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Video Head Impulse Testing in a Pediatric Population: Normative Findings

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Abstract

Background: The video head impulse test (vHIT) is a new tool being used in vestibular clinics to assess the function of all six semicircular canals (SCCs) by measuring the gain of the vestibulo-ocular reflex (VOR) in response to rapid head turns. Whereas vHIT has been validated in adults for all SCCs, there are few studies describing the normal response in children, particularly for stimulation of the vertical canals.

Purpose: The purpose of this study was to characterize the normal vHIT response for all six SCCs in children aged 4–12 years.

Research Design: A cross-sectional prospective descriptive study.

Study Sample: Forty-one participants were categorized into one of four groups based on their age (4–6 years, 7–9 years, 10–12 years, and adults) with at least ten participants in each age group.

Data Collection and Analysis: The ICS Impulse system (GN Otometrics, Schaumburg, IL) was used to perform vHIT on each participant. Lateral, anterior, and posterior SCCs were stimulated by thrusting the head in the plane of the canal being evaluated and resulting VOR gain measures were calculated as eye velocity divided by head velocity. VOR gain of the pediatric age groups was compared with adults for all SCCs.

Results: There were no significant differences in mean VOR gain between the three pediatric age groups for any SCC measured; thus, the pediatric data were combined into one group of 30 children for comparison with the adult group. Results showed that the pediatric group had significantly higher mean VOR gain than the adult group during left lateral SCC testing. A significantly lower mean VOR gain, however, was observed for the children compared with the adult participants for left anterior and right posterior (LARP) impulses. There was a large amount of variability in the data during right anterior and left posterior (RALP) impulse testing for both the pediatric and the adult groups, which was at least partially attributed to large pupil diameter in the younger participants. Test time decreased with an increase in age for all impulse conditions (lateral, RALP, and LARP). Several modifications were necessary to obtain adequate data on the pediatric participants.

Conclusions: vHIT can be used to successfully measure the function of the lateral SCC in children as young as 4 years of age. Our results provide normative gain values that can be used when testing children with lateral vHIT. Care must be taken to obtain the most accurate measures and reduce variability when testing children, particularly with LARP and RALP. Our data would suggest that lower gain cutoffs should be used for LARP and RALP testing in children than the cutoffs used for lateral vHIT. Further research is warranted to study LARP and RALP response reliability and validity in children because of the highly variable VOR gains found in this population. Pediatric modifications for successfully administering vHIT and obtaining reliable results are discussed.

Key Words: gain, head impulse, semicircular canal, vestibular, vestibulo-ocular reflex

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Abbreviations: ANOVA = analysis of variance; LARP = left anterior and right posterior; LLat = left lateral; RALP = right anterior and left posterior; RLat = right lateral; SCC = semicircular canal; vHIT = video head impulse test; VOR = vestibulo-ocular reflex

INTRODUCTION

The video head impulse test (vHIT) is a relatively new tool used in vestibular clinics to assess the function of all six semicircular canals (SCCs) (Halmagyi et al, 2008). A more diagnostic version of the bedside head impulse test first introduced by Halmagyi and Curthoys (1988), the vHIT, provides objective measurement of the vestibulo-ocular reflex (VOR) through lightweight goggles and a high-speed video-oculography system. With the advent of the vHIT, information from each of the six SCCs, three from each ear, and their neural pathways, may be obtained in a noninvasive manner. Eye movement is recorded with a high-speed camera (250 Hz), and triaxial gyroscopes depict the angular movements of the head to allow calculation of eye movement velocity in relation to head movement velocity, also known as VOR gain. In addition, a monocular camera is able to record any catch-up saccades that may occur during the head movement (covert saccades) or after the head movement (overt saccades), which is indicative of peripheral hypofunction (MacDougall et al, 2009; 2013a,b).

In fact, the vHIT has proven to be useful in diagnosing peripheral hypofunction in all vertical and horizontal SCCs in adults (MacDougall et al, 2013a,b). MacDougall et al validated vHIT responses using the commercially available ICS Impulse system by simultaneously collecting impulse data using scleral search coils placed on the eyeball. These authors concluded that vHIT responses are equivalent to the "gold standard" scleral search coil responses, but the vHIT is more comfortable for the patient, less invasive, and more practical to use clinically (MacDougall et al, 2013a,b).

Since publication of the validation studies, vHIT has been gaining acceptance as a clinical tool to measure the function of the VOR in adults, and adult normative VOR gain data for all six SCCs have been reported in several articles (McGarvie et al, 2014; 2015; Curthoys et al, 2016). Using vHIT to assess SCC function in children is also gaining interest; however, there are no studies assessing the normal VOR gain values of all six SCCs in children aged <10 years. Because maturation can affect vestibular responses, including VOR gain (Valente, 2007), it is important to determine if VOR gain changes throughout childhood using vHIT. In addition, the use of adult normative vHIT data may not be appropriate for determining vHIT normalcy in young children.

The reasons why vHIT would be beneficial for assessing the vestibular system of children are clear. Presently, the standard pediatric test battery used to evaluate the vestibular system includes rotational chair testing, videonystagmography, which culminates in caloric irrigations, cervical vestibular-evoked myogenic potential, and ocular vestibular-evoked myogenic potential testing. This current battery allows the clinician to primarily assess the function of the horizontal SCCs and the otolith organs but does not offer information about all the peripheral vestibular end organs. The function of the anterior and posterior SCC, both critical components of the vestibular system, remains unknown. Thus, even after spending a lengthy appointment time administering the current battery of tests to a child, the clinician is left with less than a complete picture of the peripheral vestibular system.

With the use of vHIT, clinicians are able to obtain information about the horizontal SCCs without the use of lengthy, uncomfortable, and often frightening techniques. Children would simply be required to wear goggles and maintain focus on a stationary target, a non-invasive task many children may be more willing to perform. In addition, information regarding the status of the anterior and posterior SCCs may be obtained in a similar manner. According to published reports on adults (Bartl et al, 2009; MacDougall et al, 2013a,b), vHIT can be completed in <15 minutes, allowing assessment of all six SCCs in a brief time period. Although this brief assessment time would be desirable when testing children, one recent study has reported that vHIT in children requires much more time, taking approximately 20 minutes to complete just the lateral vHIT in children aged 3 to 16 years (Hulse et al, 2015).

The purpose of this study was to describe the normal vHIT response in a pediatric population using a commercially available vHIT system (the ICS Impulse, GN Otometrics), following the manufacturer's specifications for testing. A healthy adult group was also studied to verify testing technique and to make comparisons to the pediatric data using the same examiners, equipment, and technique. The ICS impulse system was selected because, to date, it is the only commercially available system that has been validated against scleral search coils for all six SCCs. Additional aims of this investigation were to determine what testing modifications are necessary to successfully perform vHIT on children and determine the amount of time required to complete the test. The ICS Impulse vHIT system was purchased for clinical use by Cincinnati Children's Hospital Medical Center in October 2014 and training and practice of the examiners took place between October 2014 and February 2015. The data collection was completed at Cincinnati Children's Hospital Medical Center between February and March 2015.

METHODS

Participants

Thirty children, 4–12 years of age, with no history of vestibular dysfunction were recruited for this study. Eleven healthy adults were also recruited to verify testing technique and make comparisons with the pediatric normative data characteristics. All participants were friends and/or family members of Cincinnati Children's Hospital employees. The 30 children were recruited into three age groups (4–6 years, 7–9 years, and 10–12 years) to have a representative sample of ten participants in each age group between 4 and 12 years. At the time of this investigation, the manufacturer did not recommend testing children aged $<$4 years because of the lack of pediatric-sized goggles; therefore, the youngest participants in this study were 4 years of age. Participant characteristics can be found in Table 1. Normal vestibular function was assessed via a paper–pencil questionnaire related to developmental milestones and balance and was completed by each participant, or the participant's parent, before testing (Appendix).

Written informed consent was obtained from all adult participants and parents of minor participants after the experimental procedure was explained. A child assent was obtained from all children $>$10 years of age. The research protocol was approved by the Institutional Review Board of Cincinnati Children's Hospital Medical Center.

Procedure

All participants passed an immittance screening, using the Grason-Stadler GSI 37 tympanometer (Eden Prairie, MN) to rule out the presence of middle ear dysfunction. vHIT measurements were then recorded on all participants using the Otometrics ICS Impulse system (GN Otometrics). The ICS Impulse vHIT system consists of a lightweight goggle with an integrated high-speed camera (250 Hz) focused on the right eye and triaxial gyroscopes enabling immediate recording of head and eye movements to assess VOR gain in all planes.

Participants were seated in a standard, fixed-height chair 1 m from a visual target (1″ by 1″ sticker) on the wall at eye level. The ICS Impulse system goggles were placed on the participant's face and firmly secured with the attached elastic band provided by the manufacturer around the back of the head to prevent goggle slippage and subsequent inaccurate gain data. For the pediatric participants, a piece of 1″ thick foam, obtained from a portion of the packing and shipping material found in a hearing aid box, was placed inside the elastic band for additional security because of smaller head size. In addition, a foot stool was used to keep the children seated upright and to help stabilize the body during head movements. The pediatric test setup is shown in Figure 1. To ensure that the eye would be accurately tracked with head movements, the pupil was aligned in the region of interest box and adjusted so the cross-hair was centered on the pupil. To obtain optimal pupil recordings, the loose skin above the right eyelid was pulled up and secured with the goggles.

All testing was performed by three trained examiners, working in pairs (two with each child). The three examiners were two clinical pediatric audiologists with $>$10 years' experience each and one 4th year Au.D. student. Training consisted of hands-on instruction and practice overseen by the manufacturer's sales representative, completion of video instruction provided on the manufacturer's website, and through reading the directions for testing in the provided instruction manual. In addition, each examiner continued to practice the head thrust and recording procedure on colleagues and available family members or staff over a 3-month period. For this investigation, two examiners were present for every participant (the Au.D. student and one clinical audiologist). The primary role of the clinical audiologist was to operate the equipment, whereas the 4th year Au.D student performed the head thrusts with the participant. Three adult participants had one of the two clinical audiologists performing the impulses on them because of lack of availability of the student when the participants were available. Other than those three adults, the clinical audiologists did not perform impulses on any other adult participants or on any of the pediatric participants, so as to reduce inter-examiner variability.

Before the start of testing, calibration of the ICS Impulse goggles was performed according to the manufacturer's instructions outlined in the ICS Impulse reference manual (GN Otometrics, 2015; Doc no. 7-50-1510-EN/00, pp. 23–25). Two red laser beams were emitted from the goggles and projected onto the wall as two red dots 15° apart. Each participant was instructed to move their head to place the red dots equidistant on the left and right of the sticker and then watch the red dot as it jumped from left to right. The youngest participants were instructed to count how many times the dot jumped from side to side to ensure that the calibration dot was being watched. After calibration was accepted by the system, calibration was manually verified by slowly rotating the participant's head to the left and right while the

Table 1. Characteristics of the 41 Participants in This Study

	Age (Years)	Mean (Years)	N = 41
Group I	4–6	5.6	10
Group II	7–9	8.7	10
Group III	10–12	11.4	10
Group IV	Adults (22–45)	34.4	11

Figure 1. Test set-up used in this investigation. The child is seated 1 m from the target (a colorful sticker) on the wall, his feet are resting on a footstool and a foam pad is secured inside the elastic band on the back of his head.

participant maintained focus on the sticker, confirming that eye and head movement recordings were superimposed. All participants were able to successfully achieve calibration and the default calibration was never used.

After calibration, the participant was instructed to maintain focus on the visual target or sticker. The participant's head was rotated by the examiner using small, rapid movements to the left and right to record the VOR response from the lateral SCCs. Left anterior and right posterior (LARP) SCCs were tested with the head rotated 35°–45° to the right using rapid downward and upward head impulses. Right anterior and left posterior (RALP) SCCs were tested with the head rotated 35°–45° to the left using downward and upward head impulses. During testing, each pediatric participant was asked to answer questions about the colorful sticker to ensure the child maintained focus on the sticker. When attention began to deviate, a new sticker was used.

Head impulses in all conditions were manually delivered by the examiner with unpredictable timing and direction until the gain values of 20 acceptable impulses were obtained in each condition. According to the ICS Impulse reference manual (p. 28, 31, and appendix 2), the criteria required for the acceptance of a proper impulse included (a) a peak head velocity of >100°/sec for lateral impulses; >50°/sec for LARP and RALP and (b) the shape of the response matching the example shape on the testing screen of the system. Test time was measured by the ICS Impulse system starting at the beginning of each test (lateral, LARP, and RALP) until 20 acceptable impulses were collected in each direction. Test time did not include calibration. All participants were permitted to remove the goggles between tests for approximately 1–2 minutes, as needed, to reduce the discomfort associated with wearing the goggles. Although the ICS Impulse instruction manual states that movement of the goggles after calibration is "not recommended" (ICS Impulse reference manual, p. 27), the examiners did not recalibrate after goggle removal for any of the participants in this investigation as the patient file was not exited and reentered at any time until all subtests were completed.

Figure 2 shows an example of a vHIT hex plot obtained from an adult participant and a pediatric participant. These results are representative of the type of vHIT responses obtained in this study. Tracings containing extraneous eye movements not consistently occurring were deemed as noisy or outliers and were eliminated. Results of each test were then evaluated for the presence of saccades occurring during the head movement (covert) or after the head movement (overt). Determination of the presence of a saccade included a consistent spike in the response tracing occurring on >50% of impulses and having a magnitude greater than half the size of the head movement. Although loosely based on the recommendations of Barin (2013), this saccade criteria were purposely more conservative because the vHIT response in children has not yet been characterized.

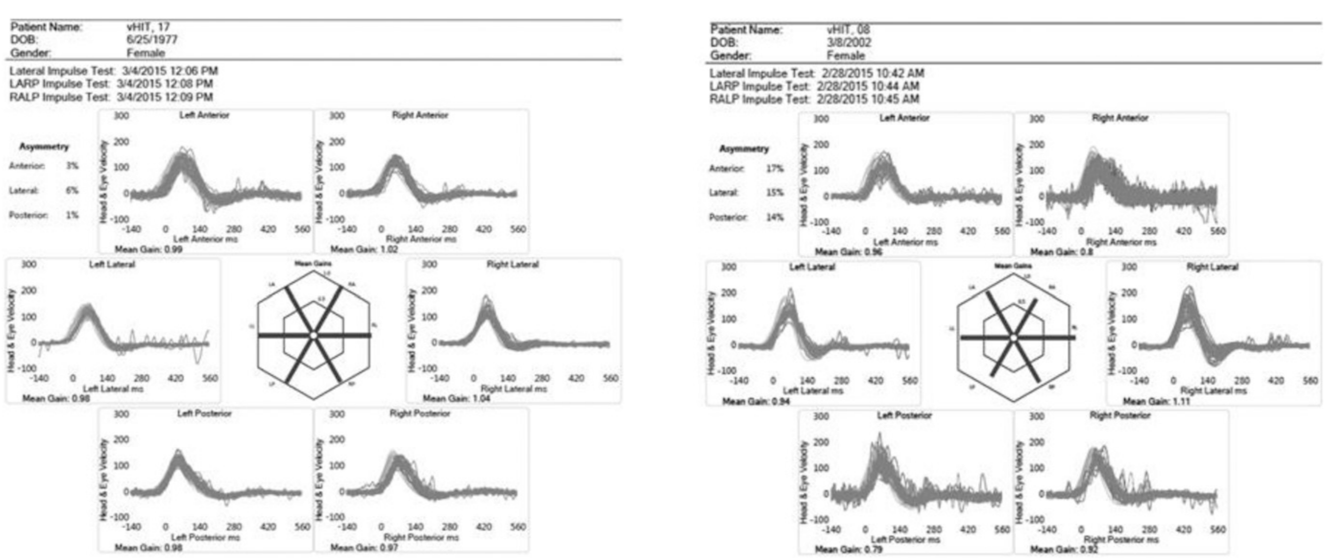

Figure 2. An example of a hex plot of an adult participant (left) and a pediatric participant (right).

Data/Statistical Analysis

Head impulses were detected by the ICS Impulse system and were either accepted or rejected based on an envelope around the expected head movement response, as well as an acceptable peak head velocity. Mean VOR gains and standard deviations were calculated for impulses in the lateral plane, as well as the LARP and RALP planes, and 95% confidence levels were calculated for each age group. Data were analyzed using SigmaPlot 13.0. Descriptive statistics, analysis of variance (ANOVA) and student *t*-tests were used to compare age groups and subtests of the vHIT battery. Nonparametric tests (Kruskal–Wallis ANOVA and Dunn's) were used if tests for normality (Shapiro–Wilk and Brown–Forsyth) were not passed. Statistical significance was set at $p < 0.05$ for all comparisons. Post hoc comparisons were adjusted using the Holm–Bonferroni method.

RESULTS

All 41 participants (100%) completed lateral head impulse testing. Forty of forty-one participants (97%) completed LARP and RALP testing. One 4-year-old participant refused to complete LARP and RALP testing because of discomfort of the goggles. For lateral head impulse testing and LARP, data were removed from one participant in group 1 because of excessive noise in the tracings, and one participant in group 2 because of goggle slippage. For RALP testing, data were removed from one participant in group 2 because of goggle slippage and one participant in group 4 because of excessive noise and eyelid artifact. Peak head velocities of 100°/sec or greater for lateral impulses was achieved for 95% of impulses across all participants and 50°/sec or greater peak head velocities were achieved in 100% of both LARP and RALP impulses for all participants.

Test Time

Table 2 shows the test time for each vHIT test across the different age groups. One-way ANOVAs were run for each of the main subtests by age group to examine if time to complete the subtest varied by age group. For Lateral test time, there was no overall difference found ($F = 2.535, p = 0.072$). Likewise, for LARP, there was not a significant difference across age groups ($H = 0.298, p = 0.960$) or for RALP ($H = 5.474$, $p = 0.140$). Significance may not have been met because of the small numbers of participants in each group. Maximum total time (worst case scenario) to complete testing of all SCCs was <15 minutes for all groups except the youngest (4- to 6-year-old) group, where test time reached a maximum of 17 minutes. It should be noted that these test times only include the time that the actual impulses were being administered and do not include the time spent placing the goggles on the participant, calibrating, instructing the participant, and allowing the participant to rest between tests. Therefore, these test times underestimate the actual time spent with a participant completing all three tests (lateral, LARP, and RALP).

VOR Subtest Gain

Analysis of VOR gain for the six subtests for children and adults, as shown in Figure 3, revealed that the mean RA amplitude was higher than the mean LA amplitude ($T = 2.23$, $p = 0.014$), the mean RP amplitude was lower than the mean LP amplitude ($T = 3.07$, $p = 0.001$), and the mean right lateral (RLat) amplitude was higher than the mean left lateral (LLat) amplitude ($T = 5.06, p < 0.001$). In other words, RALP VOR gains were significantly higher than LARP VOR gains for both children and adults.

VOR Gain by Age Analysis

Figure 3 shows a comparison of the average VOR gain for all vHIT tests between the pediatric and adult participants. As shown in the figure, pediatric gain was slightly more variable than adult gain for each of the vHIT subtests, as shown in Figure 3. VOR gain for both adults and children were most variable for right anterior canal stimulation. In addition, vertical canal stimulation produced lower VOR gain values than lateral canal stimulation for the pediatric participants, with LARP gains noticeably lower than RALP gains. One-way ANOVA revealed two subtests with significant overall ANOVAs based on age group as the between variable. These were the LA subtest ($F = 4.367$, $p = 0.011$) and the LLat subtest ($F = 3.103, p = 0.038$). For LA, age

Table 2. Mean (±SD) Test Time in Minutes for Each vHIT Subtest by Age Group

Age Group (Years)	Lateral	RALP	LARP	Maximum Total Test Time (Mean + 2SD)
4–6	2:00 ± 0:46	2:47 ± 1:40	3:23 ± 2:18	17:38
7–9	1:32 ± 0:22	1:32 ± 0:40	2:01 ± 0:47	8:43
10–12	1:18 ± 0:21	1:40 ± 0:43	2:02 ± 1:27	10:18
Adults	1:24 ± 0:30	1:26 ± 0:46	1:49 ± 1:00	9:10

Note: Maximum total test time includes the mean + 2SD of test time for each age group to complete lateral, LARP, and RALP tests and does not include time used for patient setup, calibration, breaks, or instruction. SD = standard deviation.

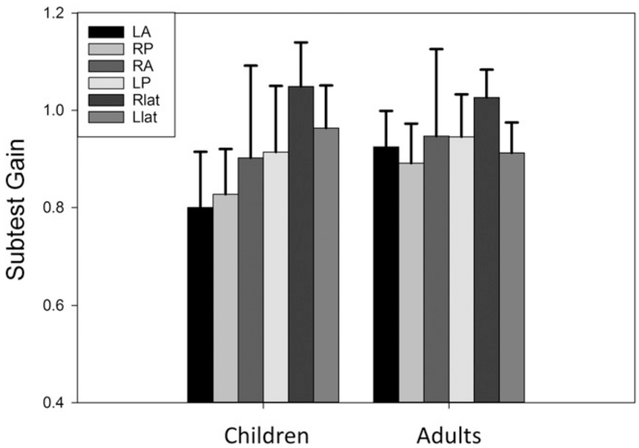

Figure 3. Mean and standard deviation for each of the VOR gain subtests, for all children combined and for adults.

group post hoc comparisons were significant for the adult group, which had higher gain with the two youngest age groups ($t = 3.103$, $p = 0.023$ for 4- to 6-year-olds compared with adults and $t = 3.052$, $p = 0.022$ for 7- to 8-year-olds compared with adults) with Holm–Bonferroni adjustment for multiple comparisons. For LLat, age group post hoc comparisons were borderline significant for the adult group, which had slightly lower gain than the 7- to 8-year-old age group ($t = 2.819$, $p = 0.045$) with Holm–Bonferroni adjustment for multiple comparisons. No significant differences were found on overall ANOVAs for RA ($F = 2.026$, $p = 0.129$), RP ($H = 4.680$, $p = 0.197$), LP ($F = 0.732$, $p = 0.540$), or RLat ($F = 2.459$, $p = 0.078$). Because the age group analyses were mostly nonsignificant or of borderline significance, normative data from Groups I to III were collapsed into one group of 30 pediatric participants aged 4–12 years, and are shown in Table 3, compared with adults in the present study and adults for two previous studies.

DISCUSSION

VHIT has previously been shown to be a useful tool in assessing the adult vestibular end organ. Accurate vHIT evaluation in children depends on careful setup and administration of the test, familiarity with what the normal vHIT response looks like, as well as having established normative VOR gain data. This is the first study reporting normative VOR gains and the normal characteristics of vHIT in children $<$10 years of age. Although vHIT was able to be performed successfully on pediatric participants as young as 4 years in this study, RALP and LARP testing proved to be the most difficult to complete. Some subject factors influencing the testing of the pediatric participants included fine, slippery hair, small head and face size, and very large pupil size.

Direct observation during testing revealed a much larger pupil size in the pediatric participants than the adults, which may have contributed to higher variability in the vHIT responses in the pediatric participants. Figure 4 shows the difference in pupil diameter between a 10-year-old and a 47-year-old. It is well documented that children have larger pupil diameters than adults (Birren et al, 1950; Jacobson, 2002). Pupil diameter increases rapidly from 5 to 6 years, up to a maximum at 13–15 years of age, and then slowly decreases into older adulthood, with major decreases beginning at 40 years of age. The range of ages in our adult group was 22–45 years with a mean of 34.4 years. Thus, the youngest members of the adult group also had somewhat large pupil diameters, causing increased variability in VOR gain when testing the anterior canals, particularly the right anterior canal. Initial attempts to constrict the pupil through use of an otoscope light or a bright lamp shining close to the eye were unsuccessful in achieving enough constriction in the pediatric participants to warrant their use.

With the use of the ICS Impulse vHIT system, larger pupil diameter resulted in less area to move the head during impulses while still allowing the entire pupil to be visualized. Anterior canal impulses were most impacted by pupil size and eyelid artifact was a problem that had to be overcome in many cases. During anterior canal testing, a downward head impulse causes the eye to rotate upward. With a large pupil diameter, this upward rotation of the eye often forces at least the top portion of the pupil up into the eyelid. As the crosshairs maintain position in the center of the pupil during testing, obfuscation of any part of the pupil, changing its shape, forces the crosshairs to move and find a "new center" of the pupil. This causes a sharp deviation of the crosshairs and a resulting dip in the response recording. In Figure 5, the left image displays a tracing for right anterior (RA) stimulation, which includes eyelid artifact, seen as the "V" in the peak of the movement. A normal tracing for RA is displayed on the right. With a large pupil diameter and a small crosshairs and tracking screen, more eyelid artifact was seen in the RA tracing of the pediatric participant on the left. Impulse data from recordings containing a "V"-shaped dip in the peak of the response must be eliminated from analysis as VOR gain calculation will be inaccurate.

The adult mean VOR gain values calculated in this study are in agreement with those previously published for all SCCs in adults. In addition, mean lateral SCC VOR gain established for the pediatric group in this study closely agreed with the adult lateral VOR gain in this study. With the exception of LA, which revealed lower VOR gain than adults, and LLat, which revealed higher VOR gain for the 7- to 8-year-olds than adults, there were no significant differences between the VOR gains of the pediatric and adult participants on the vHIT subtests. VOR gain, however, appeared to be more variable for LARP and RALP testing when compared with lateral testing.

Table 3. Mean ± Standard Deviation (5th, 95th Confidence Intervals) VOR Gain for Each SCC for Pediatric and Adult Study Groups

	Canal	Lateral		Anterior		Posterior	
Participants	Ear	Left	Right	Left	Right	Left	Right
Children 4–12 years	Present study	0.96 ± 0.09 (0.79–1.14)	1.04 ± 0.09 (0.87–1.23)	0.80 ± 0.11 (0.58–1.02)	0.90 ± 0.19 (0.53–1.27)	0.91 ± 0.14 (0.65–1.18)	0.83 ± 0.09 (0.65–1.01)
Adults	Present study	0.91 ± 0.06 (0.79–1.04)	1.03 ± 0.06 (0.91–1.14)	0.93 ± 0.07 (0.78–1.07)	0.95 ± 0.18 (0.60–1.30)	0.95 ± 0.09 (0.77–1.12)	0.89 ± 0.08 (0.73–1.05)
Adults	Kidd et al (2014)	0.98 ± 0.10 (0.82–1.14)	1.04 ± 0.11 (0.85–1.21)				
Adults	Curthoys et al (2016)	0.92 ± 0.06 (lower cutoff = 0.80)	1.00 ± 0.07 (lower cutoff = 0.86)	0.96 ± 0.12 (lower cutoff = 0.71)	0.95 ± 0.12 (lower cutoff = 0.70)	0.92 ± 0.17 (lower cutoff = 0.58)	0.98 ± 0.15 (lower cutoff = 0.68)

Examining lateral testing across all participants, the RLat VOR gain was higher than LLat VOR gain. This finding is consistent with previous normative data studies and can be attributed to the recording of the right eye only using the ICS Impulse system (Kidd et al, 2014; McGarvie et al, 2015). It is known that the eye has a farther distance to travel in the skull during adduction to maintain focus on a stationary target. Thus, monocular recording for the right eye during an RLat impulse will result in greater VOR gain than that recorded during an LLat impulse (McGarvie et al, 2015). In a similar way, and for the same reason, there is an asymmetry seen in the vertical canal gains. The right (recorded) eye has farther to travel to maintain focus on a target during RALP impulses versus LARP impulses, which results in higher gain values for RALP. This asymmetry in vertical canal gains was most pronounced in the pediatric group in this study. Furthermore, VOR gains for LARP and RALP were lower than VOR gains recorded for lateral impulses in the pediatric participants. This finding is consistent with those reported by McGarvie et al (2015) for all age groups studied. Thus, it appears necessary to adjust the VOR gain lower cutoffs for LARP and RALP testing due to the normally lower gain recorded for these tests.

During this study, several modifications were necessary to successfully complete the testing with the pediatric participants. First, pieces of foam were added to the back of the elastic band to prevent slippage of the goggles. The foam pieces aided in creating a textured barrier between the smooth elastic band and the child's hair. In addition, the foam added bulk to the child's head so that the elastic band would fit more tightly. Presently, no pediatric-sized goggles exist for the ICS Impulse System. One of the youngest participants in this study had a very small head size and, even with the use of the foam pieces placed inside the elastic band on the back of the head, the goggles had to be adjusted on the face to ensure that the camera was centered on the right eye. This increased the amount of discomfort from the goggles and the 4-year-old subsequently refused to continue the test after completing lateral vHIT because of excessive discomfort. Allowing the participants to remove the goggles between tests, while adding more time to the testing session, was deemed important by the examiners to increase participant cooperation for the subsequent tests, as well as participant retention. Because the VOR gain results achieved in this study for the adults and the pediatric participants aged ≥10 years are in close agreement with those reported in previous studies (McGarvie et al, 2014; 2015), we feel that the effect of not recalibrating after goggle removal was inconsequential.

Attention span and the ability to focus on a target are other factors affecting the successful administration of vHIT in children. The ICS Impulse system includes a blue sticker that is to be placed on the wall for the

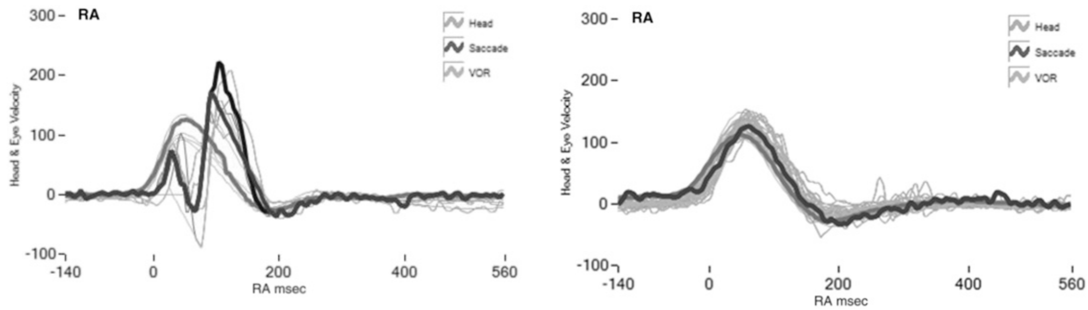

Figure 4. Example of the difference in pupil diameter between a 47-year-old (top) and a 10-year-old (bottom). These pictures were taken in the same room and lighting within minutes of each other.

participant to focus on during the test. In this study, colorful stickers of familiar objects and characters were used to keep the child's attention focused on the area of interest. The children were asked various questions about the sticker during impulse testing (How many sprinkles are on the cupcake? What colors do you see? How many wheels are on the truck?), and when attention began to deviate, a new sticker was placed on the wall. This method of keeping the child's attention worked well, but was challenging as the clinician operating the computer was also responsible for quickly changing out stickers. Some children required many sticker changes to stay focused, which no doubt increased the testing time. It is presently unknown how a constantly changing target, such as a video played on an iPod or smartphone would affect vHIT results or if it would increase extraneous eye movements.

Keeping the child seated upright is imperative to delivering accurate impulses and must be managed throughout the test as well. When moving a child's head, if not anchored to the chair or floor, the child's body will also move and become unstable. This instability can affect

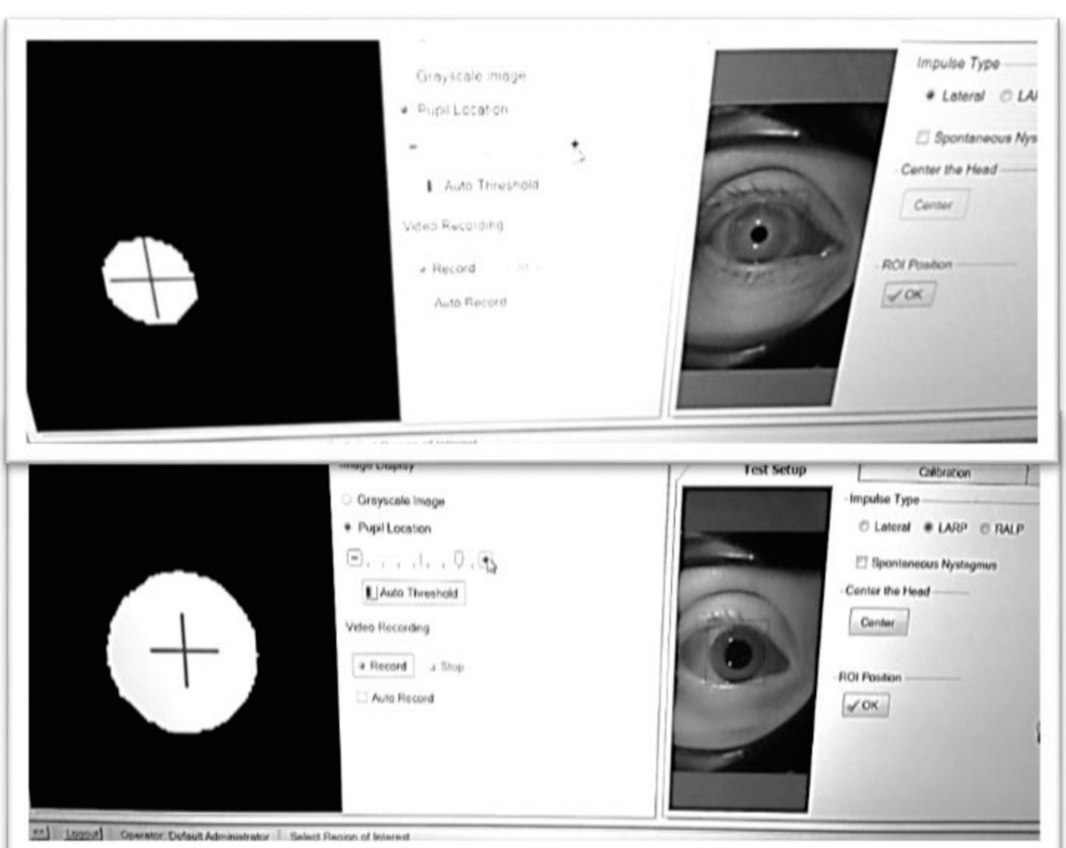

Figure 5. Example of a normal right anterior canal tracing (right) and a right anterior canal tracing with eyelid artifact (left). See text for full description.

the clinician's ability to present adequate impulses, which can increase the test time. In this study, a foot stool was used to keep the children seated upright and to help stabilize the body during head movements. Clinically, allowing a child to sit with their legs crossed also provides adequate stability.

Finally, to obtain a good pupil recording, the skin just above the right eyelid was pulled up and secured with the goggles. This effectively reduced eyelid artifact in most of the participants. Without these modifications, testing the pediatric participants would have been difficult. Further study is needed to determine the best means of keeping children focused on a visual target to decrease test time and discomfort from the tight-fitting goggles. Although the colorful stickers were a good alternative to the manufacturer-provided sticker as a focal point for the pediatric participants, it was still very challenging to keep the participant focused. Last, many of our pediatric participants left the pediatric balance lab with red marks on their faces, particularly on the sides of their noses. Pediatric-sized goggles would be a welcomed addition to the ICS Impulse vHIT system.

Limitations of the study were that children <4 years were not included and only normal participants were tested. Future studies with younger children, and those with vestibulopathy, are needed to address these areas.

CONCLUSION

VHIT is a noninvasive test that can be used to successfully measure the function of the lateral SCC in children as young as 4 years of age. Results indicate that adult VOR normative gain values may be used when testing children with lateral vHIT. Lower gain cutoffs should be used for LARP and RALP testing in children than the cutoffs used for lateral vHIT. Care must be taken to obtain the most accurate measures and reduce variability when testing children, particularly with LARP and RALP. Further research is warranted to study LARP and RALP response reliability and validity in children because of the highly variable VOR gains found in this population. Pediatric modifications for vHIT testing are necessary to reduce goggle slippage and body movement, as well as to increase attention and focus on the target. In addition, care must be taken to ensure clear visualization of the entire pupil during testing by pulling the loose skin above the right (recorded) eyelid up and securing it with the goggles, effectively opening the eye wider. The time needed to perform vHIT in children can range from just <10 minutes to >17 minutes, with younger children requiring more time. If test setup, calibration, instruction, and breaks between tests are included, the time needed to assess pediatric patients with vHIT could range from 15 minutes to well >20 minutes, realistically. Studies looking at ways to reduce test time, without sacrificing response accuracy, are presently underway.

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APPENDIX: BALANCE HISTORY

Name of child: ______________________

DOB: ______________________________

Sex: _______________

Who filled in this questionnaire: ____________________

At what age did your child learn to walk? ___________________

Has your child ever had an episode of any of the following (please check the corresponding yes/no box):

		Yes	No
1	Vertigo (the room/or your child feels like they are spinning)	☐	☐
2	Poor balance/clumsiness	☐	☐
3	Frequent falls	☐	☐
4	Brief episodes of inability to walk	☐	☐
5	Fear or panic without any obvious cause	☐	☐
6	Rapid back and forth eye movement (nystagmus)	☐	☐