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Vestibulometry, the registration of responses to stimulation of the vestibular organ with stimuli of different frequencies

Authors' Contribution:
A – Study Design
B – Data Collection
C – Statistical Analysis
D – Data Interpretation
E – Manuscript Preparation
F – Literature Search
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ABSTRACT:

Introduction: The vestibular organ (VO) is essential for maintaining balance and stabilizing visual images during head movements. To evaluate its function, the strength of the vestibulo-ocular reflex (VOR) is assessed using kinetic tests like the Sinusoidal Harmonic Acceleration Test (SHAT), video Head Impulse Test (vHIT), and slow-phase peak velocity (SPV) measurement in the caloric test (CT). Despite their limited sensitivity and specificity, they are used to determine eligibility for positions requiring strong balance control.

Aim: To determine the range of VOR gain in young healthy individuals in SHAT, vHIT and CT. To search for correlations between vestibular test results and age and gender of the subjects.

Materials and methods: Sixty two healthy individuals, with 32 males and 30 females, aged 7 to 33 who met the inclusion criteria were included in the study. Each participant underwent SHAT, vHIT and CT. Standard statistical methods and Spearman's rank correlation were used.

Results: The age of the subjects correlated negatively with the VOR gain in SHAT. There was no correlation between results for SHAT, vHIT or CT.

Discussion: Various factors, such as vestibular stimulation and anatomical variations, affect vestibular test results. While these tests complement each other in diagnosing vertigo, they are not recommended for healthy individuals qualifying for high-vestibular-performance occupations.

Conclusions: With age, the sensitivity of the VO to kinetic stimuli decreases. The inability to calibrate stimuli can result in varied responses among individuals. A comprehensive evaluation of the VO requires testing across different frequency ranges.

KEYWORDS: caloric test, SHAT, vestibulometry, vHIT, VOR

ABBREVIATIONS

CT – caloric test
ENG – electronystagmography
SCC – semicircular canal
SHAT – Sinusoidal Harmonic Acceleration Test
SPV – slow-phase peak velocity
TotL – sum of maximum SPV for the left ear
TotR – sum of maximum SPV for the right ear
vHIT – video Head Impulse Test
VO – vestibular organ
VOG – video-oculography
VOR – vestibulo-ocular reflex

INTRODUCTION

The natural stimulus for the auditory organ is sound, just as movement is a stimulus for the vestibular organ (VO). Under natural conditions, stimulation of the cochlea leads to the awareness of sound, while stimulation of the vestibular system aims to maintain balance and stabilize the image on the retina during head movement. The VO serves as a receptor for the vestibulo-ocular, vestibulo-cervical, and vestibulo-spinal reflexes.

In the vestibulo-ocular reflex (VOR) during head turn to the right, there is an increase in activity of crista ampullaris of the right horizontal semicircular canal (SCC) and inhibition of the left side. The information from the stimulated SCC is encoded in neuronal impulses of the superior vestibular nerve and transmitted to the vestibular nuclei in the brainstem. Then the signal reaches the contralateral abducens nucleus (cranial nerve VI) via the medial longitudinal fasciculus, which innervates the lateral rectus muscle. At the same time, the abducens nucleus sends a signal to the contralateral oculomotor nucleus (cranial nerve III), which innervates the eye medial rectus muscle. This means that after the right SCC is stimulated, there is simultaneous contraction of the lateral rectus muscle in the left eyeball and the medial rectus muscle on the opposite side. This results in the eyeball turning in the opposite direction of the head turn. The VOR gain is defined as the ratio of the angle of deviation of the eyeball from the resting position to the angle of head turn [1, 2].

$$VOR\ gain = \frac{The\ range\ of\ eye\ deviation}{The\ range\ of\ head\ turn}$$

This value, even in healthy and physically fit individuals, rarely reaches 1. The VOR is regulated by the activity of the cerebellar flocculonodular lobe [1, 3]. In natural conditions, the VOR is assisted by the action of the visual system, in the form of gaze fixation, smooth pursuit eye movements, optokinetic movements, and saccades. When assessing the VO performance, based on the ratio of the strength of the oculomotor response to the strength of the stimulus, the influence of other visual reactions should be eliminated. Therefore, assessing the VOR strength in kinetic and caloric tests should be performed in complete darkness [4, 5]. In video-oculography (VOG), the eye should be covered, and in electronystagmography (ENG), the patient should have their eyes closed. Conducting the test in darkness with the elimination of visual reinforcement makes the oculomotor reaction weaker and does not reflect the functioning of the VO under natural conditions [6].

In studies using Sinusoidal Harmonic Acceleration Test (SHAT) the performance of the VO is evaluated by calculating the average VOR gain from individual measurements obtained while rotating the patient on the chair to the right and left with variable frequency [7, 8]. In another kinetic test, the video Head Impulse Test (vHIT), the VOR gain value is calculated separately for the left and right VO. In this test, the VO is stimulated with short, rapid head movements, and repetitions are performed to obtain reliable results. VO paresis or paralysis can only be diagnosed if a significant decrease in VOR values is accompanied by pathological saccades [9]. In caloric tests (CT), VO capacity is assessed by the nystagmus response induced by heating or cooling of the SCC. Temperature changes in the SCC lead to increased endolymph flow, reflecting the stimulation of head movement. As the VO stimulus is not a movement, VOR gain cannot be estimated directly. VO sensitivity in this test refers to the slow phase peak velocity of the evoked nystagmus (SPV), separately for the right and left ear [10].

The VO responds most strongly to stimuli with frequencies between 0.05 and 6.0 Hz, which correspond to the range of head movements performed during normal human activities. In this frequency range, the strength of the oculomotor response in a healthy individual should be directly proportional to the strength of the stimulus applied. In SHAT, lower-frequency stimuli are used, while vHIT uses higher frequencies optimal for evoking the VOR. In CT, the vestibular system is stimulated with very low-frequency, non--physiological stimuli of approximately 0.003 Hz. The stimulation frequency refers to the period of deflection of the cupula of the SCC [3]. The pronounced nystagmus response to such a weak caloric stimulus is made possible by the amplification by the neuronal loop of the vestibular nuclei and the velocity storage fibers connecting them and the cerebellum [3, 11]. The influence of the amplifier results in an exponential relationship between the strength of the oculomotor response and the strength of the stimulation in CT. Like the cochlea, the vestibular system can also be stimulated with stimuli at different frequency ranges. However, unlike the auditory organ, the degree and strength of the vestibular response depend not only on the intensity of the stimulus, but also on its frequency [4]. In some countries, VO dysfunction is a contraindication for working in aviation, military, and police services [12–16]. Despite the low sensitivity and specificity of these tests in detecting VO impairments, they are often used for medico-legal purposes and for qualification for jobs requiring a prominent level of balance maintenance. There are cases of disqualification from such occupations due to allegedly abnormal CT results, even though candidates passed demanding physical fitness tests and presented no symptoms of vestibular dysfunction.

AIM

1. To determine the range of VOR gain in young and healthy individuals in the SHAT and vHIT kinetic tests, as well as SPV in CT;
2. To search for correlations between VOR gain values in SHAT, vHIT, SPV in CT, age, and gender in the study population;
3. To search for a screening test to assess VO performance.

The study was positively reviewed by the Bioethics Committee at the Beskid Medical Chamber. Opinion 2023/10/5/4.

MATERIALS AND METHODS

Materials

Sixty-two young, healthy individuals (32 males and 30 females) aged 7 to 33 years were included in the study.

Inclusion criteria for the study group:

1. absence of symptoms of dizziness and balance disorders;
2. normal results of Romberg, Unterberger, and Fukuda postural tests;
3. normal motor development in the early years of life;
4. absence of nystagmus and other involuntary, pathological eye movements;
5. normal hearing threshold in tonal audiometry.

Candidates were excluded from the study group if:

1. spontaneous nystagmus was recorded during the candidate's examination;

2. eye defect prevented the recording of nystagmus reactions in vestibular tests;
3. the candidate complained of previous episodes of dizziness or balance disorders;
4. disorders or defects of the nervous system were diagnosed;
5. deviations from the norm in Romberg, Unterberger, or Fukuda tests were observed;
6. lack of patient cooperation during the examination;
7. they obtain unreliable test results;
8. hearing impairment, when the average hearing loss for frequencies: 0.5, 1.0, 2.0, 4.0 KHz was greater than 25 dB HL and the hearing threshold for frequencies 6.0 or 8.0 KHz was higher than 35 dB HL;
9. the candidate did not consent to the examination or processing of personal data.

Methods

Vestibular tests (SHAT, vHIT, CT) were performed on each participant in the study group:

1. During the SHAT test, the patient is rotated on a chair around the axis of the body in a harmonic motion with sinusoidally varying acceleration to the right and left. This test was conducted at various frequencies: 0.4 Hz, 0.8 Hz, 1 Hz, 0.16 Hz, 0.32 Hz, and 0.64 Hz. The VOR was monitored using VNG goggles with covered eyes. The parameter measured during the SHAT was the VOR gain [8];
2. In the vHIT, head movements in the plane of the lateral semicircular canals were used to stimulate the VOR. The peak angular head acceleration ranged from $2000°/s^2$ to $4000°/s^2$. The VOR gain was estimated at 60 ms after the start of stimulation. Stimulation was repeated 15 to 20 times in each case to obtain reliable results [9];
3. In the CT, both VOs were sequentially irrigated with air at a temperature of 44°C, then cooled to 30°C. Between each stimulation, the test was paused to allow for equalization of temperature in both ears. Horizontal SCCs were assessed. The participant lay with their head tilted approximately 30° towards their chest. Eye movements were recorded using VNG. The parameter used to evaluate vestibular function was the SPV measured in degrees per second. The recorded and compared values of the nystagmus reaction in this test were:
   a. Caloric stimulus response calculated for each ear separately, expressed as the sum of the maximum SPV obtained by stimulating the ear with warm and cold stimuli (TotR, TotL) [10];

TotR = R44° + R30° for the right ear

TotL = L44° + L30° for the left ear

   b. Total SPV calculated as the sum of the maximum nystagmus velocity obtained in the left and right ears in response to warm and cold air stimulation.

SPV_{total} = TotR + TotL

Statistical analysis method

Standard statistical methods were used to conduct statistical analysis in the study. Qualitative data were presented as frequencies with percentages [n (%)]. The normality of the distribution of quantitative data was checked using the Shapiro-Wilk test. The obtained results in the study had a non-normal distribution, so they were presented as median with first and third quartiles [median (Q1;Q3)]. Spearman's rank correlation was used to assess the monotonic relationship between quantitative variables, and the results were presented as Spearman's Rho with a 95% confidence interval. A significance level of $\alpha = 0.05$ was adopted. All calculations were conducted using the program PS IMAGO PRO 9.0.

RESULTS

The study was conducted on a group of 62 people, with 32 men (51.6%) and 30 women (48.4%). The median age of the patients was 15 years (11;20), with an age range from 7 to 33 years. The hearing loss in the right ear ranged from 10 to 35 dB, with a median of 15 (10;20). In the left ear, the range also ranged from 10 to 35 dB, with a median of 15 (10;15). Extensive data are presented in Tab. I.

Significant correlations:

1. Age and VOR gain in SHAT – moderate negative correlation (rho: –0.44, 95%CI: (–0.63)–(–0.2), p<0.001) – as age increases, the value of VOR obtained in SHAT decreases;
2. Hearing loss in right and left ear – strong positive correlation (rho: 0.58, 95%CI: 0.38–0.73, p<0.001) – as hearing loss in one ear increases, the value of hearing loss in the other ear also increases;
3. VOR gain in VHIT for right ear and VOR gain in VHIT for left ear – strong positive correlation (rho: 0.57, 95%CI: 0.35–0.72, p<0.001) – the higher the value of VOR in the VHIT test for one ear, the higher the result in the same test for the other ear;
4. TotR and TotL – strong positive correlation (rho: 0.61, 95%CI: 0.4–0.75, p<0.001) – the higher the score in CT for one ear, the higher the score in the same test for the other ear.

There was no correlation observed between the results obtained from assessing the VO using different methods:

1. VOR gain obtained in VHIT and in SHAT: rho 0.02, 95%CI: (–0.25)–0.29, p = 0.88;
2. SPV values obtained in CT and VOR gain in SHAT: rho 0.02, 95%CI: (–0.26)–0.29, p = 0.90;
3. VOR gain obtained in VHIT and SPV in CT: rho 0.14, 95%CI: (–0.14)–0.41, p = 0.30.

It is also not possible to extrapolate the results of one study to the results of the others. A comprehensive assessment of the vestibular system requires testing in various frequency ranges.

Tab. I. Results of vestibular tests.

	MEDIAN (Q1;Q3)	MIN-MAX
Age [years]	15 (11;20)	7–33
Hearing loss in RE	15 (10;20)	10–35
Hearing loss in LE	15 (10;15)	10–35
VOR gain in SHAT	0.4 (0.3;0.5)	0–0.8
VOR gain in VHIT RE	0.93 (0.85;1.05)	0.4–1.46
VOR gain in VHIT LE	1 (0.92;1.07)	0.43–1.52
VOR in VHIT$_{mean}$	0.97 (0.89;1.06)	0.42–1.49
TotR [°/s]	19.8 (14.15;29.8)	5.2–67.3
TotL [°/s]	24.2 (15.05;34.65)	7.5–78.3
SPV$_{total}$ [°/s]	46.8 (32.65;63.7)	13.9–145.6

Q1 – quartile 1; Q3 – quartile 3; SHAT – Sinusoidal Harmonic Acceleration Test; SPV – slow phase peak velocity; TotL – sum of maximum SPV for the left ear; TotR- sum of maximum SPV for the right ear; LE – left ear; RE – right ear; VHIT – video head impulse test; VOR – vestibulo-ocular reflex.

DISCUSSION

In the obtained results of the SHAT, vHIT, and CT, a wide range of vestibular responses was recorded. Such variability in the response strength indicates the inability to establish a definitive calibration of the stimulus in these tests. Therefore, the same stimulus can evoke vestibular responses of varying intensity in two different, yet healthy and young individuals.

Factors influencing the results of each of the above vestibular tests can occur at the following levels:

1. The method of stimulating the vestibular system.
2. Receptor:
   a. anatomic structure of the vestibular system – proximity of the SCCs tested with those not tested;
   b. inaccurate alignment of the plane of the tested canal to the vector of gravity.
3. Recording of the oculomotor response of the VNG;
4. The examinee and their ability to inhibit evoked nystagmus;
5. The examiner and their experience in performing the test.

Re 1. This restriction pertains specifically to the kinetic vHIT, primarily passive head movements performed during the examination. These movements should have a jerky character with an angular deviation of about 15° in both directions. The patient's active movements may disrupt the test results, especially if there is asymmetric tension in the neck muscles, which may prevent accurate stimulation of the VO. As a result, despite repeated stimulation, the VOR value may inadequately reflect receptor performance. SHATs are less vulnerable to such variables, although the results may still be disturbed by additional head movements of the examinee, even when limiting them with the chair headrest. In CT, different thermal conduction in the right and left ear should be considered. To minimise this variable, each examination should be preceded by an otoscopic examination. If necessary, accumulated wax or epidermal masses in the ear canals should be removed. The different conduction of the thermal stimulus can also be caused by the asymmetrical structure of the external ear and surrounding tissues. Therefore, even when delivering air at the same temperature to both ears, the temperature at the receptor level may differ.

Re 2a. The proximity of the otolith organ and the SCC prevents isolated stimulation of individual parts of the VO, especially during kinetic SHAT and vHIT. By stimulating the horizontal SCC, the vertical canals, the utricle, and the saccule are simultaneously affected, which may impact the VOR. With proper head positioning, one can only assume that the response will be strongest from the canal located in the plane of stimulation.

Re 2b. In CT, the horizontal SCC should be positioned vertically, parallel to the gravity vector. Therefore, the patient lying down should have their head bent towards their chest at a 30° angle and stabilized with a headrest. For VHIT and SHAT, the sitting patient's head should be tilted 30° downwards so that the canal plane is parallel to the ground. Any deviations from these positions may lead to weaker stimulation of the VO.

Re 3. In VNG recording, the oculomotor response is significantly influenced by numerous factors. These include visual impairments, the width of the patient's palpebral fissures, blink rate, dry eye syndrome, and the possibility of goggles slipping during the subject's head movements. In the case of SHAT, the study may be disrupted by frequent changes in phase and direction of stimulation, as well as any overlapping eye movements on nystagmus reactions.

Re 4. In vestibular testing, the nystagmus response may be inhibited by the patient themself. Studies have shown that SPV values in CT and VOR strength in kinetic tests are reduced in patients who experience test anxiety. To minimize the effect of central inhibition on VOR values, it is recommended to give the patient a task to distract them from the test being performed (tasking) [17].

Re 5. Despite a detailed protocol for conducting the test, the results are influenced by the person performing the test and their experience. In this study, all tests in the research group were performed by the same experienced professional.

Although the vHIT, SHAT, and CT all examine the same sensory organ, the method and frequency of stimulation differ between these tests. The strongest oculomotor response would be expected after stimulation of the VO with head movements between 0.05 and 6.0 Hz, relating to the frequency range of head movements performed during daily human activities. In the SHAT, the VOR was stimulated with head movements at frequencies between 0.4 and 0.64 Hz, which are lower than optimal for VO stimulation. In vHIT, the stimulation frequency is higher, ranging from 0.9 to 10 Hz. In contrast, in CT, the organ is stimulated with a non--physiological stimulus at an extremely low frequency of 0.003 Hz. To elicit an oculomotor response with such a weak stimulation, it is necessary to enhance the signal through the velocity storage mechanism at the level of the vestibular nuclei. The relationship between the oculomotor response and stimulus intensity in the optimal frequency range for VO excitation, as in vHIT and SHAT, should be linear. In contrast, for weaker stimuli, as in CT, the relationship is exponential.

According to Kaga, based on studies on the Barany chair, the maturation of VOR lasts until the age of 6, which is why children younger than 7 years old were excluded from the study [5]. Younger children are also more likely to experience test anxiety and cooperate poorly during the examination. In individuals aged 7 to 33 years old, the VOR gain in SHAT decreases with age, as confirmed by observations by Chan et al. [18]. In contrast, a study by Yu et al., conducted on 109 patients aged 20 to 57, suggests that age has a minimal impact on the results of rotary chair testing [7]. However, Ghoraba et al., studying 100 individuals aged 20 to 67, did not observe an effect of age on VOR in SHAT [19]. It remains unclear whether the aging process of VO begins after reaching maturity between the ages of 6 and 7, or if a low excitability threshold of the VO is unnecessary at a later age.

In our study, we did not find a correlation between VOR in vHIT and SPV in CT in healthy individuals, confirming the observations of Liu et al. [20]. However, El Bouhmadi et al., Fattahi et al. and Strupp et al. confirmed this correlation in patients with unilateral VO weakness [21–24]. Fattahi et al. also found no correlation between vHIT, SHAT and CT results in patients with peripheral and central VO dysfunction. According to these authors, there is no single vestibular test that is universally applicable, and these tests complement each other. In case of detecting a vestibular deficit in one test, the diagnosis should be confirmed by another test [22].

In the 2018 textbook, Zalewski compared vestibular tests to audiometric tests, arguing that obtaining normal results from one trial does not necessarily indicate the efficiency of the vestibular system, just as estimating the threshold for one tone is not a reliable indicator of good hearing [8]. Vestibular tests differ significantly from hearing threshold tests, as they do not allow for a quantitative determination of vestibular impairment in different frequency ranges. They only allow a qualitative assessment of the organ's performance and enable comparison of the right VO with the left, such as vHIT and CT. Even the diagnosis of bilateral vestibulopathy requires analysis not only of the vestibular test results, but primarily of the clinical manifestation of the disease on physical examination [21–24]. Despite their numerous limitations, vestibular tests are a valuable complement to the diagnosis of dizziness and balance disorders. However, there is no justification for performing these tests on healthy candidates for specific professions, such as aviation, or police, or military service, in individuals who do not have clinical symptoms of VO dysfunction.

CONCLUSIONS

1. Vestibular tests: SHAT, VHIT, and CT do not allow for stimulus calibration; therefore, in two different healthy individuals, an identical stimulus may result in responses of different severity;
2. The sensitivity of the vestibular system to motion stimuli in people aged 7 to 33 years decreases with age;
3. In healthy young individuals, no correlation was observed between VOR gain in SHAT and VHIT, as well as SPV in CT. Therefore, in clinical diagnostics, it is important to conduct more than one vestibular test.

STATEMENT

This study is part of the doctoral dissertation of Michalina Śpiewak.

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