# Diagnostic Screening with the Vestibular Autorotation Test (VAT)

Dennis P. O'Leary Ph.D. Professor, University of Southern California, Los Angeles, California;
President, Western Systems Research, Inc., Pasadena, California

## Introduction

The primary purpose of the vestibulo-ocular reflex (VOR) is to allow clear vision during walking and other faster movements. These occur at frequencies greater than 1 Hz. Other oculo-motor systems, such as smooth pursuit and optokinetic, respond poorly at these higher frequencies. The VOR functions as the major oculo-motor system responsible for maintaining visual fixation during faster head movements.

Locomotion and other active movements generate significant higher-frequency harmonics. Fundamental stepping frequencies of 1-3 Hz result in higher harmonics extending above 5 Hz. Testing the VOR at these frequencies isn't normally done with passive whole-body rotation in rotary chairs. Torque limitations require that chair testing be limited to less than about 1 Hz.

Traditional vestibular testing addresses only the horizontal semicircular canals. Importantly, the superior and anterior vertical canals are not tested in either caloric or rotary chair testing.

These considerations (above) led us to develop a method of testing the VOR at higher frequencies based on recording eye responses to active head movements (1,2). We began this work as research projects in 1985, and then founded Western Systems Research, Inc. (WSR) in 1986 to develop a commercial system called the Vestibular Autorotation Test (VAT) for use in clinical testing of balance disorders.

The purpose of this report is to describe the current implementation of the VAT, how it is used clinically, and diagnostic test patterns correlated with specific balance disorders.

## Methods

The VAT system has evolved with new software and hardware innovations over the past 15 years. The VAT in 2002 consists of an instrumented head band worn by the patient, a control box interfaced through a serial or USB port to a notebook PC, and Windows-based software for conducting tests, displaying and printing results, and summarizing reports for a patient's chart (Fig. 1). A foam-padded case is used to transport the equipment to different test sites, such as a hospital bedside, for portable testing.

Figure 1. VAT system in a padded case for portability. The instrumented head band connects to an interface box, which is linked to a notebook PC through a USB or serial port.

The head band contains microchip preamplifier circuitry for recording horizontal and vertical eye movements with electro-oculographic electrodes, and microchip angular velocity sensors for recording side-to-side and up-down head movements. Instead of relying on pre-programmed sinusoidal movements as used in rotary chair testing, VAT software records any arbitrary

or erratic head movement, and uses spectral analysis to process the eye responses to determine VOR system characteristics. Major characteristics of interest are VOR gains, phases and asymmetry. These are defined as: Gain -- eye velocity amplitude divided by head velocity amplitude, Phase -- measurement of time (in degrees) of eye velocity relative to head velocity, and Asymmetry -- measurement of eye deviation toward a weaker side. Pre-processing is necessary to correct for three unavoidable physiological factors: 1) vergence of the eyes on near targets, 2) slippage of the head strap during faster head movements, and 3) eye blinks or momentary off-target saccades which can cause data artifacts.

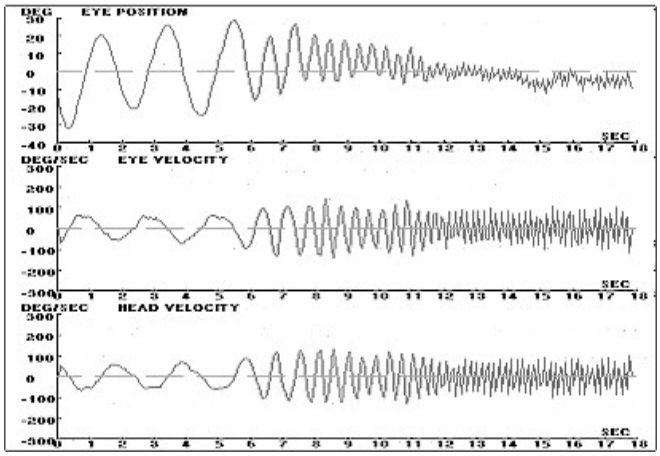


Fig. 2. Eye position (upper), eye velocity (middle), and head velocity (lower) recorded during a VAT from a normal subject.

Patients are tested in light while seated in a comfortable chair and given two instructions. 1) Keep your eyes on the spot target on the wall. 2) Move your head in time to the computer-generated tone.

The test is demonstrated to the patient to reinforce the fact that only small-amplitude head movements are required. The auditory cue paces head movements beginning at 0.5 Hz, and then sweeps linearly over a range from 1 to 6 Hz during the 18-second test duration. Only the last 12 seconds of the test are used for spectral analysis, to insure that the head was moving faster than about 2 Hz (Fig. 2).

Head and eye velocities are recorded and used to compute VOR gains, phases and asymmetry. Gain and phase results are computed from 2 to 6 Hz. Because each test is brief, 3 or more horizontal (side-to-side movement) tests are performed, followed by 3 or more vertical (nose up-down) tests. The multiple test results are used to compute means and standard deviations of a patient's data, which are then compared with normative data plotted as 2 standard deviations.

# Results

## *Normal Subjects*

Normal VOR gains are close to 1 during rapid head shaking. This means that if the head moves left at 10 deg/sec, the eyes will be driven right at 10 deg/sec. In practice, gains can vary about 15% among a normal population with no history of balance disorders. Normal VOR phases are close to 180 degrees. This means that during head shaking both the head and eyes will cross the straight-ahead center line at the same time. In practice, phases of a normal population can be delayed about 10 degrees from an ideal 180 degrees. Individual normal subjects show excellent test-retest repeatability in the VAT gain and phase patterns (Fig. 3). Each subject has a characteristic "signature pattern."

In contrast to traditional tests, nystagmus seldom occurs during the VAT. Movements of the head through small angles (< 20 degrees) during the VAT mean that the eyes can respond with equal amplitudes. There is no necessity to trigger the re-centering pathways in the brain stem to cause a fast saccade back toward the center of the eye.

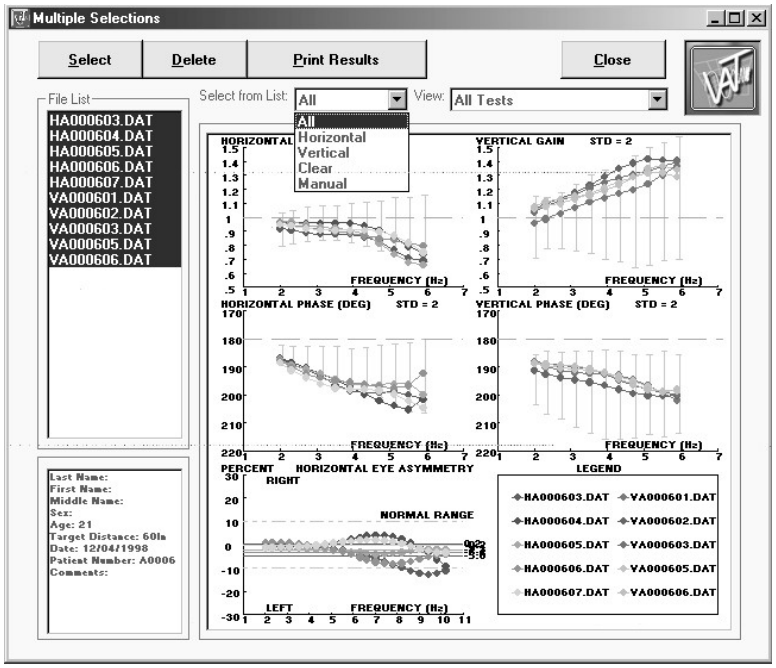


Figure 3. Points: Gains, phases, and asymmetries from 5 horizontal and 5 vertical VATs from a normal subject. Error bars: Normative data (2 standard deviations)

## *Gentamicin Ototoxicity*

Gentamicin is used systemically as an antibiotic for treatment of severe infections. It has an unfortunate side effect of ototoxicity, destroying hair cells in the semicircular canals (3,4). When cured of their infections, patients treated with gentamicin often complain of severe balance disorders, including oscillopsia (apparent motion of the visual field during active movements). A characteristic VAT pattern for gentamicin ototoxicity is shown in the graph at http://4wsr.com/wp-content/uploads/2015/03/gentamicin-10-11-04.pdf. This 79 year-old male patient (AL) had received 3 weeks of IV gentamicin for an infection following knee surgery. The patient's horizontal and vertical gains (shown as points) were markedly below normal ranges (shown as error bars), ranging as low as 0.2 at higher frequencies. The patient's horizontal and vertical phases (shown as points) ranged well above normal ranges, with the most severe differences at higher frequencies. AL complained of oscillopsia, and could walk only with the aid of a walker.

Patient AL entered a vestibular rehabilitation program at the University of Southern California Center for Balance Disorders, as a research subject. He returned periodically for repeated VAT tests, to determine whether there were objective changes in his VOR. After a year of therapy, his horizontal and vertical gains had returned to normal. But his phases remained as severely abnormal as his pre-therapy test. Nevertheless, he could then walk without a walker, and had learned sensory substitution techniques to improve his quality of life.

We learned from subsequent testing of IV gentamicin patients that the pattern shown in http://4wsr.com/wp-content/uploads/2015/03/gentamicin-10-11-04.pdf was characteristic for gentamicin. All patients with VATs which showed similar dramatic abnormal patterns had a history of IV gentamicin treatment.

## *Olympic Athlete*

Patient BB is an outstanding world-class pole vaulter, participating in several Olympics. But while walking in his house and cleaning his ear with a cotton swab, he bumped his arm and caused serve damage to his tympanum, middle and inner ear. He experienced severe balance disorders, including vertical oscillopsia. He sought treatment at several centers, but conventional vestibular testing showed normal results. When he then entered the USC Center for Balance Disorders, he described his experience during pole vaulting as follows. "When I run rapidly on the approach toward the bar, I see the vault box bouncing so much that I can't plant the pole and vault over the bar. So I can no longer practice pole-vaulting for the next Olympics."

BB's VAT results are shown in the baseline test in the left graphs shown at http://4wsr.com/rehabilitation/. His horizontal gains and phases were within normal ranges, but his vertical gains and phases were below normal (2). For example, his vertical gains were about 0.6 at his stride frequencies of 2-4 Hz, and his vertical phases were progressively lower with frequency. Both of these conditions were responsible for his vertical oscillopsia.

BB entered the vestibular rehabilitation program at the USC Center for Balance Disorders, showing remarkable objective improvement in his VAT results after 7 weeks. His post-treatment VAT is shown in the right graphs at http://4wsr.com/rehabilitation/. His vertical gains were within normal ranges. His vertical phase had markedly improved toward normal except for the highest 2 points. His horizontal gains and phases had also improved toward high normal values. However, he remained in the rehabilitation program because his preparation for the Olympic Games within the next year required that he be "super normal." After 22 weeks, his vertical gains and phases were both toward the top of the normal ranges, indicating that his VOR responded in a nearly ideal manner (2).

Outcomes measures are usually subjective in vestibular rehabilitation, but for patient BB, the results were both objective and quantitative. He successfully competed in the 2000 Olympics, and tied for 4$^{th}$ place in the final US Olympics Trials with a vault of 18 feet 4$^{1/4}$ inches. As a public figure, patient BB gave us permission to use his name – Brent Burns, because he expects to be in future Olympic games.

## Discussion

The VAT can be considered a high-frequency test of the VOR, when compared with more traditional tests. For example, the caloric test, based on stimulation of each labyrinth separately, is an ultra-low frequency test. If we consider the time to thermally stimulate the horizontal canal (about 100 seconds to reach a steady-state thermal equilibrium) to be ½ period of a sinusoid, this results in a frequency of 1/200 = 0.005 Hz. Rotary chairs available commercially span a range from 0.01 to about 1 Hz, well below the higher frequencies used in the VAT. Paradoxically, both of these "traditional" tests are well below the locomotion frequencies (>1 Hz) where the VOR is considered most active and useful during waking hours. As an analogy, just as audiometers are considered most useful at frequencies spanning the speech range, the VAT can be considered most useful because it tests the VOR over its natural performance range used in daily life – 2 to 6 Hz.

We illustrated the use of the VAT for diagnostic screening with data showing a characteristic pattern from a gentamicin ototoxicity patient, and for rehabilitation monitoring. Other studies have described use of the VAT for screening other neuro-otological disorders, test comparisons and military selection. Examples of these will be described briefly. 1) *Cis-platin ototoxicity*. Kitsigianis and colleagues (5) showed progressive reductions in both horizontal gains and phases with weekly doses of cis-platin as treatment for carcinoma. 2) *Head trauma*. This often results in horizontal gains and phases that are both high on the VAT graphs. The VAT results seldom improve toward normal ranges with rehabilitation. We speculate that head trauma can cause sufficient damage to central vestibular pathways essential for plasticity of the VOR that the self-repair mechanisms of the brain cannot respond appropriately. 3) *Meniere's disease*. Ng, et al. (6) described horizontal VAT results from patients with confirmed Meniere's disease (MD) at different stages. In contrast with the phase results from gentamicin, all MD patients showed horizontal phases low on the graph – in the opposite direction from that of gentamicin patients. Horizontal gains were either low or normal. In addition, O'Leary and Davis (7) showed that during an acute stage of MD, vertical gains were abnormally high. 4) *BPPV (Benign Paroxysmal*

*Positional Vertigo).* This common condition was shown to produce abnormally high phases at the higher frequencies (8). 5) *Comparisons of VAT with electronystagmography (ENG).* Two studies have compared the clinical practicalities of VAT with ENG for diagnostic screening (9,10). 6) *Panic disorder*. VAT results were shown to be abnormal for patients diagnosed with panic disorder (11). 7) *Military flight and diving studies.* VAT results have been used to evaluate military personnel for both flight and naval qualifications (12-14).

It is useful to examine how the VAT compares with other recent tests based on dynamic visual acuity (DVA) during faster head movements. Different approaches utilizing DVA have been described by various authors, but are all based on patients' subjective reports of identifying pictures or letters of different sizes and/or orientations. In addition to having poor resolution (e.g., 1 of about 4 different sizes) these tests rely on *subjective* information which is largely qualitative, whereas the VAT results are both *objective* and quantitative. In addition, VAT provides quantitative gain and phase information, whereas this is lacking in DVA tests. As described above, quantitative VAT gain and phase patterns are essential for differential screening of common vestibular disorders. For effective use in diagnostic screening, a picture may be worth a thousand words, but a number is worth a thousand pictures.

References:


1. O'Leary, D.P. and Davis, L.L., "High Frequency Autorotational Testing of the Vestibulo-Ocular Reflex," **Neurologic Clinics**, 8:297-312, 1990.

2. O'Leary, Dennis P., "Natural Active Head Movement Testing", **Seminars in Hearing,** Volume 23 Number 2,121-127, May 2002

3. O'Leary, D.P., Davis, L.L. and Li, S. "Predictive Monitoring of High Frequency Vestibulo-Ocular Reflex Rehabilitation Following Gentamicin Ototoxicity"**Acta Otolaryngol (Stoch)** Suppl 520: 202-204, 1995.

4. O'Leary, D.P., and Davis, L.L., "Quantitative Assessment of Drug Effects with the Vestibular Autorotation Test (VAT)", **An.ORL Mexicana**, 39:33-36, 1994.

5. Kitsigianis, G.A., O'Leary, D.P. and Davis L.L., "Active Head Movement Analysis of Cisplatin Induced Vestibulotoxicity", **Otolaryngology-Had and Neck Surgery**, 98: 82-87, 1988.

6. Ng, M., Davis, L L., and O'Leary, D.P. "Autorotation Test of the Horizontal VestibuloOcular Reflex in Meniere's Disease". **Otolaryngology-Head and Neck Surgery,** 109:399-411, 1994.

7. O'Leary, D.P., Davis, L.L., "Vestibular Autorotation Testing of Meniere's Disease", Otolaryngology-Head and Neck Surgery, 103:66-71, 1990.

8. Belafsky, Peter, Gianoli,Gerard, Soileau, James, Davidowitz, Sheri "Vestibular Autorotation Testing in Patients with Benign Paroxysmal Positional Vertigo", **Otolaryngol Head Neck Surg,** 122:163-167, 2000.

9. Murphy, T., "Vestibular Autorotational Testing (VAT) and Electronystagmography (ENG)-Which is the Most Useful in the Evaluation of the Dizzy Patient?" **American Journal of Otology,** 15, No. 4, 502-505 1994.

10. Saadat, D., O'Leary, D.P., and Pulec, J.L. "Comparison of Vestibular Autorotation and Caloric Testing", **Otololaryngology-Head and Neck Surgery**, 113: 215-22, 1995.

11. Hoffman, D.L., O'Leary, D.P., and Munjack, D.J. "Autorotation Test Abnormalities of the Horizontal and Vertical Vestibulo-Ocular Reflexes in Panic Disorder", **Otolaryngology-Head and Neck Surgery**, 110:259-269, 1994.

12. Klokker, M., Brock—Nannestad, Vesterhauge, S. "Vestibular Autorotation Test is Primary Selection of Military Pilot Students Using Neural Networks", **Aviation, Space & Environmental Medicines,** 70: No.10: 959-961, Oct 1999

13. Spitzer, O, Nahum, Z., Shahal, B., Gonen, A., Shupak, A. "Vestibular Autorotation Test (VAT) and Seasickness Susceptibility", as presented at **Aerospace Medical Association 69th Annual Scientific Meeting,** Seattle, May 1998.

14. Hamilton, K. Laliberte, M.-F., Heslegrave, R. and Khan, S., "Visual/Vestibular Effects of Inert Gas Narcosis", **Ergonomics**, 00:437-444, 1993.

## Author's Biographical Sketch

Dennis O'Leary graduated from the University of Chicago with a B.S. in physics, and received a Ph.D. in Physiology & Biophysics from the University of Iowa. He was a NIH postdoctoral fellow at UCLA. He has held faculty appointments at UCLA, University of Pittsburgh, Carnegie-Mellon University, and the University of Southern California, where he is currently Professor in the Departments of Otolaryngology-Head & Neck Surgery, Physiology & Biophysics, and Biomedical Engineering. He is co-founder and president of Western Systems Research, Inc., Pasadena, California, which develops and manufactures advanced medical diagnostic equipment.

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