Evaluation of the rotatory vestibular test: exploration of stimulus parameters

L. Maes, B. M. Vinck, E. De Vel, W. D’haenens, A. Bockstael and I. Dhooge

University of Ghent, Faculty of Medicine, ENT department, Ghent, Belgium

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Abstract. Evaluation of the rotatory vestibular test: exploration of stimulus parameters. Objectives: The aim of this study was to construct a rotational test protocol after exploring the stimulus parameters of the rotatory vestibular test. Methodology: Twenty-four normal subjects were submitted to three different rotational paradigms: the sinusoidal harmonic acceleration test (SHAT), the pseudorandom rotation test (PRRT), and the velocity step test (VST). We investigated the influence of frequency and velocity on gain, phase and asymmetry values for the SHAT and the PRRT. In the case of the VST, we examined the influence of velocity and deceleration on gain, slow component velocity at deceleration, time constant, nystagmus preponderance, and time constant asymmetry. Results: Frequency affected the SHAT response parameters, with significant phase differences between the frequencies 0.01, 0.02, 0.05, 0.1, and 0.2 Hz, while velocity, if kept below 150°/s, had no influence on the results. In the case of the VST, responses were influenced by stimulus velocity and not by stimulus deceleration, with significantly higher gain values for the velocities 50 and 250°/s. Conclusions: A velocity of 50°/s tested at the frequencies 0.01, 0.02, 0.05, 0.1, and 0.2 Hz was suggested for the SHAT and PRRT protocol, whereas a velocity of 100°/s with a deceleration of 200°/s² was preferred for the VST. The relevance of this rotational protocol has yet to be established from patient data.

Introduction

For decades, rotational testing has been used in clinical practice to examine vestibular problems. Historically, there has been a tremendous evolution in the design of rotational vestibular testing techniques. The modern era of rotational testing began in the 1960s with the torsion swing test, using a rotational chair mechanically controlled by the action of a calibrated spring. However, the torsion swing test has proven to be relatively unreliable and insensitive to lesion detection, since it rotates at a single frequency of 0.05 Hz, which is too low to represent an accurate detection of the vestibular function as it occurs in daily life. Another drawback is the variation of the stimulus intensity, which is controlled by the characteristics of the spring and the weight of the subject. The availability of computer-driven rotational chairs with a servo-controlled motor in the 1970s provided considerable diversity in stimulus algorithms, enabling precise control of angular acceleration. Several rotational paradigms were subsequently developed, the first of which was the sinusoidal harmonic acceleration test (SHAT), which is actually a sequence of sinusoidal angular velocity signals presented at several test frequencies. Testing at a wide span of frequencies unfortunately lengthens testing time, with the associated negative effects on the subject’s comfort and vigilance. Using lower frequencies in the test protocol also requires careful control for subject bias because of predictability and arousal effects. To shorten testing time and eliminate this predictability, the pseudorandom rotation test (PRRT) was developed, implying a sum of several individual frequencies, delivered simultaneously as a composite stimulus. A Fast Fourier Transformation (FFT) analysis allows for the separation of the compound response, producing detailed information about all sinusoidal components. A third rotational paradigm known as the velocity step test (VST) involves abruptly stopping the chair after a constant velocity rotation in both clockwise and counter-clockwise directions. It is hoped that this test will provide information comparable to the caloric test. A more detailed description of the physiology and technique of those rotational paradigms was described by, among others, Ledoux et al., Halmagyi et al., Stockwell and Bojrab, and Katsarkas et al.

With the aim of improving diagnostics for the patient population, the vestibular laboratory of the Ghent University Hospital was recently equipped with a computer-driven rotational chair, allowing...
for the replacement of the mechanically driven torsion swing test with the stimulus algorithms referred to above, i.e. the sinusoidal harmonic acceleration test (SHAT), the pseudorandom rotation test (PRRT), and the velocity step test (VST). The implementation of those rotational paradigms will only be useful with optimal stimulus parameters.

Unfortunately, in the literature, various protocols have been used to examine the vestibular functions, making it difficult to compare and integrate findings. The aim of this study was therefore a critical exploration of stimulus parameters that are valid for each of those paradigms, and the subsequent construction of a standard protocol that can be used to examine various vestibular pathologies.

Materials and methods

Twenty-four volunteers with no history of otological, visual or neurological disorders participated in this study and were subjected to a combination of sinusoidal harmonic acceleration tests, pseudorandom rotation tests and velocity step tests. The patients were seated in a rotary chair (version 1.70; Toennies Nystagliner, Germany) with Ag/AgCl hat electrodes placed bitemporally and a ground electrode on the forehead to record horizontal eye movements. A monocular infra- and supra-orbital placement was used to monitor eye blinks exclusively. Impedances were checked and accepted if below 10 kΩ. In order to increase gain, the alertness of the subjects was maintained throughout testing by assigning them a series of counting tasks.9 Higher gains were also achieved by testing them with eyes open in a completely darkened room9 and maintaining a head upright position instead of the 30° forward inclination.10

Informed consent was obtained after full explanation of the experimental procedure. The protocol was approved by the ethics committee of the University Hospital of Ghent and was in accordance with the ethical standards stipulated in the 1964 Declaration of Helsinki for research involving human subjects.

The volunteers were divided into two subgroups of twelve subjects. Group A (4 men and 8 women, mean age of 24 y 4 m) was submitted to all three types of rotational tests. Only two series of rotational testing were applied to group B (5 men and 7 women, mean age of 23 y 1 m). Three response parameters were measured during the SHAT and the PRRT, while five parameters were retained for the VST. An overview is provided in Table 1.

Table 2 shows corresponding stimulus parameters for the three types of rotary tests. This study explores the most relevant stimulus frequencies and velocities for the SHAT. Two frequency patterns are often used in the literature, one using harmonically-related frequencies with octave spacing (0.01, 0.02, 0.04, 0.08, 0.16, ... Hz) and one using sinusoidal “non-harmonic” frequencies following a 1-2-5 pattern (0.01, 0.02, 0.05, 0.1, 0.2, 0.5, 1, 2, and 5 Hz). To maintain some connection with the formerly used 0.05 Hz torsion swing test, the authors tested group A with the 1-2-5 pattern. Limitations of the chair restricted this pattern to frequencies ranging from 0.01 to 0.2 Hz. The influence of frequency on the response parameters was tested at 50°/s, a frequently used velocity in literature. Group B was submitted to five different velocities (25, 50, 75, 100, and 125°/s) in order to determine the relevance of each of those velocities. For this purpose, a frequency of 0.05 Hz was used, since this frequency resulted in the highest gain values in group A. Velocities were restricted to 125°/s in view of patient comfort.

| Table 1 |
| Description of SHAT, PRRT, and VST response parameters |

<table>
<thead>
<tr>
<th>SHAT and PRRT</th>
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<tr>
<td><strong>Gain</strong>: ratio of the peak slow phase eye velocity to the peak head velocity (expressed as a percentage)</td>
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<tr>
<td><strong>Phase</strong>: temporal relationship between peak eye and peak head velocity, expressed in degrees and calculated by subtracting the inverted eye velocity from the head velocity</td>
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<tr>
<td><strong>Asymmetry</strong>: percentage difference between the peak slow component eye velocities on the right and on the left</td>
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<th>VST</th>
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<td><strong>Gain</strong>: ratio of the maximum slow phase velocity at deceleration to the maximum head velocity (expressed as a percentage)</td>
</tr>
<tr>
<td><strong>Time Constant</strong>: time, in seconds, required for the response to decline to 37% of its initial peak value</td>
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<tr>
<td><strong>SCV deceleration</strong>: Maximum Slow Component Velocity at deceleration</td>
</tr>
<tr>
<td><strong>Nystagmus preponderance</strong>: percentage difference between the peak slow component eye velocities on the right and on the left</td>
</tr>
<tr>
<td><strong>Time constant asymmetry</strong>: comparison between the time constant values on the right and on the left (expressed as a percentage)</td>
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Exploration of stimulus parameters

For the PRRT, the influence of frequency was also explored in group A using the same five frequencies and a velocity of 50°/s, as with the SHAT. In the case of the PRRT, it was not possible to repeat testing for the influence of velocity on the response parameters at a single frequency as described above for the SHAT, since this paradigm consists of a sum of multiple frequencies. The aim of testing with the PRRT was mostly to establish a comparison with the SHAT in order to demonstrate the relevance of both rotational paradigms.

The literature data about the VST is conflicting with respect to stimulus velocity and deceleration. Parameters were determined on the basis of the chair capacity and patient comfort. Five velocities in group A and five decelerations in group B were explored. They were similar to the number of frequency and velocity points for the SHAT and PRRT, avoiding unnecessary lengthening of the test duration. Velocities of 50, 100, 150, 200, and 250°/s at an arbitrarily chosen deceleration of 200°/s² and decelerations of 100, 200, 300, 400, and 500°/s² were employed. The aim was to demonstrate their relevance. The influence of deceleration was tested at 50°/s, since this velocity produced the highest VST gain values in group A.

All statistical analyses were performed with a general statistics package (Statistica for Windows, Release 7) available commercially. Analyses of variance (ANOVA) were conducted for all relevant data using Tukey post-hoc testing with p <0.05 as the criterion for statistical significance and p <0.001 for extreme significance.

Results

The results are presented without standard deviations to avoid Type II statistical errors due to the limited test population.

I. Sinusoidal Harmonic Acceleration Test (SHAT)

1. Influence of frequency on SHAT response parameters

In group A, subjects were submitted to five different frequencies (0.01, 0.02, 0.05, 0.1, 0.2 Hz) at a velocity of 50°/s. The influence of frequency on the gain, phase, and asymmetry values was analysed. Although there were no significant differences for the gain values, an increment from 0.01 to 0.05 Hz was observed, followed by a decrease. In the case of the phase, significant differences (p <0.001) were found between all five frequencies. A phase lead was observed at the lowest frequencies, decreasing with increasing frequency and shifting to a phase lag at the highest frequency. No significant differences were found for parameter asymmetry. Figure 1 shows the mean gain, phase, and asymmetry values for the SHAT.

2. Influence of velocity on SHAT response parameters

Since the first series of experiments showed that the highest gain values were obtained at 0.05 Hz, this frequency was applied in group B, where the volunteers were tested at five different velocities (25, 50, 75, 100, 125°/s). Statistical analysis did not identify any significant differences between the velocities for gain, phase or asymmetry values.

II. PseudoRandom Rotation Test (PRRT)

Subjects from group A were tested with a total of five frequencies (0.01 + 0.02 + 0.05 + 0.1 + 0.2 Hz) at a velocity of 50°/s. The influence of frequency on the gain, phase, and asymmetry values was analysed; there were no significant differences. Again, the highest gain values were obtained at the frequency 0.05 Hz. Figure 1 also shows the mean PRRT gain, phase, and asymmetry values.

A comparison of the SHAT and PRRT revealed significant higher gain (p <0.05) and phase (p <0.05) values and significant lower asymmetry (p <0.001) values for the SHAT compared with the PRRT.
III. Velocity Step Test (VST)

1. Influence of velocity on VST response parameters

In group A, acceleration and deceleration were fixed at 2°/s² and 200°/s² respectively, while velocity ranged from +/- 50°/s to +/- 250°/s, in steps of 50. Statistical analysis was performed on the mean values for clockwise and counter-clockwise rotations. A significant main effect was found for the gain (%), phase (°), and asymmetry (%) at five different stimulus frequencies (0.01, 0.02, 0.05, 0.1, and 0.2 Hz). Note that asymmetry values are expressed as absolute values, and indicate how much the depicted values deviate from perfect symmetry.

![Figure 1](image)

**Figure 1**
Mean values for the SHAT and PRRT response parameters gain (%), phase (°), and asymmetry (%) at five different stimulus frequencies (0.01, 0.02, 0.05, 0.1, and 0.2 Hz). Note that asymmetry values are expressed as absolute values, and indicate how much the depicted values deviate from perfect symmetry.

2. Influence of deceleration on VST response parameters

In group B, velocity was fixed at +/- 50°/s and five different decelerations were examined ranging from 100°/s² to 500°/s². Unfortunately, no data were obtained: applying this high velocity ten times in succession made most subjects nauseous. The mean values for clockwise and counter-clockwise rotations were again subjected to statistical analysis. No significant results were found for the five different response parameters, as shown in Figure 3.

Discussion

The aim of this study was to develop a standard protocol for the rotational test to enhance its diagnostic value in vestibular clinical practice. The stimulus parameters obtained for the sinusoidal harmonic acceleration test (SHAT), the pseudorandom rotation test (PRRT) and the velocity step test (VST) were therefore explored.

I. Sinusoidal Harmonic Acceleration Test (SHAT)

1. Influence of frequency on SHAT response parameters

For the gain values, no significant differences between frequencies were found in group A when tested at a velocity of 50°/s. However, we did find increasing gain values with increasing frequencies and a decline at the highest frequencies. Similar tendencies were found by Engelken et al.,11 Henry and Dibartolomeo,12 Li et al.,13 Wall 3rd et al.,14 and Wolfe et al.,15 although they did not test the same frequencies. Most authors found increasing gain values with increasing frequencies, but did not report any drop at the higher frequencies.1,2,9,16-20

Significant differences were found for phase values between all frequencies. A phase lag was found at the highest frequency (0.2 Hz), whereas increasing phase leads were noticeable with decreasing frequencies. This phase pattern corresponds to many reports in the literature,1,2,11,14,16,17,19 although the shift to a phase lag could not always be found at the same frequency.

As far as the choice of the “best frequency” is concerned, we can state that all five frequencies may
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be relevant, since significantly different results were obtained at each frequency for the phase parameter. Testing a patient population will demonstrate whether those phase differences still prevail, allowing for a reduction of the test protocol. This study suggests that the focus should be on a frequency of 0.05 Hz tested at 50°/s since it delivered the highest gain values. The importance of the frequency 0.05 Hz was confirmed by Honrubia et al.\textsuperscript{21} and by Jenkins et al.,\textsuperscript{22} who demonstrated that phase differences between normal subjects and patients become greater at 0.05 Hz and also at 0.0125 Hz.

The lower frequencies used in group A (0.01 and 0.02 Hz) appear to be of some interest, too. Mathog\textsuperscript{23} has stated that low frequencies (0.02 Hz) can distinguish between severe and milder vestibular pathology. Wolfe et al.\textsuperscript{15} demonstrated that frequencies below 0.04 Hz are more sensitive in detecting phase-lead abnormalities. In the case of gain, Honrubia et al.\textsuperscript{24} found that the most significant differences between normal subjects and patients were at very low frequencies (0.0125 Hz). The importance of low frequencies was also stressed when comparing results from SHAT testing with those from caloric testing. Suzuki et al.\textsuperscript{25} indicated that more attention should be given to the frequency of 0.02 Hz (tested at a maximum velocity of 50°/s); according to Wolfe et al.,\textsuperscript{26} the frequency 0.01 Hz merits further study since sensitivity for vestibular lesions was higher than in the caloric test. Myers\textsuperscript{27} also indicated that testing at frequencies below 0.05 Hz (i.e. 0.01 an 0.02 Hz) appears to confirm best cases of bilateral caloric weakness, which is in accordance

**Figure 2**
Mean values for the VST response parameters gain (%), slow component velocity at deceleration (SCVdec) (°/s), time constant (TC) (s), nystagmus preponderance (NP) (%), and time constant asymmetry (TCasymm) (%) at five different stimulus velocities (+/- 50°/s, +/- 100°/s, +/- 150°/s, +/- 200°/s, and +/- 250°/s). Note that nystagmus preponderance and time constant asymmetry values are expressed as absolute values, and indicate how much the depicted values deviate from perfect symmetry.

**Figure 3**
Mean values for the VST response parameters gain (%), slow component velocity at deceleration (SCVdec) (°/s), time constant (TC) (s), nystagmus preponderance (NP) (%), and time constant asymmetry (TCasymm) (%) at five different stimulus decelerations (100°/s\^2, 200°/s\^2, 300°/s\^2, 400°/s\^2, and 500°/s\^2). Note that nystagmus preponderance and time constant asymmetry values are expressed as absolute values, and indicate how much the depicted values deviate from perfect symmetry.
with the results of Baloh et al.,16 Hamid et al.24 Hess et al.25 and Honrubia et al.10

Where low frequencies seem to be important in the detection of abnormal phase leads and gain reductions, high frequencies can be used to detect asymmetries.3 The results at the lowest frequency concur with Wolfe's1 data indicating no significant phase differences, whereas the 0.2 Hz gain and phase values differed significantly between SHAT and PRRT, as in the present study. The significantly higher PRRT asymmetry values resulted from the fact that single sinusoids are capable of quantifying the left-right asymmetry at each frequency, whereas one single measure of asymmetry is obtained for each sum of frequencies with the PRRT.1

If the gain, phase, and asymmetry values of the SHAT and the PRRT did not differ significantly, the elimination of the SHAT from the test protocol would have been logical, because of the reduced testing time and low predictability of the PRRT. For now, it would be advisable to include both stimulus types in the test protocol, because the relationships found between SHAT and PRRT have yet to be established in patient populations.

II. PseudoRandom Rotation Test (PRRT)

The most important contribution of the PRRT is the comparison with the SHAT results with the aim of establishing the relevance of both, or the superfluity of one, of these rotational paradigms. As a consequence, no further attention was paid to the fact that no significant frequency differences were found for gain, phase, and asymmetry values, suggesting that only one of those frequencies would suffice in the test protocol.

The significantly higher gain and phase values of the SHAT compared to the PRRT did not correspond to the results of Wolfe et al.,1 who did not find phase differences. Peterka et al.15 compared SHAT and PRRT gain and phase values at 0.05, 0.2, and 0.8 Hz. The results at the lowest frequency differed significantly between SHAT and PRRT, as in the present study. The significantly higher PRRT asymmetry values would have been logical, because of the reduced testing time and low predictability of the PRRT. For now, it would be advisable to include both stimulus types in the test protocol, because the relationships found between SHAT and PRRT have yet to be established in patient populations.

III. Velocity Step Test (VST)

1. Influence of velocity on VST response parameters

The influence of stimulus velocity was not taken into account. This parameter was therefore kept very low (2°/s²).

In this way, nystagmus and unpleasant sensations were kept to a minimum, as was the risk of interaction between the acceleration and deceleration response.

The response parameters of gain and time constant are the most widely discussed parameters in literature. In group A, the latter does not seem to be influenced by stimulus velocity, while significantly higher gain values were obtained for the velocities +/- 50°/s, followed by +/- 250°/s. The resulting question is whether velocities of +/- 50°/s are high enough to demonstrate asymmetric responses in a specific patient population; on the other hand, one might ask whether velocities of +/- 250°/s will not be too high. Schmidt's33 indicated that high plateau speeds between 60 and 90°/s were required for causing extreme post-rotatory responses. Wuys et al.14 used velocities of 90°/s and 100°/s for testing clinical populations and, for screening purposes, Sills et al.15 used velocities of 100°/s. Baloh et al.16 found that velocities of 256°/s were mandatory to demonstrate significant asymmetries, whereas Huygen37 wondered whether responses at such high velocities should not be classified as somatosensory nystagmus. The present study also refrained from such high velocities, because they often induce nausea in test persons. In accordance with the findings stated above, velocities between 60°/s and 120°/s would be advisable in a rotational testing protocol, with 100°/s as the preferred velocity because of its frequent use in the literature.

2. Influence of deceleration on VST response parameters

Testing group B at a velocity of +/- 50°/s revealed no significant differences for gain or time constant. This concurs with the findings of Schmidt,33 who indicated that post-rotatory intensity
is a function of rotational speed and not of deceleration. It might be asked whether these findings would remain valid when testing at higher velocities of ± 250°/s. These tests resulted in nausea and therefore had to be abandoned prematurely, making this question superfluous. In order to make the stop fast but not too uncomfortable for the patient, a deceleration of 200°/s² was preferred.

Conclusion

Three types of vestibular rotational paradigms were discussed: the sinusoidal harmonic acceleration test (SHAT), the pseudorandom rotation test (PRRT), and the velocity step test (VST). For the SHAT, 0.01, 0.02, 0.05, 0.1, and 0.2 Hz all seem to have their reasons for implementation in the test protocol. Since velocities below 125°/s did not influence the test results, the frequently used velocity of 50°/s would be an interesting choice. Although significant gain, phase, and asymmetry differences were found between the SHAT and the PRRT, both should be included in the test protocol, since their relevance will only become clear when analysing patient data. The VST results depended heavily on the stimulus velocity, favouring a 100°/s velocity. Since the deceleration did not influence the test results, a not too abrupt stop of 200°/s² was suggested. The impact of this rotational test protocol on diagnostic precision will have to be proven through application to a large population of individuals with and without vestibular pathologies.

References

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