a UK-based study from 2023[8]. This involved consultations with a general practitioner and possibly an otologist, cardiologist, and/or neurologist. In the best case scenario, the cost of medical assessment required for a diagnosis was approximately £681, while the cost could rise to £1355 in the worst case scenario[8]. Additionally, vertiginous patients have significantly higher levels of anxiety, depression, and distress[9] with an intrusive impact on a person's daily life.

When considering the above-mentioned accompanying factors, it is essential that a correct diagnosis is made as fast and accurately as possible. In relation to this, quantitative vestibular tests, like the video head impulse test (vHIT), have revolutionized vestibular diagnostics[10].

1.2. The Video Head Impulse Test

Semicircular canal (SCC) VOR testing used to be carried out with expensive, complicated, and semi-invasive test tecniques[11]. That was until 2009 when the vHIT became commercially available[11]. Today, several vHIT systems are commercially available both with and without goggles, enabling testing for subjects between 3 months old to those exceeding 90 years[12–15].

The video head impulse test is a non-invasive, quick, and dynamic physiological test, which enables evaluation of the vestibulo-ocular reflex (VOR) of each separate SCC and thus the two paired vestibular nerves[16]. In healthy individuals, the VOR stabilizes the visual image on the retina during head movement by moving the eyes in the opposite direction of the head movement at equal velocity[16]. Loss of VOR function is reflected in the vHIT as a reduction of gain values and/or pathological refixation saccades[10,16].

Gain is a numeric value defined as the ratio between the compensatory eye movement velocity and the cohesive head impulse velocity, both measured in degrees per second. The reference value differs between SCCs being examined[17]. Saccades are defined as either physiological or pathological according to certain, often predefined, criteria[17]. Saccades appear as additional curves on the accompanying vHIT graphs that also visualize the corresponding curves for eye- and head movements[17].

The vHIT should not be considered a "plug and play" test. It is highly dependent on several factors: 1) the skills of the examiner, 2) the degree of cooperation of the participant, 3) the test protocol adhered to, and 4) the type of equipment used[18].

1.3. Specific Vestibular Disorders and Diagnostic Methods

The selection of appropriate diagnostic tests for VDs depends on the underlying pathoetiology[19]. Conventional vestibular test methods contain several limitations, including 1) a high degree of patient cooperation, 2) considerable time requirements, and 3) often uncomfortable tests or test conditions (e.g., rotational chair testing and caloric stimulation)[20]. Moreover, many of these tests are static in nature and therefore do not directly evaluate the dynamic performance of patients[21]. The required test set-up with expensive equipment and highly trained personnel is also rather costly[22]. Bedside examinations, although less expensive, still depend heavily on examiner expertise and patient compliance, and their diagnostic conclusions may therefore be less reliable[23].

1.3.1. Benign Positional Paroxysmal Vertigo

Benign Positional Paroxysmal Vertigo (BBPV) is the most common VD, with a lifetime prevalence of approximately 10%[24]. The condition is characterized by brief attacks of positional vertigo and nystagmus lasting seconds. These attacks can persist for days to months, often followed by spontaneous remission. BPPV is caused by utricular otoconia, which are displaced into the semicircular canal(s)[24].

A diagnosis of BPPV requires 1) a typical BPPV case history of sudden, brief episodes of spinning vertigo triggered by specific head movements and 2) positional tests that provoke positional nystagmus specific to the affected canal(s). Additional testing is only necessary if other co-occurring VDs are suspected or if targeted treatment fails[24].

1.3.2. Ménière's Disease

Ménière's disease (MD) is thought to be associated with pressure-related changes in the endolymphatic space within the inner ear[25]. MD is characterized and diagnosed by a triad of attacks of unilateral sensorineural hearing loss, unilateral tinnitus/aural fullness, and vertigo that lasts for hours[25]. Criteria for definite MD include episodes of vertigo, audiometric and fluctuating aural symptoms, and exclusion of other accountable vestibular diagnoses[25].

1.3.3. Vestibular Neuritis

Vestibular neuritis (VN), also referred to as an acute unilateral vestibulopathy, is characterized by an acute unilateral loss of peripheral vestibular function with no accompanying auditory deficits or objective signs of acute central pathology[26].

The diagnostic criteria include a characteristic patient history with acute onset of continuous vertigo of moderate to severe intensity lasting more than 24 hours, head motion intolerance, and oscillopsia. In addition, an objective vestibular assessment is required in order to confirm if the VOR function is reduced[26].

1.3.4. Vestibular Schwannoma

Vestibular schwannoma (VS) is the most common cerebellopontine angle tumor[27]. Patients often present with unilateral sensorineural hearing loss, aural fullness, and tinnitus, whilst vestibular symptoms vary widely between patients (40-75%)[28]. Contrast-enhanced T1-weighted MRI is the gold standard for initial evaluation[29].

1.3.5. Other Vestibular Disorders

The International Classification of Diseases, 10th revision, is limited and outdated when it comes to VDs. This study will therefore primarily focus on the four abovementioned vestibular diagnoses, which are clearly defined with a separate diagnosis code (BPPV, MD, VN, and VS). Other VDs, which are included in the analysis (but will not be further mentioned), include vestibular hypofunction, labyrinthine fistula, semicircular canal dehiscence syndrome, vestibulopathy not otherwise specified, labyrinthitis, and disorder of the vestibular system not otherwise specified[30].

1.4. Study Aim

The primary aim of this study was to assess the utility of vHIT as a possible screening tool for VD. The secondary aim included an evaluation of the performance of individual vHIT parameters and assessment of vHIT as a screening tool for specific VDs. The tertiary aim of this study included the identification of the most common factors contributing to low vHIT quality.

2. Methods

2.1. In- and Exclusion Criteria

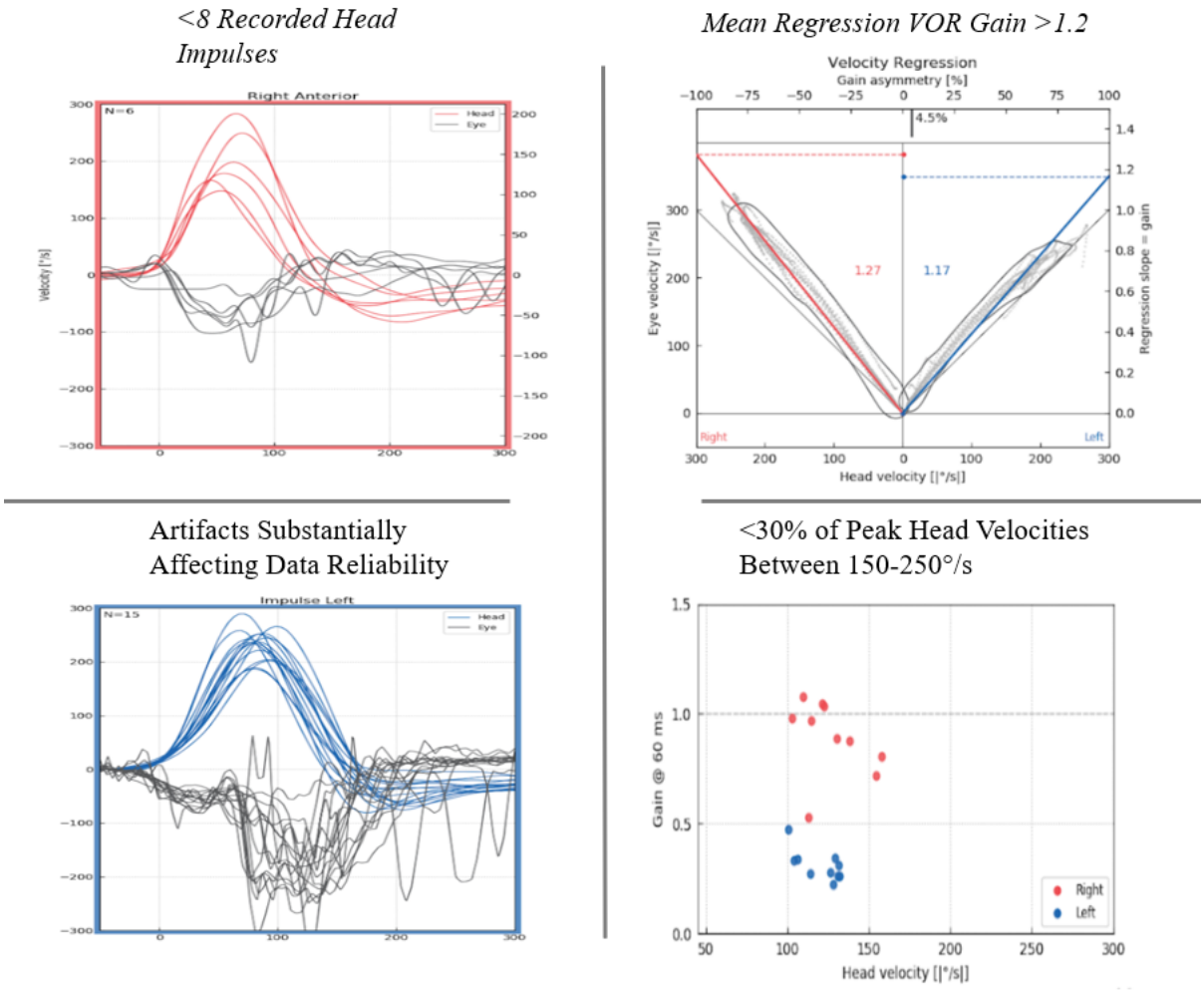
Inclusion criteria were structured across two levels: subject record criteria and vHIT quality criteria. For the subject record criteria, only subjects aged 18 years or older examined with vHIT were eligible. Subjects were excluded if no diagnosis was established at the conclusion of the clinical assessment.

2.2. Quality of the Video Head Impulse Test

In this study, vHIT quality was evaluated by using predefined poor-quality markers (PQMs) and artifacts. PQMs were applied as exclusion criteria and included:

a. Mean regression VOR gain greater than 1.2[10].
b. Less than 30% of examinations with peak head velocities between 150–250°/s[10].
c. Fewer than eight recorded head impulses (HIs) per SCC.
d. Mean VOR instantaneous gain value at 60 ms not in accordance with the mean regression VOR gain value (prerequisite: both mean VOR gain values should lie within either the normative or the pathological ranges)[31].
e. More than 50% of individual VOR gain values lie outside the normative or the pathological ranges when compared to the mean VOR gain.
f. Examination fulfills the quality criteria, but the vHIT report has one or several artifacts that affect data reliability across at least two-thirds of the head impulse sequences.

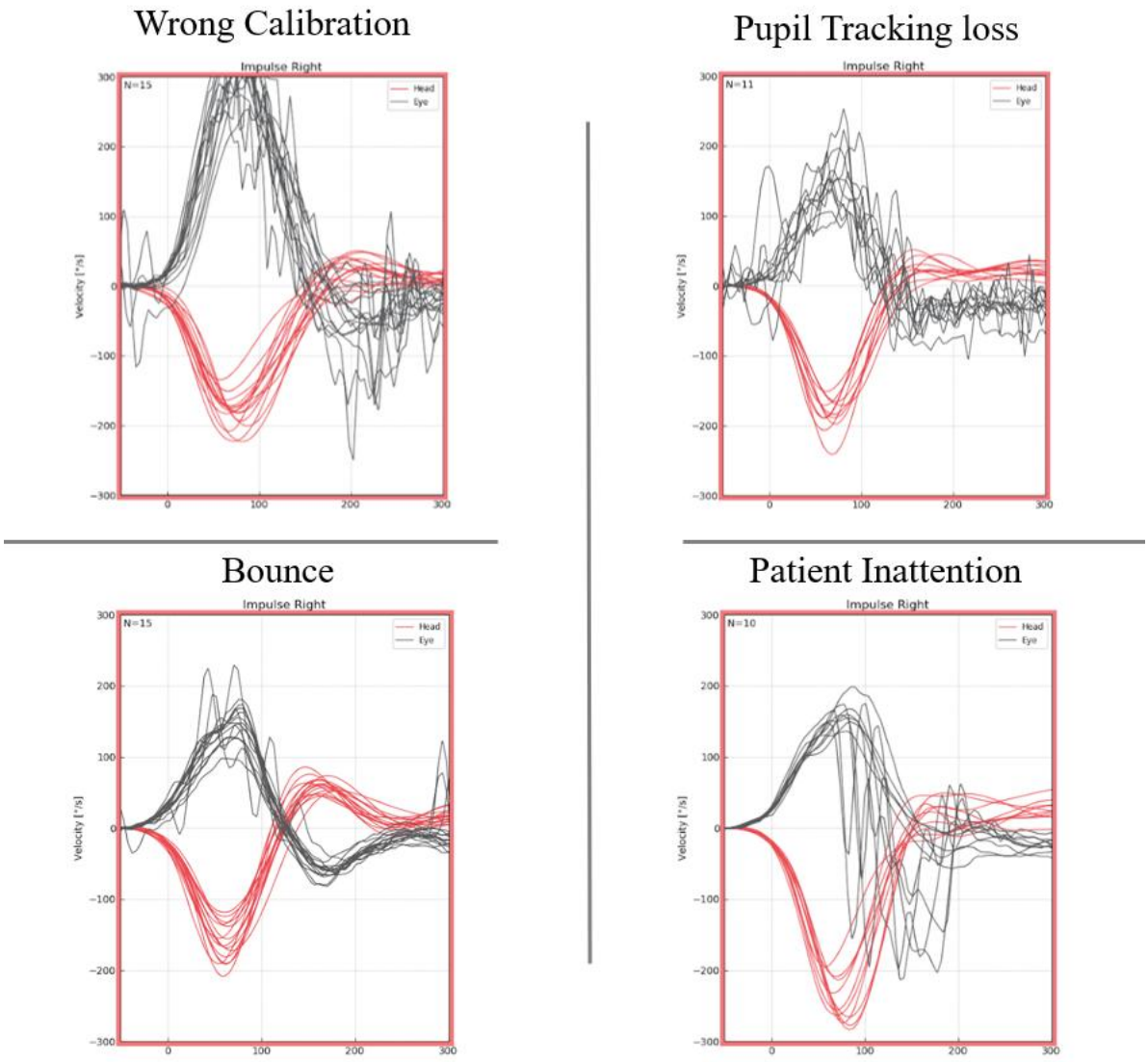
Figure 1. Examples of Selected Poor-Quality Markers



The figure visualizes examples of poor-quality markers (PQM), from upper left to lower right: *PQM c* 'Fewer than eight recorded head impulses per SCC', *PQM a* 'Mean regression VOR gain greater than 1.2', *PQM f* 'Examination fulfills the quality criteria, but the vHIT report has one or several artifacts that affect data reliability across at least two-thirds of the head impulse sequences', and *PQM b* 'Less than 30% of examinations with peak head velocities between 150–250°/s'. Regarding the examples on the left side of the vertical line, the y-axes and x-axes are measured in degrees per second and milliseconds, respectively. The x-axes, for the two examples on the right side of the vertical line, are measured in degrees per second. Red lines represent head movement, whilst black lines represent eye movement. Blue dots and lines represent left-sided head impulses, whilst red dots and lines represent right-sided head impulses.

Artifacts, defined as disturbances in vHIT data that differ from the true VOR response[32], were registered as: Wrong calibration, patient inattention, pupil tracking loss, bounce, mini-blink, blink, touching goggles, and loose straps[33]. These factors were recorded to identify potential causes of reduced test reliability. Both PQMs and artifacts were registered using a multiple-choice format.

Figure 2. Examples of Selected Artifacts



The figure visualizes the following artifacts, from upper left to lower right: wrong calibration, pupil tracking loss, bounce, and patient inattention. The y-axes and x-axes are measured in degrees per second and milliseconds, respectively. Red lines represent head movement, whilst black lines represent eye movement.

2.3. Assessment of the Video Head Impulse Test

Pathological saccades were defined according to Abrahamsen et al. (2018) as compensatory and corrective eye movements if they fulfilled the following four criteria[17]:

- Must occur in more than 50% of all HIs.
- Must have a minimum peak eye velocity amplitude of 50% of the peak head velocity amplitude.
- Must appear in the opposite direction of the head turn.
- Must occur within a time frame from 100 ms after the onset of head movement to 100 ms after the end of head movement.

Pathological VOR gain was defined according to Abrahamsen et al. (2018) as a mean VOR gain below 0.8 in the horizontal SCCs[17]. Notably, only the horizontal SCCs were assessed in this study.

2.4. Data Selection

The EyeSeeCam® (Interacoustics©, Middelfart, Denmark) was used, and data were obtained from a secure database, OtoAccess® version 1.2 and 1.3 (Interacoustics©, Middelfart, Denmark). Data included vHIT recordings from 2015 to 2025 for subjects referred to a tertiary University Hospital-based outpatient dizziness clinic at Aalborg University Hospital in Denmark.

2.5. Vestibular Diagnoses

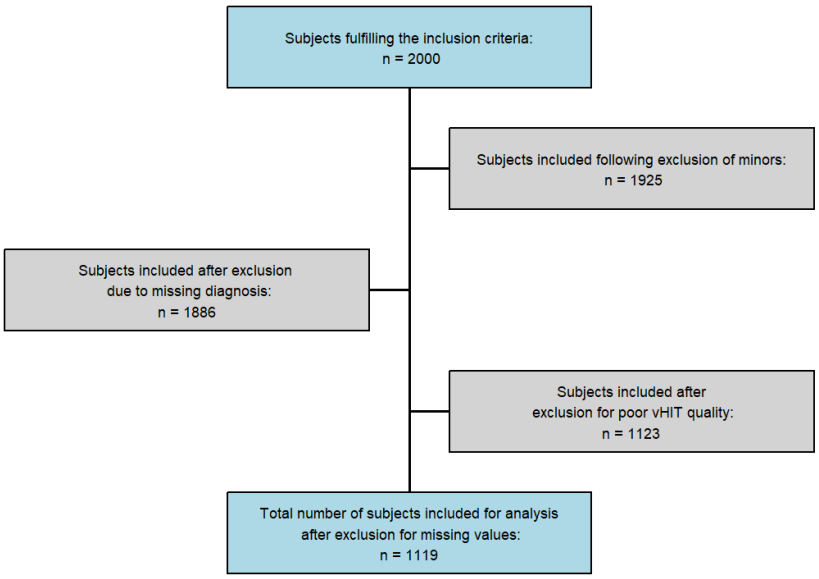
Medical records were accessed through electronic data record searches to identify and register all vestibular diagnoses for the VD population. Each subject was classified as either non-VD (if they had no vestibular disorder-related diagnosis) or VD (if they had a vestibular disorder-related diagnosis).

Vestibular disorder-related diagnoses included BPPV, MD, VN, VS, VH, and other vestibular disorders. The latter consisted of less well-defined diagnoses, which were included in the VH population as per Table 1. If a vestibular diagnosis was placed from the day of the vHIT examination until January 2025, it was registered in the study database. In case subjects had more than one vestibular diagnosis, they were excluded from the sub-analyses involving specific VDs.

2.6. Data Processing and Analysis

All data was recorded in a secure database, RedCAP (Vanderbilt University, Nashville, USA)[34]. Which complies with all formal requirements for secure data handling, including a logging function and storage of data on a secure server within the Region of Northern Denmark. The statistical software 'R' (version 4.5.2) was utilized for data processing[35].

Figure 3. Trial Profile



Patients fulfilling the inclusion criteria were progressively screened according to age, diagnoses, and video head impulse test (vHIT) data quality.

The Population characteristics (Table 1) included age (mean, SD, median, IQR, range), sex distribution, vestibular status (non-VD vs. VD), and specific vestibular diagnoses, presented by individual frequency and percentage of total VDs.

Three main analyses (Table 2) were carried out to evaluate the performance of vHIT as a predictive tool for VD overall. Furthermore, the performance of saccades and gain was assessed, both individually and in combination. Additionally, four sub-analyses were done in order to examine predictability of BPPV, MD, VN, and VS following vHIT examination with combined parameters (Table 3).

True positives, true negatives, false positives, and false negatives were calculated by using 2x2 contingency tables for the total population and with each subpopulation. Crude sensitivity, specificity, positive predictive value (PPV), negative predictive value (NPV), overall agreement, and Cohen's kappa were calculated within these strata. Additionally, the most frequently occurring PQMs and artifacts were quantified for the excluded population (Table 4), and overlapping cases (VDs and BPPV) were identified.

3. Results

3.1. Population Characteristics

The population had a mean age of 59.3 years (SD 16.7; range 18.8–100.0) and a median age of 60.1 years (IQR 47.3–72.7). Of the 1119 eligible subjects, 645 were female (57.6%). When classified in terms of vestibular health status, 582 subjects (52.0%) were diagnosed with at least one VD, while the rest were classified as non-VD.

Ranked by prevalence, BPPV had 188 subjects (32.3%), VH 170 (29.2%), VS 121 (20.8%), VN 83 (14.3%), and MD 41 (7.0%).

Table 1. Population Characteristics

Overall, number	**1119**				
Age					
Mean (SD)	59.2	(16.7)			
Median [IQR]	60.1	[47.3-72.7]			
Range (min, max)	18.8	100			
Sex, number (percentage)					
Male	474	(42.4)			
Female	645	(57.6)			
Vestibular disorder, number (percentage)					
	Non-VD		VD		
Total	537	(48.0)	582	(52.0),	p> 0.05
Male	214	(39.9)	260	(44.7),	p> 0.05
Female	323	(60.1)	322	(55.3),	p> 0.05
Age, mean (SD)	56.4	(17.3)	61.8	(15.7),	p< 0.001
Diagnosis, number (percentage)					
BPPV	188	(32.3)			
Ménière's disease	41	(7.0)			
Vestibular neuritis	83	(14.3)			
Vestibular schwannoma	121	(20.8)			
Vestibular hypofunction	170	(29.2)			
*Overlapping pathologies	21	(3.6)			

*Mean age, gender, and VDs were registered. Diagnoses were registered as multiple-choice, resulting in overlapping VDs. Cumulative percentages exceed 100% as diagnoses were recorded applying a multiple-choice format. *Overlapping pathologies included patients diagnosed with more than one vestibular disorder.* Abbreviations: BPPV, benign paroxysmal positional vertigo; VD, vestibular disorders.

3.2. Diagnostic Performance of Video Head Impulse Test for Vestibular Disorder

Table 2. Main Analyses with Parameters Defining Vestibular Disorder

	Number of subjects			Sensitivity			Specificity			PPV			NPV			Overall agreement			Cohen's kappa		
Parameters	**Total**	**Diagn. VD**	**Pos. vHIT**	**Per-centage**	**CI**	**p-value**	**Per-centage**	**CI**	**p-value**	**Per-centage**	**CI**	**p-value**	**Per-centage**	**CI**	**p-value**	**Per-centage**	**CI**	**p-value**	**Coeffi-cient**	**CI**	**p-value**
Gain and Saccades	1119	582	274	43.5	39.4-47.6	0.999	96.1	94.1-97.6	**<0.001**	92.3	85.5-95.2	**<0.001**	61.1	57.7-64.4	**<0.001**	68.7	65.9-71.4	**<0.001**	.387	35.8-41.6	**<0.001**
Gain only	1119	582	307	47.2	43.1-51.4	0.914	94.0	91.7-95.9	**<0.001**	89.6	85.6-92.8	**<0.001**	62.2	58.8-65.5	**<0.001**	69.7	66.9-72.3	**<0.001**	.405	37.6-43.4	**<0.001**
Saccades only	1119	582	402	54.3	50.1-58.4	**<0.05**	84.0	80.6-87.0	**<0.001**	78.6	74.3-82.5	**<0.001**	62.9	59.2-66.4	**<0.001**	68.5	65.8-71.2	**<0.001**	.378	34.9-40.6	**<0.001**

The table summarizes the total number of subjects included in each analysis, along with the number of subjects diagnosed with a vestibular disorder (diagn. VD) and positive video head impulse test (pos. vHIT). The table also shows sensitivity, specificity, positive predictive value (PPV), negative predictive value (NPV), overall agreement, and Cohen's kappa, each with corresponding 95% confidence interval (CI) and p-values. Analyses were conducted separately for the three main conditions: 1) gain and saccades (condition: pathologically low mean VOR gain values AND pathological saccades), 2) gain only (condition: pathologically low mean VOR gain), and 3) saccades only (condition: pathological saccades). Statistically significant results are shown in bold.

Across the three main analyses, the diagnostic performance of the vHIT varied depending on whether a pathological vHIT examination was defined by a pathologically low mean VOR gain value and/or pathological saccades. If both parameters were combined, a sensitivity of 43.5%, specificity of 96.1%, PPV of 92.3%, and NPV of 61.1% was observed. If a pathological vHIT examination was defined solely by a low mean VOR gain value, sensitivity increased slightly to 47.2%, while specificity remained high at 94.0%. PPV and NPV were 89.6% and 62.2%, respectively. If pathological saccades alone were the sole criterion defining a pathological vHIT examination, the highest sensitivity was seen (54.3%) along with the lowest specificity of 84.0%. A concurrent PPV of 78.6% and NPV of 62.9% were observed. Overall agreement ranged from 68.5% to 69.7%, and Cohen's kappa values indicated fair agreement across all three analyses. Notably, combining both criteria resulted in the lowest number of VD positive subjects (274), while pathological saccades as the sole criterion resulted in the highest number of VD positive subjects (402). All analyses showed statistically significant results (shown in bold in Table 2), except for the sensitivity of combined parameters and gain only.

Table 3. Sub-analyses of the Diagnostic Performance of vHIT for Specific Vestibular Disorders																				
	Number of subjects			**Sensitivity**			**Specificity**			**PPV**			**NPV**			**Overall Agreement**			**Cohen's Kappa**		
Sub-analyses for specific VDs	**Total**	**Diagn. VD**	**Pos. vHIT**	**Per-centage**	**CI**	**p-value**	**Per-centage**	**CI**	**p-value**	**Per-centage**	**CI**	**p-value**	**Per-centage**	**CI**	**p-value**	**Per-centage**	**CI**	**p-value**	**Coeffi-cient**	**CI**	**p-value**
BPPV	710	173	39	10.4	6.3-15.9	1.00	96.1	94.1-97.6	**<0.001**	46.2	30.1-62.8	0.739	76.9	73.4-80.0	**<0.001**	75.2	71.9-78.2	**<0.001**	.088	6.7-10.9	**<0.05**
MD	575	38	23	5.3	0.6-17.7	1.00	96.1	94.1-97.6	**<0.001**	8.7	1.1-2.8	1.00	93.5	91.1-95.4	**<0.001**	90.1	87.4-92.3	**<0.001**	.017	0.6-2.7	0.679
VN	612	75	85	85.3	75.3-92.4	**<0.001**	96.1	94.1-97.6	**<0.001**	75.3	64.7-84.0	**<0.001**	97.9	96.3-99.0	**<0.001**	94.8	92.7-96.3	**<0.001**	.770	73.7-80.3	**<0.001**
VS	651	114	61	35.1	26.4-44.6	1.00	96.1	94.1-97.6	**<0.001**	65.6	52.3-77.3	**<0.05**	87.5	84.5-90.0	**<0.001**	85.4	82.5-87.9	**<0.001**	.382	34.4-41.9	**<0.001**

The table summarizes the total number of subjects included in each analysis, along with the number of subjects diagnosed with vestibular disorder (diagn. VD) and pathological video head impulse test (pos. vHIT). Furthermore, it presents diagnostic performance of vHIT for specific VD subgroups, including benign paroxysmal positional vertigo (BPPV), Ménière's disease (MD), vestibular neuritis (VN), and vestibular schwannoma (VS). The table also shows sensitivity, specificity, positive predictive value (PPV), negative predictive value (NPV), overall agreement, and Cohen's kappa, each with corresponding 95% confidence interval (CI) and p-values. Statistically significant results are shown in bold.

With the *BPPV* sub-analysis, sensitivity was 10.4%, while specificity remained 96.1%. *VN* exhibited the highest sensitivity of 85.3%, with a specificity of 96.1% and NPV of 97.9%. In contrast, *VS* and *MD* showed substantially lower sensitivities of 35.1% and 5.3% albeit preserved specificity of 96.1%. Overall agreement ranged from 75.2% to 94.8%, with *VN* showing the strongest agreement. Cohen's kappa values indicated substantial agreement for *VN*, fair agreement for *VS*, and slight agreement for *MD* and *BPPV*. Notably, *VN* was the only sub-analysis that showed statistically significant results across all measured parameters, whereas the other sub-analyses displayed varying statistical significance across different statistical metrics.

3.3. Poor-Quality Markers and Artifacts

763 (40.5%) of 1886 eligible subjects were excluded due to poor quality of the vHIT examination, from which the specific PQMs and artifacts were recorded.

The most frequent PQMs, *PQM a* and *b* (further elaborated in the methods section), were present in 239 (31.3%) and 232 (30.4%) of the vHIT examinations, respectively. The third most common, *PQM c,* was present in 135 (17.7%) vHITs.

Only 1 (0.1%) vHIT contained three or more PQMs, whereas 81 (10.6%) vHITs had two PQMs. The final 681 (89.3%) vHITs only contained one PQM.

The most frequently recorded artifacts were *Wrong calibration* and *Patient inattention,* present in 157 (32.5%) and 124 (25.7%) vHITs, respectively. Other recorded artifacts included *Pupil-tracking loss* 78 (16.1%), *Bounce* 59 (12.2%), *Mini-blinks* 29, (6.0%), *Blink* 19 (3.9%), and less frequent artifacts such as *Touching goggle*s 12 (2.5%) and *Loose straps* 5 (1.0%).

Additionally, 290 (77.3%) vHITs contained only one artifact, 64 (17.1%) had two recorded artifacts, and 21 (5.6%) had three or more artifacts recorded. 388 vHITs contained zero artifacts.

Table 4. Poor-Quality Markers and Artifacts			
Poor-quality markers (n = 845) **Number (percentage)**		**Artifact triggers (n = 483)** **Number (percentage)**	
1. *PQM a)* Mean regression VOR gain above 1.2	239 (31.3)	1. Wrong calibration	157 (32.5)
2. *PQM b)* Less than 30% of peak head velocities between 150-250°/s	232 (30.4)	2. Patient inattention	124 (25.7)
3. *PQM c)* Less than eight recorded head impulses per SCC	135 (17.7)	3. Pupil tracking loss	78 (16.1)
4. *PQM f)* Examination meets quality standards But artifacts substantially compromise vHIT data reliability	102 (13.4)	4. Bounce	59 (12.2)
5. *PQM d)* Discrepancy between the VOR gain value at 60ms and the mean VOR gain	99 (13.0)	5. Mini-blink	29 (6.0)
6. *PQM e)* Discrepancy between individual VOR gain values and the mean VOR gain	38 (5.0)	6. Blink	19 (3.9)
		7. Touching goggles	12 (2.5)
		8. Loose straps	5 (1.0)
Distribution of poor-quality markers and artifacts per subject **Number (percentage)**			
Subjects with PQMs	**763**	**Subjects with artifacts:**	**375**
Subjects with 1 PQM	681 (89.3)	Subjects with 1 artifact	290 (77.3)
Subjects with 2 PQMs	81 (10.6)	Subjects with 2 artifacts	64 (17.1)
Subjects with ≥3 PQMs	1 (0.1)	Subjects with ≥3 artifacts	21 (5.6)
		Subjects with no artifacts present	388*

Poor-quality markers (PQM) and artifacts are shown from most to least frequent (1–6 for PQMs, 1–8 for artifacts). Cumulative percentages exceed 100% as PQMs and artifacts were recorded applying a multiple-choice format**.** Distribution of PQMs and artifacts per subject is also listed. *No percentage is specified for 'Subjects with no artifacts present', as all excluded subjects with PQMs did not have accompanying artifacts. Abbreviations: PQM, poor-quality marker; SCC, semicircular canal; vHIT, video head impulse test;VOR, vestibulo-ocular reflex.

3.4. Overlapping Pathologies

Of the 21 overlapping pathologies mentioned in Table 1, 15 (71.4%) included BPPV. Among the 188 patients diagnosed with BPPV, the majority (173, 92%) had no concomitant VD. Co-existing vestibular disorders were identified in a small subset of BPPV subjects, including VN (5), VS (5), VH (4), and MD (1).

4. Discussion

4.1. Results

4.1.1. Predictability of Vestibular Disorder and Performance of Parameters

The main analyses presented in Table 2, *Gain and saccades,* and *Gain only* showed similar, but poor ability to identify the VD population with a sensitivity of only 43.5-47.2%, slightly outperformed by *Saccades only (54.3%)*. This is markedly lower than the recommended minimum of 70% for a fairly sensitive screening tool[36]. In addition, the sensitivity of *Gain and saccades* and *Gain only* were not statistically significant, making the interpretation of this metric unreliable.

The high specificity with the combination of *Gain and saccades* (96.1%) indicates that the combination of these two parameters provides a better ability to identify the non-VD population. This is in accordance with a previous study that found a specificity of 99.9% with analysis of 2,880 SCCs with similar combined criteria of both pathological saccades and low mean VOR gain values[37].

The NPV with all three analyses ranged from 61.1-62.9%, indicating that any combination of the two parameters would not be able to reliably confirm the absence of VD. Considering this, the most applicable statistical metric seems to be PPV. By this metric, *Gain and saccades* appear to be the superior analysis with a PPV of 92.3%, making the combination of mean VOR gain values and saccades the most reliable measure for determining whether VD is present or not.

Although the low sensitivities seen with vHIT testing do not support implementation of vHIT as a screening tool for VD, it is still recommended as a first-line screening tool by van Esch et al (2016) and Abrahamsen et al. (2018)[17,38]. In case of a normal vHIT, because of the low NPV, additional vestibular testing is recommended to reliably exclude any vestibular pathology. Conversely, a pathological vHIT, because of the high PPV, should be sufficient to conclude that there is a vestibular hypofunction, with further vestibular testing warranted only for a more precise etiological classification.

As mentioned in the methods section, vHIT is generally considered an objective test. However, the assessment of a vHIT examination might be prone to some degree of both intra- and inter-examiner variation[17]. Considering *Gain only* and *Gain and saccades*, it can be observed that the statistical metrics are nearly identical. Thus, if one were to assess a vHIT report with pathologically low mean VOR gain values without easily identifiable or characteristic saccades, the assumed rational choice would be to deem the test pathological. This is due to the high PPV of *Gain only,* that 89.6% of the time would correctly confirm the presence of VD.

Overall agreement indicated that vHIT assessment and clinical diagnoses matched in roughly two-thirds of cases (68.5-69.7%) across all three analyses. However, the corresponding Cohen's kappa were only in the fair range (.378-.405), suggesting that most of the agreement may be due to chance rather than true diagnostic concordance.

In a similar study by Janky et al. (2018), mean VOR gain values remained the strongest single vHIT parameter to predict VD with an overall agreement of 83.8%, closely followed by saccades with 83.1%, while the combination of the two yielded the best result of 84.6%[39]. Although outperforming the overall agreement of this study's analyses, it shows a similar pattern, where the combined parameters offer a slightly increased reliability.

4.1.2. Predictability of Individual Vestibular Disorders

For this section, when comparing studies, the number outside the parentheses will represent the findings of the mentioned studies, whilst those inside the parentheses will represent the findings of this study.

The expected prevalence of the individual VDs differed from those observed in Table 1, including BPPV 50% (32.3%) and MD 18% (7.0%), whereas the anticipated prevalence of VN closely approximated that observed in this study 14% (14.3%)[4].

Since the non-VD population was identical for all the sub-analyses, the specificity (96.1%) was indistinguishable throughout the analyses. It is also noted that the number of VD-positive subjects for the individual VDs differed from those mentioned in Table 1. This was due to the subjects with overlapping pathologies being excluded from the subgroup analyses to establish homogenous samples. Also, the definition of a pathological vHIT test for all sub-analyses was the combination of both a low mean VOR gain value and concomitant saccades. Lastly, no sub-analysis for vestibular hypofunction was undertaken due to the marked etiological heterogeneity of the disorder, which would have rendered any such analysis unreliable.

BPPV performed poorly on all metrics except for the NPV (76.9%) and overall agreement (75.2%), both statistically significant. It can therefore be concluded that vHIT cannot reliably predict BPPV, expectedly, since loose otoconia cause brief, position-dependent cupular deflection[40] rather than a sustained high-frequency VOR deficit[16]. Therefore, vHIT should remain normal even in clear and classical cases of BPPV. In accordance with this, Abduralrahim et al. (2022) found that vHIT currently has no use in BPPV diagnostics, regardless of the affected SCC[41]. Conversely, a meta-analysis by Elsheriff et al. (2021) observed a statistically significant association between the presence of reduced VOR gain and posterior SCC lithiasis[42]. However, no statistically significant association was found in the case of anterior and horizontal SCC lithiasis[42]. This suggests that any inference of vHIT as a predictor of BPPV should include analysis of the posterior SCCs[42,43], as 47.8–85.2% of BPPV cases involve these canals[44,45]. Finally, Castelucci et al. (2020) reported vHIT sensitivities of 72.9–88.6 % for identifying vertical canal BPPV, supporting its potential use in detecting anterior SCC involvement[46].

MD included the least prevalent VD within the VD population. This disease had the lowest sensitivity, PPV, and Cohen's kappa, all not statistically significant. Overall, the sample size was insufficient to assess vHIT in this population. The high specificity (96.1%), NPV (93.5%), and overall agreement (90.1%), all statistically significant, suggest that a normal vHIT reliably indicates the absence of MD. Conversely, Cohen's kappa of .017 suggests that it is only slightly more effective than would be expected by chance. Tamanini et al. (2023) reported that patients with MD often will present with a positive caloric test and a normal vHIT[47]. Notably, only 47% showed the combination of an abnormal caloric test with a normal vHIT, highlighting that this

dissociation is a common finding in MD[47]. This is similarly observed in two studies, which found no correlation between the presence of MD and a pathological vHIT[48,49]. Kaci et al. (2020) reported reduced VOR gain associated with the ictal paretic phase for MD. However, no association for reduced VOR gain was found for the rest of the ictal phase or outside the ictal period[50].

VN had the highest sensitivity (85.3%), NPV (97.9%), and concordance of all (94.8% and .770). Interestingly, the PPV was only 75.3% and is assumed to be underestimated, which is attributed to the mismatched proportion of the VN to the non-VD population. The proportion of VN subjects could have been greater, since VN subjects may have been asymptomatic at the time of assessment or were never evaluated, as more than 40% experience complete remission[51]. Still, VN is the most reliably assessed VD by means of a vHIT examination. VHIT is especially useful for this disorder in terms of identifying the non-VD population due to the high specificity (96.1%) and NPV (97.9%). All mentioned metrics were statistically significant. A systematic review by Manzari et al. (2021) found nearly identical sensitivity 87.9% (85.3%), specificity 94.8% (96.1%), and NPV 95.8% (97.9%) to those of this study. However, as expected, a markedly increased PPV of 85.3% (75.3%) was observed, confirming the authors' assumption of underestimation[52].

VS showed the second lowest sensitivity (35.1%), although not statistically significant. PPV (65.6%) and Cohen's kappa (.382), both statistically significant, were low, which discredits vHIT's ability to confirm the presence of VD and merely indicates fair agreement when accounting for chance. However, the high specificity (96.1%) and NPV (87.5%) indicate that vHIT is of value when predicting non-VS cases. A similar study done by Aalling et al. (2020) involving 42 unilateral VS patients found similar sensitivity, 40.5% (35.1%), and specificity 97.6% (96.1%) to those of this study. However, markedly distinct NPV 62.1% (87.5%) and PPV 94.4% (65.6%) were observed[53]. The discrepancy of NPV and PPV may be attributed to the major proportional difference between the healthy and non-healthy groups in the studies. Moreover, Aalling et al. tested all six SCCs, and therefore both the inferior and superior vestibular nerves, with two separate vHIT systems[53]. In contrast, this study only included tests of the VOR of the horizontal SCCs. Therefore, the function of the posterior canal and the inferior vestibular nerve (the origin of 90% of vestibular schwannomas) was not part of the assessment[53].

4.1.3. Poor-Quality Markers and Artifacts

The majority of subjects, who were excluded from analyses due to poor quality, had only one PQM that was accountable for the exclusion. In addition to this, most of the excluded subjects had either one artifact or none. In a clinical setting, this means that examiners should be aware of the most common PQMs as listed, as only one PQM may substantially impair or alter the post-vHIT evaluation. Also, examiners should keep in mind that while artifacts do not occur in approximately half of the poor-quality vHIT examinations, it might only require one artifact to substantially impair the "visual" interpretation of the vHIT test report.

4.1.4. Overlapping Pathologies

Murphy et al. (2024) and Roberts et al. (2020) display BPPV as one of the most frequently co-occurring VDs, estimating involvement of BPPV in 62.9-69% of cases for multiple VD pathologies, which was similar to the 71.4% observed in this study[54,55]. However, this overlap only accounted for 8.0% of BPPV subjects. As such, the rate of co-occurring vestibular pathologies may not be sufficiently large as to warrant implementation solely out of concern for missing other VDs. It is noted that only the BPPV subjects with high vHIT quality were included, since this study focused on reliable vHIT assessments.

4.2. Video Head Impulse Test Quality Assessment and Interpretation

Consensus on quality control (QC) and parameters defining a vHIT examination of sufficient quality for evaluation has yet to be established. This leads to ambiguous guideline recommendations.

The general consensus on the appropriate number of HIs is 10-20 per SCC[10], whilst the manufacturer of the vHIT system used with this study and Wenzel et al. (2019) argue that 2-5 high-quality HIs are sufficient[56,57]. Heuberger et al. (2018) defined QC as peak head velocities >100°/s and no artifacts, where only 3.2% of vHITs were excluded due to poor quality[58]. Mantokoudis et al. (2014) defined QC as peak head velocities between 100-200°/s and 10-50 HIs. Similar artifacts to this study were implemented as well, classified as either interpretable or uninterpretable[59]. 42% of vHIT examinations were classified as uninterpretable, similar to the 40.5% of excluded vHIT examinations in this study.

Thus, it remains difficult to establish boundaries and precise definitions for optimal and sufficient QC, as there is substantial variation between individual studies.

Abrahamsen et al. (2018) reported that interexaminer limits of agreement, who followed the same protocols with the same subjects, were up to 0.24 for the horizontal SCCs[17]. This emphasizes the need for a uniform consensus, as this trend is more likely to worsen when protocols vary.

With respect to mean VOR gain values, Curthoys et al. (2023) reported the use of three different gain calculation methods with different types of vHIT equipment (instantaneous-, regression-, and area under the curve gain)[60]. With the definition of a pathologically low mean VOR gain value, Faranesh et al. (2023) reported that the established cut-off value of VOR gain <0.80, indicative of SCC dysfunction, was associated with a substantial risk of false positives and recommended reconsideration of this limit[61].

With classification of pathological saccades, no cut-off values regarding size or occurrence exist as they vary substantially among different examiners and are based on non-vestibular factors[60]. With the interpretation of saccades, analysis differs from visual assessment by expert opinion (lowest grade of evidence-based practice)[53] to quantitative assessment (PR score)[62].

Overall, due to the lack of consensus on all factors related to vHIT testing (participant-based factors, tester/examiner-based factors, protocol-based factors, and equipment-based factors) inter-vHIT study comparisons remain difficult.

VHIT has the potential to revolutionize vestibular testing. However, the immense lack of consensus with all factors related to this test, the vHIT examination remains subject to a large degree of intra- and inter-examiner variation. One very important factor also worth considering is the fact that 40.5% of vHIT analyses in this study had to be excluded due to poor test quality.

4.3. Strengths and Limitations

This study chose to limit vHIT assessment to the horizontal SCCs, as studies argue that the vertical HIs are more difficult to perform reliably than the horizontal HIs[33,37]. The vHIT system used with this study has, in previous vHIT studies, shown to exhibit an alarmingly high intra- and interexaminer variability with vertical SCC testing and has moreover not been validated for vertical SCC testing[37]. However, testing of the horizontal SCCs with this vHIT system has shown equal (and low variability) when compared to another vHIT system[37]. Conversely, exclusion of the vertical SCCs might also pose as a limitation, as a higher sensitivity across all analyses may have been observed. This is likely attributable to some pathologies primarily identified through examination of these[43]. That would include a VS and a VN with affection of the inferior vestibular nerve only[43,53] as well as otoliths affecting the function of the posterior SCC[43].

A key aspect of this study was the focus on the quality of the vHIT test reports. An evident problem, as 763 out of 1886 (40.5%) were excluded due to poor test quality. This might have caused the exclusion of subjects that could have contributed significantly to the study results. On the other hand, it also allowed conclusions to be drawn with greater confidence. This was due to a reduced risk of both intra- and interexaminer variation with the rather subjective vHIT evaluation. Furthermore, the diagnostic reasoning of this study adheres to the International Classification of Vestibular Disorders according to the Bárány Society, ensuring the validity of the VD population. The extended time frame for subject diagnosis was also a strength, as it allowed the inclusion of conditions that require lengthy observations and evaluations beyond the initial consultation.

5. Conclusion

With overall screening for a vestibular disorder, results from this study favor combining both vHIT parameters (gain and saccades) with assessment of the VOR function of the horizontal SCCs. In case of a vHIT examination with pathological mean VOR gain values and ambiguous pathological saccades, the parameter of gain only should be applied. VHIT in isolation cannot be recommended for an overall screening for VD; however, the results of this study suggest the use of vHIT as a first-line vestibular test. The results of this study do not favor the use of vHIT for the identification of specific VD in general, but show promising results with the identification of a VN. A large proportion of vHIT examinations (40.5%) had to be excluded due to poor test quality. As a direct consequence hereof, it is of paramount importance for clinicians to establish consensus protocols that define specific criteria for all factors that are known to be at risk for altering vHIT results. This study especially recommends inclusion of criteria for maximum VOR gain and head impulse velocity, as well as being mindful of wrongful calibration and patient inattention when conducting vHIT examination.

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