Visual Acuity While Walking and Oscillopsia Severity in Healthy Subjects and Patients With Unilateral and Bilateral Vestibular Function Loss

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Objectives: To assess visual acuity (VA) while the patient is walking and to evaluate oscillopsia severity in patients with bilateral vestibulopathy (BV) and in patients with unilateral vestibular loss (UVL).

Design: Prospective study with a group of patients with BV, a group of patients with UVL, and a control group of healthy subjects.

Setting: Tertiary academic center.

Participants: Thirty seven patients with BV (age range, 29-80 years), 11 patients with UVL (age range, 48-75 years), and 57 healthy subjects (age range 20-77 years).

Intervention: Computation of the difference between the VA measured in static conditions and in dynamic conditions while walking on a treadmill at 2, 4, and 6 km/h. Oscillopsia severity was assessed with a questionnaire that we developed.

Main Outcome Measures: Differences in VA at 2, 4, and 6 km/h and oscillopsia severity score.

Results: As a group, patients with BV showed a significant increase of the VA differences compared with healthy subjects (P < .001) and patients with UVL (P < .001) for all 3 walking velocities. Normality thresholds were defined as healthy subjects’ 95% CI. Sensitivity of the test was 97% for discriminating patients with BV. Moderate to extreme oscillopsia severity was found in 81% of patients with BV and in 9% of patients with UVL. Differences in VA did not correlate with oscillopsia severity scores in patients with BV (P > .05 for all comparisons).

Conclusions: We designed a highly sensitive, simple, cost-effective protocol to assess dynamic VA under physiologic conditions and a questionnaire to determine oscillopsia severity. Both tools could be used for the evaluation of new treatments for BV and patients with UVL.


Walking is probably the most common form of motion for an active adult. During moderately fast walking (6 km/h), a combination of vertical and horizontal translational and rotational head movements is induced. Vertical head translation occurs at the stepping frequency (2 Hz), and lateral head translation at the stride frequency (1 Hz). Peak head pitch and yaw angular velocities are around 17°/s, which is in the functional range of vestibuloocular reflex (VOR).1 The induced image slip on the retina is greatly compensated by the VOR, which generates compensatory eye movements opposite to head movements. In healthy subjects, a gain (eye velocity/head velocity) close to 1 allows efficient image stabilization on the retina. In with bilateral vestibulopathy (BV), the VOR is significantly impaired or absent. Thus, with high-frequency head movements (>1 Hz), the retinal slip cannot be optimally compensated. Because the threshold for perception of retinal drift is close to 1°/s in healthy subjects,2 high-frequency head movements can lead to oscillopsia, an illusion of movement of the visual environment. For low-frequency head movements (<1 Hz), the optokinetic reflex and, to a certain extent, the cervicoocular reflex can generate compensatory eye movements.3 Efficient stabilization of the image on the retina is also necessary to preserve visual acuity (VA) during head movements. Indeed, VA decreases rapidly when the retinal slip exceeds the threshold of few degrees per second (2.5°/s-4.0°/s).4 Illusory perception of motion and decreased VA during head movements can be experienced simultaneously by pa-

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tients with BV, and the combination is often described without distinction as “blurred vision,” one of the main complaints of patients with BV, and can lead to a significant deterioration of quality of life. Although patients with BV have reported a certain subjective improvement after vestibular rehabilitation, there is unfortunately no evidence of an efficient treatment. Zingler et al. found that, independent of the etiology, in more than 80% of 82 patients with BV who had at least 3 months of vestibular training, there was neither a subjective improvement in their condition nor an improvement in their vestibular reflexes (follow-up range, 3 months to 13 years after initial diagnosis).

The idea of a vestibular implant that could provide the central nervous system with information about head angular velocities by electric stimulation of the vestibular nerve has emerged. Recently, partial recovery of the VOR has been achieved by electric stimulation of the semicircular canals of labyrinthine-defective monkeys. In humans, important steps toward the development of a vestibular implant have been made. Surgical approaches to electrode implantation sites have been described, and the first electric stimulations of the vestibular nerve have shown that it is possible to elicit controlled eye movements.

If VOR can be restored in humans, specific tests to select and monitor vestibular implant candidates will be needed. Gaze stabilization can be tested with the Head Impulse Test (HIT) in the 3 different semicircular canals planes. The presence of corrective ocular saccades reveals an abnormal VOR function. Gaze stabilization performance can also be evaluated by measurement of the VA during active or passive, vertical and horizontal head movements; this process is called dynamic VA (DVA). Passive high angular velocity (150°/s) movements allow best discrimination between patients with unilateral vestibular loss (UVL) or bilateral vestibular loss and normal subjects.

A drawback of these approaches is the nonphysiologic stimuli that are applied. In the present study, we opted for VA measurements while the patient was walking on a treadmill at different velocities, which corresponds to physiologic stimuli. The fact that the test cannot discriminate the side, in a case of unilateral vestibular loss, is not relevant because we aim to select patients with bilateral impairment of the vestibular function.

Visual acuity testing has already been investigated under similar conditions, showing a significant DVA decrease in patients with BV compared with healthy subjects. The correlation between DVA and oscillopsia severity was not assessed. For horizontal movements, it was shown that oscillopsia severity is most likely related to retinal slip tolerance level and not to retinal slip amplitude itself. Our aim was to develop and implement a DVA protocol for a patient walking on a treadmill that is simple, cost-effective, quick, and sensitive. Second we aimed to correlate DVA performance to oscillopsia severity assessed with a questionnaire that we also developed. Grading of oscillopsia severity has been previously demonstrated with a visual analog scale or a questionnaire developed by researchers for that specific purpose. Nevertheless, to our knowledge there is no standardized way of assessing oscillopsia severity. Both the DVA protocol and the oscillopsia severity questionnaire described herein should allow evaluation of treatments for patients with BV and patients with UVL.

### METHODS

#### TEST SUBJECTS

Thirty-seven patients (20 men and 17 women; mean age, 56 years; age range, 29-80 years) with BV were observed at the Division of Balance Disorders at Maastricht University Hospital between January 2010 and May 2011. They all fulfilled inclusion criteria: (1) mean peak slow phase velocity of 5°/s or less in bilateral bithermal caloric irrigations; (2) pathologic HIT for horizontal and vertical canals; and (3) a gain of 25% or less on rotatory chair tests. Electronystagmography (ENG) was used for vestibular testing. Bilateral bithermal (30°C and 44°C) caloric irrigations with water were performed by experienced technicians under standard conditions. Rotatory chair tests consisted of horizontal torsion swing (0.1 Hz; maximum velocity, 100°/s) and bilateral velocity steps (velocity, 250°/s). Manual HITs were recorded with a high-speed camera (Casio Exilim, Pro EX-F1; Casio) at 12× optical zoom and 300 frames per second in the 3 semicircular canal planes. Presence of corrective saccades was considered pathologic. All recordings were analyzed by an experienced otorhinolaryngologist. All patients had a normal neurologic status and normal oculomotor function.

A group of 11 patients (7 men and 4 women; mean age, 61 years; age range, 48-75 years) with UVL was also included. They all fulfilled the following criteria: (1) unilateral mean peak slow phase velocity of 9°/s or less in unilateral bithermal caloric irrigations; (2) unilateral pathologic HIT for horizontal and vertical canals; and (3) a gain of more than 30% for horizontal torsion swing (0.11 Hz; maximum velocity, 100°/s).

As a control group, 57 healthy subjects were included (32 men and 25 women; mean age, 41 years; age range, 20-77 of years), who had no prior vestibular symptoms and normal HIT findings in the 3 semicircular canal planes.

#### VA TESTING

Visual acuity was measured in the 3 groups using a chart of Sloan letters (CDHKNORSVZ). The chart consisted of rows of 5 randomly chosen letters. As for the standard Snellen chart used by ophthalmologists, VA decreased 0.1 log unit per row on the logMAR scale. The VA scale was adapted to the test subject distance, which was 2.8 m for all measurements. The chart was positioned at eye height. Visual acuity was tested binocularly. Measurements were performed with eye corrections in place for subjects who wore glasses or contact lenses. Measurement procedures were identical in static and dynamic conditions. The experimental setup was calibrated and validated by comparison with the known VA (determined at the department of ophthalmology) in 10 healthy subjects.

Starting with letters in a row corresponding to a VA value of 1.25, test subjects had to read out the 5 letters from left to right. The VA value of the last row with at least 3 correctly named letters was recorded. Tests were performed while the subject was standing or walking on a standard fitness treadmill. The protocol started with evaluation of the static VA (SVA) while the subject was standing still on the treadmill. Then, VA was evaluated while the subject walked 2, 4, and 6 km/h. Static VA evaluation was repeated at the end of the procedure. For every measurement, the Sloan letter chart was replaced by a new one with a different letter order.

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OSCEILLOPSIA SEVERITY SCORE

A questionnaire assessing oscillopsia severity was developed specifically for this study and was administered to patients with BV and patients with UVL. Oscillopsia was defined as a “sensation that the visual environment is moving when it’s not.” The 9-item questionnaire investigated oscillopsia frequency in different situations encountered in daily life. Each item was scored 1 (never), 2 (seldom), 3 (sometimes), 4 (often), or 5 (always). Scores were averaged to provide an oscillopsia severity score ranging from 1 to 5. A mean score higher than 3 was considered to indicate moderate to extreme oscillopsia severity. Internal consistency of the questionnaire was measured with the Cronbach α statistic. The coefficient α would be 1 if questionnaire items were perfectly correlated and 0 if they were completely independent. The Cronbach α was 0.88 in the group of patients with BV. Values above 0.7 are generally considered acceptable (Figure 1).

DATA AND STATISTICAL ANALYSIS

For each velocity, the VA difference (mean SVA−DVA) was obtained. Five healthy subjects repeated the protocol 5 times. Measured VA differences were not significantly different (Friedman, Bonferroni corrected). The coefficient of variance was less than 20% for each velocity, indicating good test reproducibility. Linear regressions were used for evaluation of a correlation between healthy subjects’ VA differences at 2, 4, and 6 km/h and age. The VA differences in patients with BV were compared with those in healthy subjects and in patients with UVL using a nonparametric Mann-Whitney U test. For all 3 velocities, patients with BV and patients with UVL were considered abnormal when the VA difference was above the threshold (healthy subjects’ 95% CI [mean±2SDs]). Sensitivity of the protocol was determined for each velocity and for combinations of velocities with the following equation: true positives/(true positives + false negatives). True positives were patients with BV and an abnormal VA difference, and false negatives were patients with BV and a normal VA difference. For patients with BV and patients with UVL, correlations between the VA difference at each velocity and the oscillopsia severity score were determined with the Pearson correlation coefficient. Scores of each item of the oscillopsia severity questionnaire were compared between patients with patients with BV and those with UVL using a nonparametric Mann-Whitney U test.

RESULTS

In healthy subjects, regression analysis showed a significant relationship between VA differences and age at 4 km/h ($F = 13.71, P < .001$) and 6 km/h ($F = 4.64, P = .04$) but not at 2 km/h ($F = 0.367, P = .55$). At 4 km/h, age accounted for 19% of the variance of the VA differences and at 6 km/h, 6% (Figure 2). As a group, healthy subjects showed a significant increase of the mean VA difference between 4 and 6 km/h ($P = .002$) but not between 2 and $4 \text{ km/h} (P = .06$).

Patients with BV were therefore compared with age-matched control group A, made up of 29 healthy subjects (16 men and 13 women; mean age, 56 years; age range, 32-77 years). Mean (SD) VA differences at 2, 4, and 6 km/h were $-0.166 (0.081), -0.238 (0.119)$, and $-0.340 (0.138)$, respectively, in patients with BV and $-0.015 (0.045), -0.043 (0.037)$, and $-0.066 (0.041)$ in control group A. Mean VA differences were significantly higher in patients with BV than in healthy subjects at all 3 velocities ($P < .001$ for all). As a group, patients with BV showed a significant increase in their mean VA difference between 2 and $4 \text{ km/h} (P = .01$) and between 4 and $6 \text{ km/h} (P = .03$).

Patients with UVL were compared with age-matched control group B, made up of 20 healthy subjects (11 men
and 9 women; mean age, 60 years; age range 47-74 years). Mean (SD) VA differences at 2, 4, and 6 km/h were −0.022 (0.032), −0.061 (0.047), and −0.103 (0.090), respectively, in patients with UVL and −0.011 (0.052), −0.040 (0.040), and −0.069 (0.045) in control group B. For all 3 velocities, the mean VA difference was not significantly different (P > .05). As a group, patients with UVL showed a significant decrease in mean VA difference between 2 and 4 km/h (P = .03) but not between 4 and 6 km/h (P = .12).

Compared with patients with UVL, the mean VA difference in patients with BV was significantly increased at 2, 4, and 6 km/h (P < .001 for all) (Figure 3).

The mean VA difference 95% CIs in control group A were −0.091, −0.074, and −0.147 at 2, 4, and 6 km/h, respectively. Those values were considered as normality thresholds. At 2 km/h, 76% of patients with BV had an abnormal VA difference (n = 28). All patients with BV could perform the test at 2 km/h. At 4 km/h, 84% of patients with BV had an abnormal VA difference (n = 31); 11% had a normal VA difference (n = 4) and 6% were not able to walk at that pace (n = 2). At 6 km/h, 73% of patients with BV had an abnormal VA difference (n = 27); 6% had a normal VA difference (n = 2); and 22% could not walk so fast (n = 8).

Only 1 patient with BV had a normal VA difference at all 3 velocities. Two patients with BV had a normal VA difference at 4 km/h, with abnormal values at 2 and 6 km/h. One patient with BV had a normal VA difference at 6 km/h, with abnormal values at 2 and 4 km/h.

The sensitivity of the complete protocol, including measurements of the VA difference at 2, 4, and 6 km/h, was 97%. When testing patients’ VA differences exclusively at 2 km/h or 4 km/h, we found the sensitivities to be 76% and 84%, respectively. By combining 2 and 4 km/h, we calculated the sensitivity to be 95%.

The mean VA difference 95% CIs in control group B were −0.114, −0.120, and −0.159 at 2, 4, and 6 km/h, respectively. Those values were considered normality thresholds. Among those with normality. All of them could perform the test at all 3 velocities.

None of the healthy subjects complained of oscillopsia. In contrast, all patients with BV experienced oscillopsia. We collected 36 oscillopsia severity score questionnaires from patients with BV, and 11 from patients with UVL. Scores higher than 3 were considered to indicate moderate to extreme oscillopsia severity. No significant correlations were found at any of the 3 walking velocities between oscillopsia severity scores in patients with BV and VA differences (P > .05 for all). In Figure 4, patients with BV and patients with UVL VA differences at 4 km/h are plotted vs the oscillopsia severity scores.

Except for the mean score of item 5, patients with BV, as a group, had significantly higher individual item scores than patients with UVL (P < .05 for all comparisons) (Figure 5).

To our knowledge, the present study includes the largest group of patients with BV ever evaluated for DVA and oscillopsia severity. The proposed protocol for DVA evaluation has a high sensitivity for discriminating BV. Our data would suggest that VA measurements should be performed while the patient is walking at 2 and 4 km/h. In cases of normal VA differences, testing at 6 km/h should be added. It is a simple, cost-effective procedure that can be performed in less than 10 minutes. Prior practice or training is not necessary to perform the test, which can easily be performed by a single person. Most patients with BV could perform the test without difficulties. Nevertheless, owing to imbalance, 2 of them could not walk at 4 km/h, and 8 could not walk at 6 km/h.
This protocol evaluates the vestibular system in physiologic conditions and could be used as a complementary vestibular clinical test. Moreover, in contrast to other commonly used vestibular tests such as caloric or rotatory tests, specific training in neurotology is not necessary for adequate interpretation of the results. This test could therefore be used by general practitioners, neurologists, or otolaryngologists to reveal BV in patients presenting with oscillopsia. More specifically, it could help assess the functional outcome of a vestibular training protocol. Regarding the development of a vestibular implant, we think that our DVA protocol is suitable for candidate selection and might also play a role in assessment of the functional benefit after implantation.

Among patients with BV, walking at a velocity as low as 2 km/h already induced a substantial VA decrease. The severity of oscillopsia was not correlated with the amount of VA loss during walking at any of the 3 tested velocities. This is in accordance with findings of a previous study using a DVA protocol with predictable active head movements. Nevertheless, this study was limited to a small number of patients with BV (n = 13), and only the DVA improvement after vestibular training was considered, not the absolute value of the DVA.

A DVA protocol with passive head movements should be preferred because patients with BV can develop central mechanisms that could partially substitute for the VOR, such as compensatory corrective saccades, which are more effective during self-generated than manually imposed head rotations. It has been shown, using a self-motion vs a visual motion psychophysical test and a self-perceived handicap questionnaire, that amplitude of retinal slip was not correlated with the severity of the handicap due to oscillopsia. By increasing their threshold for visual motion detection as a result of a central adaptive process, patients with BV could improve their tolerance to retinal slip. On the other hand, in a functional MRI study, it was shown that when patients with BV were compared with healthy subjects, optokinetic stimulation induced a higher activation of the visual cortex and oculomotor areas in patients with BV, especially of the primary visual cortex and of the motion-sensitive areas in the temporal lobe. It is still not clear how these 2 apparently opposed mechanisms interact during locomotion, for instance.

In the present study, none of the healthy subjects reported oscillopsia. As a group, our patients with BV scored significantly higher than patients with UVL for 8 of the 9 oscillopsia severity questionnaire items. Items 4 and 5 revealed that patients with BV can experience oscillopsia while reading or watching television. This finding indicates that certain situations that are considered static for healthy subjects should be considered dynamic for patients with BV. Indeed, most patients with BV mentioned the necessity for active head stabilization in such situations. Only 1 of our patients with UVL had an oscillopsia severity score higher than 3 (9%), whereas 29 patients with BV had a score higher than 3 (81%). This finding indicates clearly that despite having central adaptive mechanisms increasing their tolerance to retinal slip, most patients with BV experience moderate to extreme oscillopsia. These results seem to indicate that unilateral recovery of the VOR might reduce significantly the severity of oscillopsia. Furthermore, the oscillopsia severity score could be used to assess the subjective benefit of treatments, such as a vestibular training protocol, in patients with BV and UVL.

Our results showed a significant relationship between VA differences and age when walking at 4 and 6 km/h. Age accounted for 19% of the variations of the VA differences at 4 km/h and for 6% at 6 km/h. This is slightly higher than reported in a study using a DVA protocol with high angular velocity (>150°/s) elicited by passive head movements around the yaw axis, where age accounted only for 4% of the VA variations in 100 healthy subjects. In another study, using a DVA protocol with predictable active head movements, age accounted for 40% of the DVA variations in healthy subjects.

Among our healthy subjects and patients with BV, only 1 was older than 75 years. For this population, VOR performances are known to be significantly diminished. Therefore, a significant DVA performance decrease can be expected, which could also explain abnormal VA differences at 6 km/h in 2 patients with UVL who were older than 75 years. Apart from those 2 patients, the only abnormal VA difference among patients with UVL was found in a 64-year-old patient at 6 km/h, which indicates that in most cases, unilateral recovery of the VOR could potentially allow normalization of the DVA when walking.

In conclusion, the DVA protocol proposed in this study is simple, quick, and cost-effective. It can reveal a bilateral vestibulopathy with a sensitivity as high as 97%. The oscillopsia severity scores showed that despite central adaptive mechanisms, most patients with BV experience moderate to extreme oscillopsia severity. There is no clear correlation between the DVA and oscillopsia severity. Both the DVA protocol and the oscillopsia severity score could be used to assess the functional and subjective benefits of treatments, such as vestibular training, for patients with BV and UVL. Furthermore, it could help to select and monitor potential vestibular implant candidates.
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Author Contributions: Drs Guinand and Kingma had full access to all the data in the study and take responsibility for the integrity of the data and the accuracy of the data analysis. Study concept and design: Guinand, Pijnenburg, Janssen, and Kingma. Acquisition of data: Guinand, Pijnenburg, and Kingma. Analysis and interpretation of data: Guinand, Pijnenburg, and Kingma. Drafting of the manuscript: Guinand. Critical revision of the manuscript for important intellectual content: Guinand, Pijnenburg, Janssen, and Kingma. Statistical analysis: Guinand and Pijnenburg. Obtained funding: Guinand and Kingma. Administrative, technical, and material support: Guinand and Kingma. Study supervision: Janssen and Kingma.

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