Rotational Vestibular Assessment

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Rotational Vestibular Assessment

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Contents

Preface

The last one and one-half decades have seen a significant advancement in the range of clinical assessment techniques for the identification of vestibular pathology. Such changes have demanded a concomitant expansion in our understanding of vestibular anatomy, physiology, and symptomatology. To meet this growing need, many academic doctoral programs have augmented their curriculum to include a comprehensive course (or courses) on the assessment and management of vestibular function. Concurrently, our construct of what constitutes a comprehensive vestibular assessment during routine clinical practice has also swelled over the past 10 to 15 years with the addition of cervical and ocular VEMP testing, vHIT testing, and more enhanced rotational test paradigms. Collectively, this evolution of vestibular knowledge and clinical assessment techniques have significantly increased the need for specialized academic and clinical resources. In fact, rotational vestibular assessment is a perfect example of this evolutionary resource need.

When asked if I would be willing to write a textbook on rotational testing, I thought back to my first rotational assessment 15 years earlier. There was little in the way of didactic writing on the subject. Aside from a few chapters in Shepard & Telian's text *Practical Management of the Balance Disordered Patient* and in Jacobson, Newman, and Kartush's text *Handbook of Balance Function Testing* (1st ed.), there was not a single text dedicated to the subject of rotational testing. Fifteen years later, and (unfortunately) the same can still be said. As such, I agreed to this project with one singular goal; to write a comprehensive text that would not only detail the various tests associated with rotational assessment, but also intertwine a comprehensive understanding of how the vestibular system's anatomy and physiology function with respect to each rotational test. In doing so, this text will hopefully provide the vestibular clinician with a greater understanding of vestibular function, and disease.

A tremendous amount of science has brought us to our current understanding of vestibular function (and dysfunction). This text explores the humble beginnings of vestibular science, and the brilliant scientists and physicians who advanced this understanding. The first chapter begins by highlighting the progression of human rotation from the eightieth century, to the discovery of the vestibular sixth sense. Ever since the acceptance of the vestibular sixth sense, rotational testing has continued to evolve throughout the twentieth and twenty-first centuries to better meet the challenges of diagnosing complex vestibular pathology.

Rotational testing continues to hold a unique position in the comprehensive vestibular assessment. Between its natural acceleration stimuli and its detailed outcomes measures, its analysis is unparalleled for the identification of peripheral and central vestibular disease. This textbook details the various tests conducted during rotational assessment, most notably sinusoidal acceleration testing and velocity step testing. It also explores more specialized rotational tests of visual-vestibular interaction, as well as tests of otolith function (e.g., unilateral centrifugation testing, as well as a brief overview of off-vertical axis rotational testing). It includes a detailed discusion on the anatomy and physiology of the peripheral and central vestibular systems, as well as a thorough review of the vestibular ocular reflex (VOR). It was written from the point of view of a vestibular clinician, for the vestibular clinician.

As with all things, as rotational testing continues to advance into the twenty-first century, it will be essential to stay current with our understanding of the various assessment techniques and outcomes measures associated with normal and abnormal vestibular function. It is my hope you will find this text to be a step toward that direction.

Some of the material found in this textbook is supplemented with a PluralPlus companion website that provides a selection of videos showing the various rotational tests, which illustrates the rotational stimuli and the VOR response generated during each test. When viewing each video, please keep in mind that ALL rotational tests are performed in a lightproof environment; that is with the lightproof booth door *closed* (or the video goggles covered in a boothless rotational suite). Videos shown on the PluralPlus companion website often show the rotation of the chair with the door open. This is for illustrative purposes only

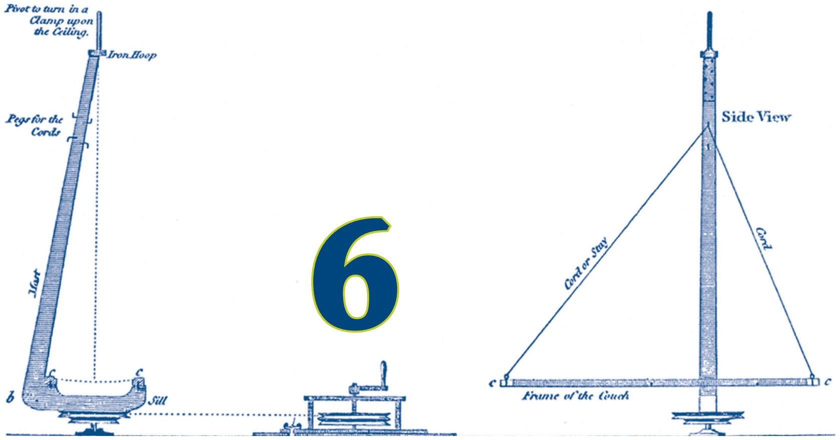
Acknowledgments

My life's accomplishments are the culmination of my individual experiences, but one of the greatest lessons I learned in life is from my parents:

> *Anything is possible; but nothing will*
> *happen unless you take the first step.*

This book has been a labor of love. And despite a single name on its cover, it would not have been possible without the support and encouragement from my beautiful and amazing wife Christine, and my two beautiful daughters Maddie and Katie. In a way that no words could ever convey, I wish to express my love, gratitude, and unending thankfulness to them. I also wish to thank my friends and colleagues who provided insight, motivation, guidance, and knowledge. And finally, to my students, whose curiosity continues to inspire me.

> *"The energy of the mind is the essence of life"*
> —Aristotle



6

Sinusoidal Harmonic Acceleration (SHA) Testing

INTRODUCTION

Rotations of an upright head and body about a fixed earth vertical centric axis are the simplest and most fundamental stimuli provided during rotational vestibular testing (Figure 6–1). This form of rotational stimulation efficiently produces a horizontal vestibular ocular reflex (VOR) and a subsequent peak eye velocity that approximates a given rotational velocity (Brey, McPherson, & Lynch, 2008a; Goulson, McPherson, & Shepard, 2016). In general, as the velocity of chair rotation increases, so does the peak eye velocity of the responding VOR. By comparing the velocity of the responding VOR against a known velocity of chair rotations (for a variety of stimulus frequencies), the reactivity of the vestibular system can be inferred across a broad frequency range. Examining the responsiveness of the vestibular system across a broad frequency range provides a more comprehensive evaluation of vestibular integrity, particularly in the presence of a bilateral absent caloric response. Similar to an audiometric assessment, which identifies normal to near normal low frequency hearing with a concomitant profound high frequency hearing loss, the vestibular system is also subject to frequency dependent damage. Assuming an absence of vestibular response based on an absence of caloric response would be similar to concluding complete anacusis based on a single absent audiometric threshold at 8000 Hz.

When a vertically upright individual is rotated (or oscillated) back and forth in the horizontal (or yaw) plane, the responsiveness of the vestibular system to such rotations can be determined across a known frequency range of stimuli. Rotational stimuli are most commonly presented as sinusoids, with the chair first accelerating in one direction until a peak target velocity is achieved (usually 50°/sec or more commonly 60°/second), after which the chair slows and reverses to the same peak velocity in the opposite direction. This periodic motion, whereby the chair (head) oscillates about a centric position, is known as sinusoidal acceleration testing. Provided the rotational frequencies being administered are simple harmonics of one another, this form of stimulation is known as sinusoidal harmonic acceleration testing, or SHA testing (Stockwell & Bojrab, 1997a). For a visual introduction into the various SHA rotational stimuli (or harmonic frequencies), the reader is encouraged to review the companion website for an example of each rotational SHA frequency.

FIGURE 6–1. Rotational chair showing direction of clockwise (rightward) and counterclockwise (leftward). Image courtesy of Micromedical, Inc.

Although rotational testing can be composed of a variety of rotational frequencies, it is not required that SHA testing be administered in octave or harmonic intervals. Certain test paradigms may often omit certain frequencies to conserve clinical test time, whereas other rotational paradigms can also be administered whereby a series of oscillation frequencies can be combined and presented simultaneously. This later rotational paradigm is known as *sum of sines* and is rarely (if ever) performed in the clinical assessment of vestibular function. The primary reason for the infrequency by which a sum of sines rotational paradigm is used is due to the significant loss of energy (physiologic response) that occurs secondary to a significant spread of VOR response over multiple frequencies of simultaneous stimulation (Wall, 1990). Although the single-frequency oscillation paradigm employed during the more common type of SHA testing takes considerably longer than the sum of sines paradigm, having all the response energy concentrated at a single frequency of rotation is quite adventitious when analyzing response parameters, particularly those produced from weak vestibular physiology (either by a low-frequency stimulus or pathology) (Wall, 1990).

SINUSOIDAL HARMONIC ACCELERATION (SHA) STIMULUS

Chair rotations, or oscillations, are most often delivered in the yaw, or horizontal, plane in both the clockwise and counterclockwise directions.

Chair rotations are defined by the frequency of rotation, or simply, how many back-and-forth oscillations are delivered within a given time period (usually one second). Rotational frequencies are expressed in hertz (Hz). The frequencies

Determining the Difference Between Clockwise and Counterclockwise Rotations

For those just becoming acquainted with visualizing the direction of rotation, the clockwise or counterclockwise vector is best described from a vantage point above the rotational chair (Figure 6–2).

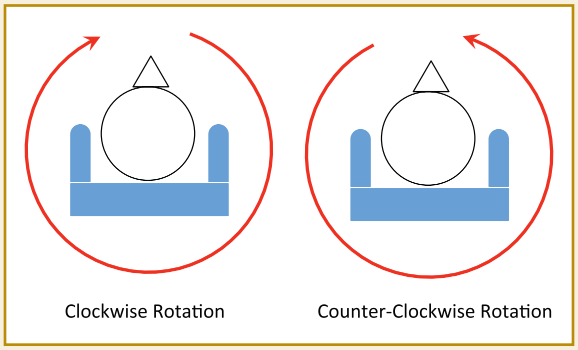


FIGURE 6–2. Rotational chair showing direction of clockwise (rightward) and counterclockwise (leftward) rotation as viewed from above.

most commonly administered are harmonic or octave frequencies between 0.01 and 0.64 Hz (that is; 0.01, 0.02, 0.04, 0.08, 0.16, 0.32, and 0.64 Hz). Additional frequencies can be administered, which include 1.28 Hz and even 2.0 Hz (or higher). However, stimulus frequencies above 1 Hz can be progressively problematic for many reasons. Most notably, the resulting VOR eye data become increasingly difficult to accurately capture, as the precise acceleration of the chair is not exactly translated to the head due to dermal slip against the skull for most standard head restraint devices. As a result of the slight dermal slip, head acceleration lags slightly behind chair acceleration and produces an inadvertent delay in the initiation of the compensatory VOR that, in turn, produces an artificial and nonphysiologic VOR delay that was never intended. This often leads to aberrant results that fail to adequately reflect true physiology of the vestibular system. This concept will be revisited later when discussing the timing relationship of the VOR response (known as phase) in relation to certain rotational frequencies. High frequency rotations greater than 1 Hz are more often confined to research trials or within animal studies where unwanted dermal slippage can be negated through the use of bite blocks, molded face restraint devices, or surgically implanted head posts.

It is critical to keep in mind that the rotational stimuli applied during SHA testing are unique, insomuch that the acceleration of the rotating chair is always changing. That is, the rotation of the chair is under constant acceleration until the target velocity of rotation is achieved (most often 60° per second), at which time the rotation of the chair immediately begins decelerating until the chair returns to a velocity of 0° per second (i.e., no movement). At this *instantaneous* moment of zero movement velocity, the chair reverses rotational directions and once again is subject to constant acceleration until the target rotational velocity is reached, at which time the chair is once again decelerated back to 0° per second. This process of acceleration followed by deceleration repeats itself both in the rightward (or clockwise) and leftward (or counterclockwise) directions for a predetermined series of back and forth oscillations. Sinusoidal harmonic acceleration testing is always performed with the chair moving (or oscillating) back and forth in such a sinusoidal fashion.

Performing *Sustained* Rotations during Rotational Testing . . . A Peek into Chapter 7 Using Velocity Step Accelerations

In addition to SHA testing and its unique oscillatory stimulus, a VOR response can also be recorded following *sustained* rotations in both the CW and CCW directions. This form of vestibular stimulation is known as velocity step acceleration and is discussed in Chapter 7. Both the SHA and VST tests are critical to the RVT test battery and comprise the essential components of RVT testing. Fundamentally, it is the measurement and analysis of the VOR response during both SHA and step testing that is most relevant during a RVT assessment.

The omnipresent acceleration and deceleration stimuli associated with SHA testing are absolutely critical for effective stimulation of the vestibular system. We are reminded of the principal mechanics of the vestibular system, more specifically the cupulae; that cupular *deflection* and subsequent saltation of an afferent neural response is entirely dependent on *acceleration*, not velocity. Simply put, the cupulae are accelerometers that detect changes in movement, not necessarily movement itself, and cupular deflection is completely reliant on such *changes* in motion.

So, it is the ubiquitous acceleration and deceleration of the rotational stimulus during SHA that creates the subsequent VOR due to ever-present cupular mechanics. It stands to reason then, that the stronger (or quicker) the acceleration, the greater the cupular deflection and stronger the subsequent VOR response. Simply put, the stronger the input, the more robust the output. That being said, it is then critical to remember that the opposite is true. Because the cupulae *are* accelerometers, the weaker the stimulus input, the less effective the vestibular system will be at generating an output response. If you recall from our discussions on the anatomy and physiology of

Velocity Versus Acceleration: What Exactly Is the Difference?

Velocity vs. Acceleration. To better understand the difference between velocity and acceleration, imagine yourself traveling in a car with your eyes closed. Your cupulae are designed exquisitely to detect accelerations and decelerations as you speed up or slow down. However, if it were possible that the car's motion was constant, say traveling at 60 mph with absolutely no change in acceleration or deceleration, your cupulae are not designed to detect the constant motion of the car traveling at 60 mph. Of course, other cues will tell your brain that you are moving, such as bumps in the road, and possibly wind noise or even road noise. However, if all other variables were removed, your vestibular system would be oblivious to the constant (non-changing) velocity of the car's movement—until it decelerated or accelerated. This is the difference between the cupulae being accelerometers and not velocitometers (if such a word exists!). This concept will again be revisited during our discussion on velocity step testing (Chapter 7) where cupular deflection actually dampens to their resting state despite ongoing constant-velocity chair rotation.

the vestibular system, this is indeed true as the efficiency of the vestibular system (acceleration detection) suffers dramatically below 0.1 Hz. We will see this reflected later when we review the differences in VOR output with respect to the various frequencies employed during SHA testing.

SHA STIMULUS PROPERTIES

The oscillation stimulus delivered during SHA testing can be characterized by a variety of parameters, most notably: frequency, cycle duration or period, angular acceleration, angular displacement, and number of oscillations (or rotations). Table 6–1 lists the relative rotational properties for each given frequency of rotation during SHA testing as well as some of the parameters for the caloric stimulus commonly employed during videonystagmography (VNG) testing.

Stimulus Frequency

As mentioned earlier, the *frequency* of chair rotation is defined as the number of oscillations (or cycles) competed per second. This is depicted by the equation:

$$\text{Hz} = \frac{\text{cycles of rotation}}{\textit{second}}$$

That is:

1 hertz = 1 cycle of rotation completed
in 1 second of time

Frequency can, therefore, be simplified and expressed as the quotient between one (1) and the time (T) it takes to complete a single cycle of rotation, or:

$$\frac{1}{T} = \text{Frequency (Hz); or}$$

$$\frac{1}{100\ \textit{secs}} = 0.01\ \text{Hz; and}$$

$$\frac{1}{50\ \textit{secs}} = 0.02\ \text{Hz; etc.}$$

SHA testing is generally performed in octave frequencies between 0.01 and 0.64 Hz (and sometimes higher). The most common octave frequencies performed during SHA testing are provided in Table 6–1.

Table 6–1. Relative Rotational Properties by Frequency of Rotation

Stimulus (Hz)	Cycle Duration (s)	Velocity (ω)	Acceleration (α)	Angular Displacement (½ cycle)	Cycles of Oscillation (# of rotations)
0.004	250		~ 1.2°/sec^2		
0.01	100	60	2.4°/sec^2	1500°	4⅓
0.02	50	60	4.8°/sec^2	750°	2⅙
0.04	25	60	9.6°/sec^2	375°	1 1/12
0.08	12.5	60	19.2°/sec^2	187.5°	~ ½
0.16	6.25	60	38.4°/sec^2	93.75°	~ ¼
0.32	3.125	60	76.8°/sec^2	46.875°	~ ⅛
0.64	1.5625	60	153.6°/sec^2	23.4375°	~ 1/16
1.28	0.78125	60	307.2°/sec^2	11.71875°	~ 1/32
2.0	0.5	60	480°/sec^2	7.5°	1/48

Stimulus Period

Although the term "*period*" is not frequently discussed in the clinical literature, it is significant in determining other parameters during the analysis of SHA data. The period of rotation is simply the time (*T*) it takes to complete one cycle of rotation. One complete *cycle* is defined as a single acceleration and deceleration of chair rotation to the right followed by acceleration and deceleration to the left. This is illustrated in Figure 6–3. However, because acceleration is frequency dependent (acceleration increases as frequency increases, see Table 6–1), the period of time (*T*) it takes to complete one cycle of rotation will vary depending on the rotational frequency being administered. For example, when conducting rotations at 0.01Hz, the lowest common rotational frequency performed during SHA testing, the chair will complete one full cycle of rotation in 100 seconds (Figure 6–4). The period (*T*) of this cycle is simply the inverse of the frequency of chair rotation, and is expressed by the equation:

$$\text{Hz} = \frac{1}{T\ (sec)}$$

$$\text{Solving for T; T} = \frac{1}{Hz}$$

$$\text{Therefore, T} = \frac{1\ cycle}{0.01\ Hz}$$

$$T = 100 \text{ seconds}$$

In contrast, when conducting SHA testing using a higher rotational frequency of 0.32 Hz, the time needed for the chair to complete one full cycle of oscillation is only 3.125 seconds. This is depicted in Figure 6–5 and is determined by the equation:

$$\text{T} = \frac{1\ cycle}{0.32\ Hz}$$

$$T = 3.125 \text{ seconds}$$

The stimulus period for each of the frequencies performed during SHA testing is provided in Table 6–1.

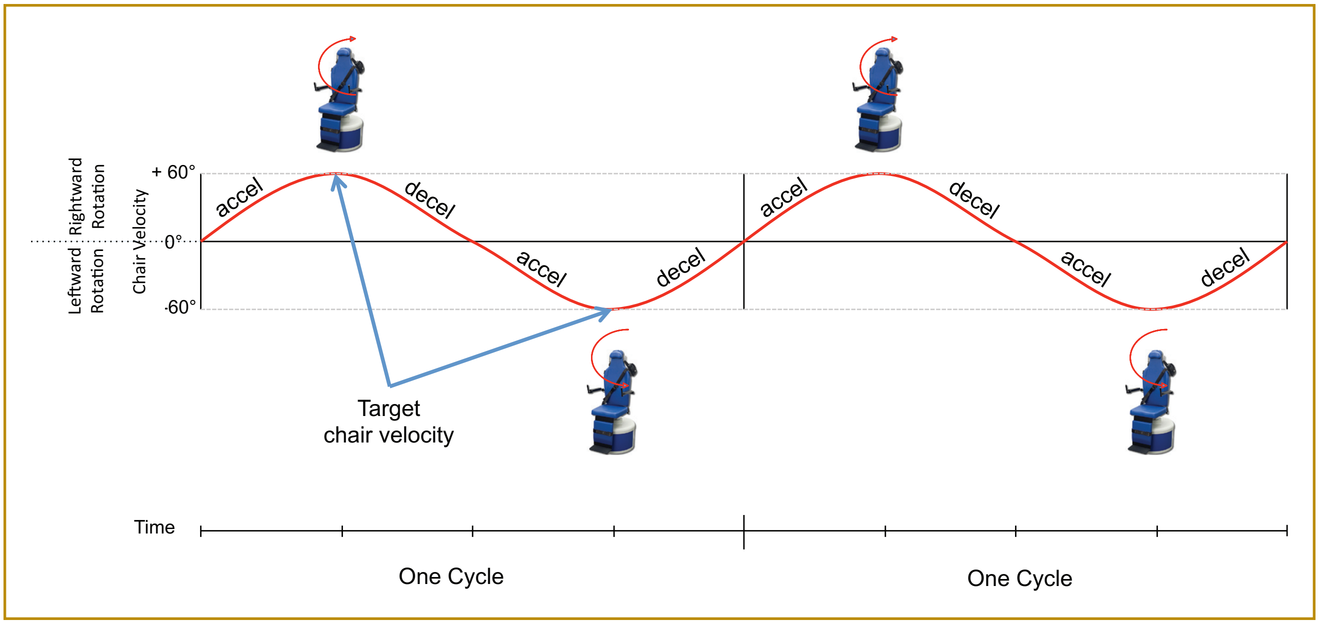


FIGURE 6–3. Rotational plot showing two cycles of rotation and the corresponding direction of chair rotation during each one-half cycle of rotation.

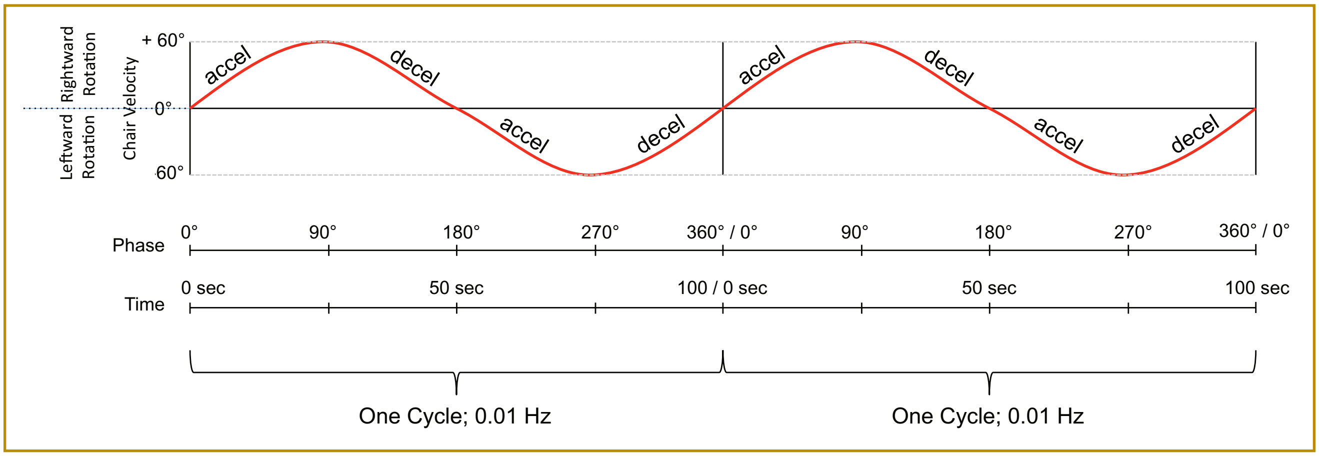


FIGURE 6–4. Rotational plot showing two cycles of rotation for 0.01 Hz. The time and degree of chair rotation are plotted for each cycle of rotation.

Angular Acceleration

As already mentioned, acceleration is frequency dependent and increases as frequency increases. When discussing acceleration is terms of a rotational stimulus, it is known as *angular acceleration* (α). Angular acceleration can be thought of as how many degrees the chair rotates in a certain period of time. Angular acceleration can be mathematically defined as the quotient of the change in angular velocity (ω) divided by the change in time (t), and is expressed by the equation:

$$\alpha = \frac{\Delta\omega}{\Delta t}$$

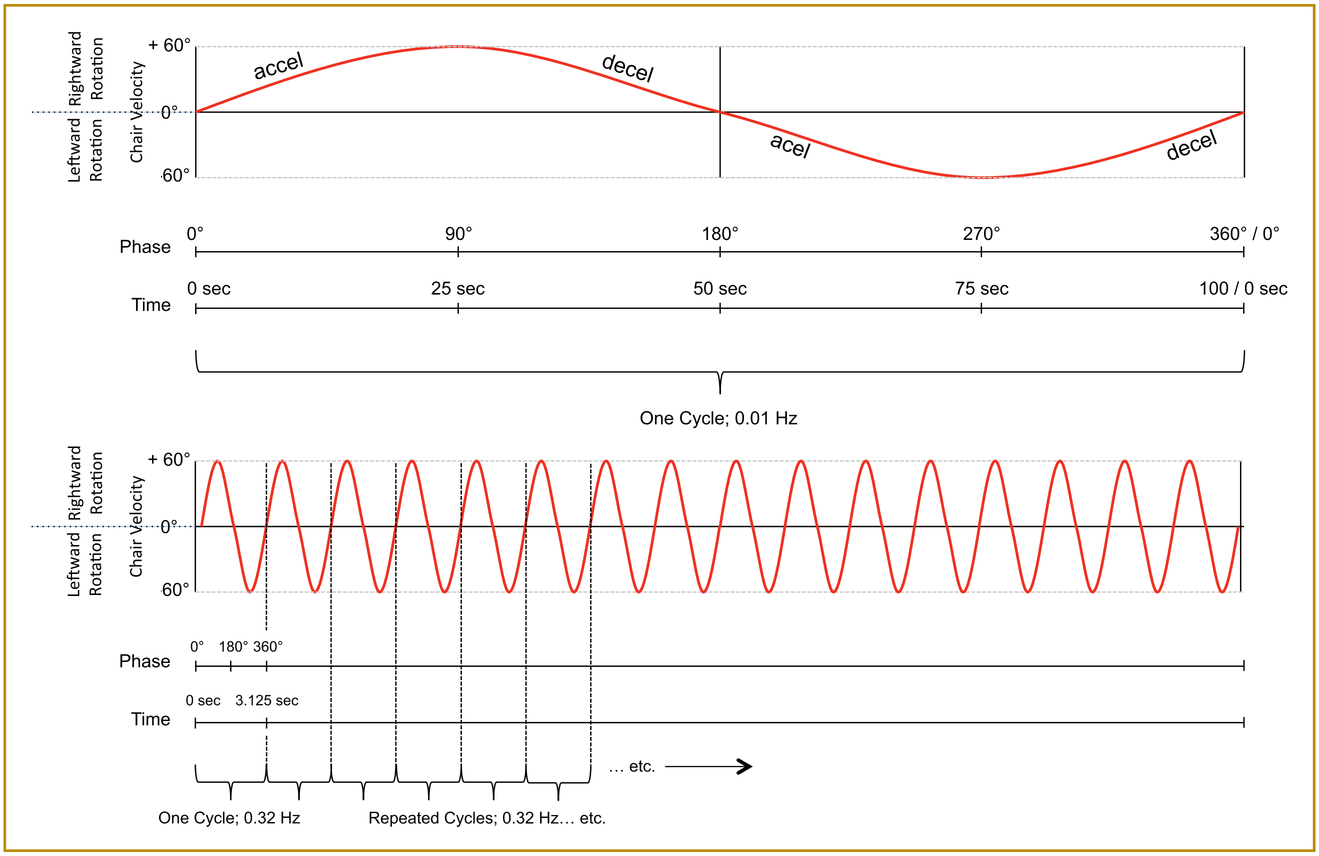


FIGURE 6–5. Comparison of rotational characteristics for 0.01 Hz and 0.32 Hz. *Note: The time scales between both examples are not relative to one another*.

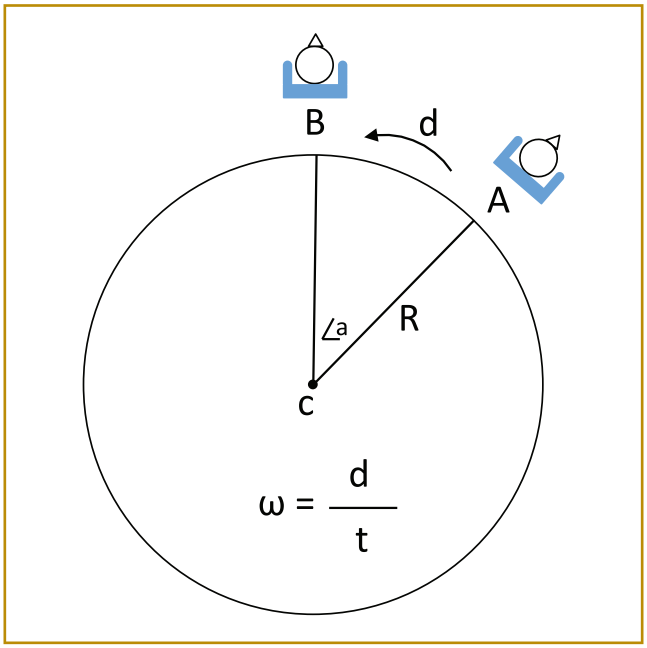


FIGURE 6–6. Angular velocity of chair rotation; (d) Equals distance in degrees traveled (A → B) in a known period of time (usually one second); ω = angular velocity; when R = 1; d = ∠a. *Note: cartoon of chair rotates at point "c". Chair is depicted off center of axis for illustrative purposes.*

In this equation, change in angular velocity is equal to the target velocity of chair rotation during SHA testing (a constant value either 50°/s or 60°/s), and change in time is equal to 1/4 duration of one full cycle of rotation, which is the time needed to accelerate to the stimulus target velocity before decelerating back to 0°/sec (see Figure 6–5). Using 0.01 Hz as an example, the angular acceleration of the chair is as follows;

$$\alpha = \frac{\Delta\omega}{\Delta t}$$

$$\alpha = \frac{60°/sec}{25\ sec}$$

$$\alpha = \frac{2.4°}{sec^2}$$

The angular acceleration for each of the stimulus frequencies performed during SHA testing is provided in Table 6–1.

Number of Required Cycles of Oscillation

One can quickly determine that the number of cycles conducted can have a significant impact on the overall time required to complete each rotational frequency, and ultimately impacting the total time required to conduct a complete range of frequencies during SHA testing. It stands to reason that a greater number of oscillations (or cycles) will invariably produce more compensatory VOR data during the test, which would undoubtedly result in greater reliability, validity, and repeatability of data. If one were to randomly assign a minimum number of ten cycles to be conducted for each rotational frequency, the total test time to complete 0.32 Hz would be 31.25 seconds (3.125 seconds times ten cycles). This is not unreasonable in a clinical setting. However, the time needed to complete ten cycles of 0.01 Hz would be 1,000 seconds, or 16 minutes and 40 seconds for a single frequency, which *is* clinically unreasonable. So how does one determine the best number of oscillations to administer?

To answer this question, we must first be cognizant that collection of a "bad cycle" of VOR response data has traditionally been highly problematic. This was due to the forced "deletion" of the *entire* cycle of data when "bad" data was collected, even if only a *portion* of a cycle was "bad." This was often secondary to the limitations of some analysis algorithms. This limitation has traditionally plagued rotational testing, as the deletion of an entire cycle of "bad" data, when only two cycles of data are collected, can be disastrous for data analysis and subsequent clinical interpretation, particularly if both cycles have periods of bad data and you are forced to delete both cycles or, worse, analyze "bad" data. Thankfully, this problem is becoming less of an issue as data analysis algorithms continue to improve in their ability to detect and remove discrete spurious data points/regions within distinct portions of any particular cycle. This eliminates the "forced deletion" of an *entire* cycle of data due to a small portion of the cycle containing "bad data."

Second, and perhaps the most important factor when determining the number of oscillations needed for reliable data, is that the test time must be long enough to allow for the characterization of the steady-state response of the vestibular system (Wall, 1990). For the lower frequencies of rotation (0.01 to 0.02 Hz), this will generally occur after 45 seconds of slow oscillatory stimulation (Wall, 1990). In general, the *minimum* number of cycles for any frequency should be two full cycles for frequencies less than 0.04 Hz, with a higher number of cycles for frequencies above 0.02 Hz. For the lower two frequencies, this would equate to a testing time of 200 seconds for 0.01 Hz and 100 seconds for 0.02 Hz. If you are to add in the 45 seconds of test time needed prior to initiation of the steady-state response, this would calculate to 245 seconds for 0.01 Hz (or 4 minutes, 5 seconds) and 145 seconds for 0.02 H (or 2 minutes, 25 seconds). Although more data during these low frequencies of rotation is seldom discouraged, one must be cognizant of the added test time required and subsequent mental tasking demand placed on the patient, which could potentially lead to poorer data, secondary to reduced mental alertness. The tradeoff between a limited amount of robust clean data, and more data that are less robust, is undoubtedly important and can often be patient-dependent with respect to how adept they are performing mental tasking as well as each patient's relative fatigue. Most SHA rotational protocols typically present two to three cycles of rotation for 0.01 Hz and 0.02 Hz, and up to 10 cycles for the remaining frequencies between 0.04 and 0.64 Hz. To account for adaptation of the steady-state response, most current analysis paradigms delete a portion of, or the entire first and last half of, the beginning and ending cycle, respectively.

Chair Rotation Versus Chair Revolution

Finally, it is important to make a distinction between the rotational chair completing one full cycle of *rotation* versus making one full *revolution*. This distinction is relevant as one quickly realizes that the rotational chair no longer completes a full 360° revolution for stimulus frequencies above 0.04 Hz. This can clearly be seen when critically examining the video for each SHA frequency on the companion website. The reason for this lies in the test's terminal target velocity of 60° per second. Recall that as soon as the acceleration of the chair reaches the target velocity of 60° per second (which is achieved at 1/4 of one full cycle), the chair immediately begins to decelerate back to 0° per second (full stop at 1/2 cycle) before changing directions and completing the second half of the cycle (Figure 6–7). For SHA test frequencies greater than 0.04 Hz, the increased acceleration stimulus achieves this target velocity rather quickly and is able to both accelerate to the target velocity and decelerate back to full stop prior to completing a full 360° revolution. That is, the time needed to complete one-half a cycle of oscillation (acceleration and deceleration in the rightward or leftward direction) at a rotational frequency of 0.08 Hz is approximately 180° of rotational displacement, or just one-half a full revolution.

When considering the example using a rotational frequency of 0.01 Hz, where the rotational acceleration is slow (2.4°/sec^2), the chair will take 25 seconds to accelerate to the target velocity of 60° per second (1/4 cycle) and another full 25 seconds to decelerate back to 0° per second (full stop at 1/2 cycle) before reversing direction of rotation. During these 50 seconds of rightward (or leftward) rotation, the chair will actually travel (or rotate) a full 1500°, or 4⅓ revolutions in 1/2 cycle before coming to a full stop and reversing directions. During the next 50 seconds of acceleration and deceleration in the leftward direction, the chair will once again make 4⅓ revolutions during this second, 1/2 cycle. However, during a rotational frequency of 0.16 Hz, because the rotational acceleration is much faster (38.4°/sec^2), the chair will only take 3.125 seconds to accelerate to the target velocity of 60° per second and only another 3.125 seconds to decelerate back to 0° per second (full stop) before reversing direction of rotation. During these 6.25 seconds of rightward (or leftward) rotation, the chair will actually travel (or rotate) only 93.75°, or approximately ¼ of one revolution during this ½ cycle before coming to a full stop and reversing directions. The angular displacement and revolutions for each of the frequencies performed during SHA testing is provided in Table 6–1.

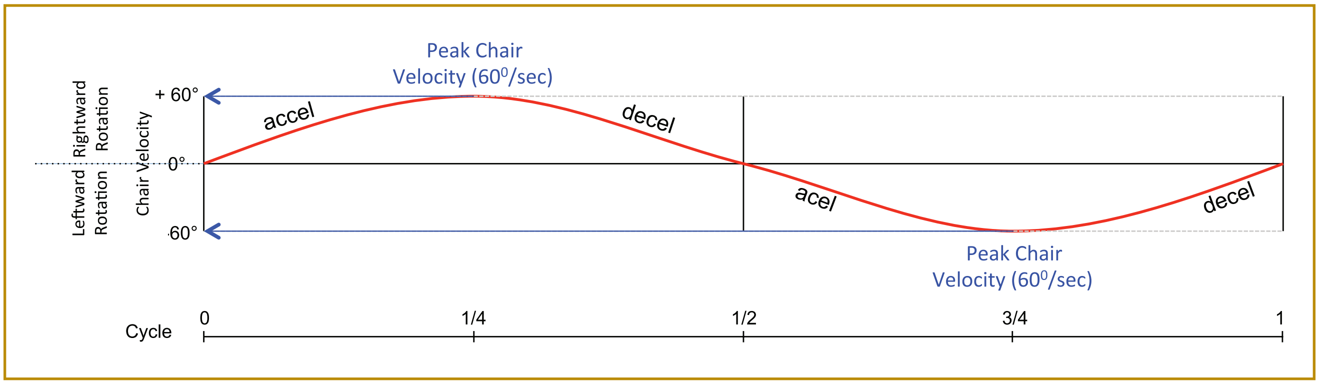


FIGURE 6–7. One cycle of rotation showing peak target chair velocity for both rightward and leftward rotations. Chair velocity always peaks at predetermined target velocity (60°/second in the example).