Computerized Rotational Head Impulse Test: Age-Dependent Normative Data

du Plessis et al.: crHIT: Age-Dependent Normative Data

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Abstract

Purpose:

The objective of this study was to determine the normative vestibulo-ocular reflex gain output values of the computerized rotational head impulse test (crHIT) with stationary visual targets (earth bound) in healthy participants in each decade age band of life: 10–19, 20–29, 30–39, 40–49, 50–59, 60–69, and 70+ years.

Method:

Seventy-seven community-dwelling participants (10–85 years of age) with normal lateral semicircular canal (SCC) functioning and no symptoms or history of vestibular dysfunction were recruited through convenience sampling and assessed with the crHIT using stationary targets. These participants were assessed using two standard protocols in a randomized order.

Results:

Results from 77 participants (M_{age} = 46 years; 43 women, 34 men) were analyzed. Pearson's correlation coefficient and simple linear regression indicated a statistically significant relationship between crHIT gain output and age ($p > .05$) for right gain, 1030°/s^2, and left gain, 1005°/s^2. Although a statistically significant relationship was found, the slope was minor, demonstrating that the clinical effect of age on crHIT gain output was insignificant. Furthermore, no statistically significant relationship exists between crHIT gain output and gender ($p > .05$). Age-dependent normative data were calculated using the 2.5th and 97.5th confidence interval (CI) percentile method. The responses of angular vestibulo-ocular reflex (aVOR) gain values for crHIT are expected to occur within the range for lower limit reference interval (RI) of 0.85–0.9 and upper limit RI of 1.11–1.18 for 1030°/s^2 and lower limit RI of 0.86–0.92 and upper limit RI of 1.13–1.16 for 1005°/s^2. It can be expected that 90% CI of the population with normal lateral SCC functioning will have aVOR gain values that fall within this range.

Conclusion:

Despite a statistically significant relationship that exists with aVOR gain output and age, the changes are minor, declining by 0.0088 units per 10 years, justifying the same normative data for all decade age bands.

Vertigo, dizziness, and balance disorders alter the sense of motion and the perception of instability, which directly affects vision and gait (Suparmin & Indriani, 2022). Balance disorders also negatively affect quality of life physically and psychologically by increasing the risk for falling, limiting participation in daily activities, mobility and overall functioning, development of depression and anxiety, and social withdrawal (Lindell et al., 2021; Ranjan et al., 2017; Suparmin & Indriani, 2022). Hence, because of the growing concern, there has been an emphasis on the need for appropriate vestibular tests (MacDougall & Curthoys, 2012). The peripheral sensory apparatus of the vestibular system consists of 10 balance organs (five on each side). The 10 balance organs from both inner ears include six semicircular canals (SCCs) and four otolith organs, which activate and maintain the peripheral sensory apparatus of the vestibular system (Glover, 2004). These vestibular end-organs are one of the main input channels facilitating dynamic movement; however, they work together with the proprioceptive and visual sensory systems, providing the ability to orient ourselves in space (Delong, 2013; Glover, 2004). The vestibular system directly contributes to motor output, which is generated via three reflexes originating from our peripheral vestibular system, specifically the vestibulo-ocular reflex (VOR), the vestibulo-spinal reflex, and the vestibulo-colic reflex. The VOR has two components, namely, the linear VOR (lVOR) and the angular VOR (aVOR; Delong, 2013). Linear acceleration is detected and encoded by the otolith organs through the lVOR, while the SCCs are responsible for encoding angular acceleration, also known as rotational acceleration, through the aVOR (Delong, 2013). Gaze stabilization during head movement is mainly achieved through the aVOR (Halmagyi et al., 2006). Without the aVOR, the view of the world would move across the retina, creating a blurry image every time the head is turned.

Loss of peripheral vestibular function in people with vestibular pathologies can lead to substantial handicap, in part due to impacts on the aVOR, the primary oculomotor system that stabilizes visual gaze during rapid head rotation (Schubert et al., 2008). Researchers are continuously developing and refining vestibular assessments to provide clinicians with more reliable and objective tools to assist in the diagnosis and treatment of vestibular pathologies, particularly on the functioning of the SCCs by observing the aVOR response, which resulted in the development of the computerized rotational head impulse test (crHIT; Furman et al., 2017). The crHIT provides clinicians with an objective means to assess the lateral SCC and aVOR function in the vestibular system of patients, especially those with balance disorders (Furman et al., 2017).

Clinical tests of the aVOR typically include caloric testing with the videonystagmography (VNG) goggles and rotary chair testing. The caloric test is considered to be the “gold standard” for evaluating aVOR at a very low frequency of 0.003–0.008 Hz (Shepard & Jacobson, 2016). The sinusoidal harmonic acceleration rotary chair test evaluates the aVOR in the mid frequencies between 0.01 and 1.28 Hz, and the video head impulse test (vHIT) provides a quick and objective quantification of the aVOR in response to high-frequency head movements in the natural range of daily motions (MacDougall et al., 2009; Shepard & Jacobson, 2016). The well-known and utilized vHIT was developed to quantify the degree of SCC function and was first introduced by MacDougall et al. in 2009 (Chen & Halmagyi, 2020). The vHIT has since become a commonly used tool in assessing SCC functioning; however, it is associated with its own set of challenges (MacDougall et al., 2009). The vHIT needs to be performed by a trained, experienced clinician to obtain accurate and reliable results; thus, the degree of variability in the results obtained by different clinicians may have an impact on interrater reliability (Mutlu et al., 2020). Furthermore, the positioning of the clinician’s hands plays a large role in slippage and may consequently result in slippage if in contact with the vHIT goggles (Halmagyi et al., 2017). Second, the peak velocities of the lateral head impulses are difficult to precisely replicate as they are not known until after the head impulse has been administered (MacDougall et al., 2009). Despite the vHIT’s consistency and reliability having been established (MacDougall et al., 2009), these factors continue to have an impact on the results obtained. Patients who have spinal problems and neck fusions or stiffness may experience discomfort during the testing procedure, and the vHIT may be harmful to some of them, leaving a small population untestable (Alhabib & Saliba, 2016).

The crHIT is based on the same physiological principles as the vHIT and was specifically designed to overcome its challenges. These principles imply that the aVOR will generate saccades, which are compensatory eye movements, in an equal and opposite direction when evoked by natural head rotations (Halmagyi et al., 2017). One major difference is that the crHIT utilizes a rotary chair positioned in a lightproof booth, combined with high-speed data acquisition, eye-tracking video-oculography (VOG) goggles. Patients are safely secured using neuro-otologic test center (NOTC) restraints, including ankle straps, a lap and shoulder belt system, and two molded foam pads to secure the head. These restraints play a vital role in ensuring that the results obtained are consistent and that all other external factors that might influence the results, such as unwanted neck movement and goggle slippage, are reduced (Furman et al., 2017).

The crHIT utilizes computer-controlled, rapid whole-body rotations to generate a controlled, repeatable, and reliable stimulus, thus eliminating the need for manual head-on-torso rotation as utilized by the vHIT (Furman et al., 2017). Furman et al. (2017) found that crHIT does not completely eliminate goggle slippage due to abrupt high-speed accelerations; however, it significantly decreases the possibility thereof by comfortably securing the patient's head with two molded foam pads against a molded occipital and cervical support. Furthermore, the whole-body rotations eliminated the need for any neck movement—reducing patient discomfort accompanied with head-on-neck rotations and allowing anyone, including patients with a limited range of head motions, to be tested. Additionally, the crHIT generates more data for every impulse, thereby lessening the number of impulses needed and minimizing patient prediction by allowing a random magnitude and direction of rotation (Furman et al., 2017).

Published research on the crHIT is limited, with only one other published study currently available. This study, conducted by Furman et al. (2017), compared data collected from the crHIT with data from caloric and the vHIT. The study demonstrated that the crHIT provided a reliable laboratory-based measure of unilateral horizontal SCC function and, as mentioned above, that the crHIT successfully overcame the challenges of the manual vHIT. No published research has been conducted that provides clinicians with the necessary values to accurately analyze crHIT responses aiding in the detection and diagnoses of horizontal SCC dysfunction.

Normative data values are essential in providing clinicians with a sense of distribution in a population that determines a baseline against which measurements can be compared, which allows clinicians to accurately interpret responses that may be obtained with vestibular dysfunction. The physiological effect of age on the aVOR function has been well documented in published studies. In a study conducted by McGarvie et al. (2015), the authors indicated that age causes histological changes in structures supporting the aVOR, yet results suggested an insignificant effect of age on aVOR gain values, which was likely due to central compensation mechanisms (McGarvie et al., 2015). Agrawal et al. (2009) found that a decline in the function of the semicircular plays a significant role in age-related decline in the vestibular system with a significantly higher prevalence and severity than otolith-associated age-related decline. Given that the SCCs' purpose is to assess angular acceleration, it could be hypothesized that deterioration in these structures may be more closely related to dizziness described by patients, the presence of which significantly increases their risk of falling (Agrawal et al., 2009). Therefore, the purpose of this study is to investigate the effect of age and to determine age-dependent normative gain output data for the crHIT. Determining these values will allow the crHIT responses of future patients to be accurately analyzed using age-specific norms.

Method

Participants with no history of vestibular and neurological disorders were recruited using convenience sampling. The study was approved by the Research and Ethics Committee at the University of Pretoria, South Africa (HUM038/1120) and conducted under the guidelines set out in the Declaration of Helsinki. All participants provided written informed consent prior to partaking in the study and were able to withdraw at any point throughout the study. Participants under the age of 18 years required parental consent to participate in the study; thus, they signed a child assent form, while their parent(s)/guardian(s) signed parental consent.

Participants

Seventy-seven participants, ranging from 10 to 85 years of age, with a mean age of 46 years (SD = 21.47), were included in the study. Of the 77 participants, 43 were women (M = 47.21 years, SD = 22.05) and 34 were men (M = 44.62 years, SD = 20.95). All participants were required to present with no history of hearing loss, or vestibular or neurological disorders. A standardized questionnaire was conducted with each participant, as well as vHIT to exclude lateral canal SCC dysfunction. A minimum of 10 impulses in each direction was administered. The vHIT excluded only two participants due to VHIT gain of less than 0.8. The first patient who was excluded presented with a bilateral vestibular hypofunction with vHIT gains of 0.23 bilaterally. The second participant presented with a clear right vestibular hypofunction with vHIT gains of 0.39 for the right and 0.75 in the left. These results were indicative of a vestibular dysfunction, and therefore, these patients were excluded from the study. Participants with a gain of 0.8–1.2 and no detectable catch-up saccades went on to do the final screening, which included ocular motor testing (horizontal smooth pursuit and random saccades) to exclude ocular motor disorders. The demographics for the decade age bands are shown in Table 1.

Table 1. Demographics of data for decade age bands.

Decade age band	Total (*n*)	Female (*n*)	Male (*n*)
10–19	10	7	3
20–29	12	5	7
30–39	10	3	7
40–49	11	8	3
50–59	10	7	3
60–69	10	5	5
70–89	14	8	6
Total participants	77	43	34

Devices

The crHIT was administered using the Neurolign, LLC (USA) I-Portal NOTC and was conducted using Version 8.0.2 of the VEST software at the University of Pretoria, South Africa. Participants were firmly secured in the computerized rotary chair (a peak torque of 185 ft lb) enclosed in a lightproof booth (Model No. RCS-035) and were required to wear binocular infrared VOG goggles. High-resolution eye-tracking images were obtained through two high-speed digital infrared cameras (940 nm; with a sampling rate of 100 frames/s). Spatial resolution for horizontal and vertical eye tracking and torsion is < 0.1°; eye-tracking range is at least ±30° horizontal, ±20°

vertical, and ±10° torsional. These VOG goggles also have an embedded three-axis rate sensor to record head velocity. Participants were secured using restraints, which included two ankle straps, a lap and shoulder belt system to secure the torso, and two molded foam pads to comfortably secure the participant's head against a molded occipital and cervical support (Furman et al., 2017).

Procedure

To create age-dependent normative gain data for the crHIT, two different crHIT assessment protocols with stationary (earth bound) target were utilized for each test participant. The protocols differed in number of impulses, velocity, and order of the direction of rotations (clockwise [CW] and counterclockwise [CCW]). Protocol 1 consisted of 12 impulses (six CW and six CCW) with a nominal velocity of 155°/s and acceleration of $1000°/s^2$. Protocol 2 consisted of 14 impulses: 12 impulses (six CW and six CCW), which had a nominal velocity of 187°/s and accelerations of $1000°/s^2$, which is identical to Protocol 1, and an added component of two low-acceleration impulses (one CW and one CCW). These two additional low-acceleration impulses have a nominal velocity of 110–120°/s (rotations, at $520°/s^2$ and $635°/s^2$), aiming to further minimize the participants' ability to predict the direction of the whole-body rotations.

The order of the different protocols mentioned above was assigned to each test participant in a randomized manner. The restraints used to secure the participants in the NOTC were rechecked and readjusted after each of the assessment protocols. This was done to ensure that the results from each protocol were consistent and further reduced any external factors that could have influenced the results of the assessment. Participants were moved into the appropriate testing position, and a calibration protocol was administered prior to testing, with earth-fixed targets at 10° from the primary position to account for the participant's eye position and movement (horizontal and vertical) in relation to the goggles (McGarvie et al., 2015). Thereafter, participants were assessed in the order of the assigned protocols, during which the researcher checked for slippage of the VNG goggles by observing the location of the eye orbits in the software.

The test participants were instructed to keep their gaze fixed on a dot, which was 1 m away, while computer-controlled rapid, unexpected, and unpredictable whole-body rotations were delivered. The visual target remained illuminated during the rotational impulses. The rotary chair accelerated randomly in either a CW or CCW direction rapidly and abruptly for 12 sequential rotations in Protocol 1 and 14 sequential rotations for Protocol 2. For the first stationary assessment protocol ($1030°/s^2$), six whole-body rotation impulses were administered in a CW manner, while the other six occurred in a CCW manner (e.g., CW, CCW, CW, CW, CW, CCW,

CCW, CW, CCW, CCW, CW, CCW). These accelerations varied from 750°/s^2 to 1000°/s^2, followed by a deceleration to a stop at a rate of 150°/s^2 to 200°/s^2. The rotary chair stayed in the position in which it stopped for a brief interval. The interval in which the chair remained stationary between the subsequent impulses was random and varied from 3 to 5 s. The second stationary protocol (1005°/s^2) was similar to the first; however, it included two low-acceleration impulses at 520°/s^2 and 635°/s^2 to further reduce predictability. These rotations were administered to each direction (one CW, one CCW), in addition to the accelerations mentioned in the first protocol. Thus, a total of 14 rotational impulses were administered, with seven in a CW manner while the other seven occurred in a CCW manner. The gain for the crHIT is calculated by using the ratio of the eye velocity and chair velocity; thus, $\text{Gain} = \frac{\text{Eye velocity}}{\text{Head velocity}}$ as it produces the least variability and smallest standard deviation (Furman et al., 2017).

Statistical Analysis

The raw data collected were captured into Microsoft Excel. It was in a numerical format on the Excel spreadsheet and imported for computerized statistical analysis using the R software (RStudio, Version 1.4.1717). The data imported were analyzed using descriptive and inferential statistics. Normal distribution of crHIT gain values for both protocols was confirmed for rightward and leftward gains separately for the entire population through kurtosis of normal distribution, skewness, and the Kolmogorov–Smirnov (K-S) test. The data were normally distributed (significance levels using the K-S test are above .5; Teegavarapu, 2019); thus, it was appropriate to use statistical methods that assume normality such as Pearson's correlation coefficient and linear regression.

Pearson's correlation coefficient and linear regression were used to examine the relationship between the crHIT gain outputs and age (in years) and gender. Since the categorial variable "age group" is measured on an ordinal scale, Spearman's correlation was utilized to examine the relationship. Spearman's correlation coefficient allows for the investigation of a monatomic relationship, which is not necessarily linear. Furthermore, the 2.5th and 97.5th percentiles confidence interval (CI) was used to determine age-depended normative data for both protocols. CIs describe an interval that will, on average, contain the true population parameter with a given probability; therefore, the 95% CI calculated for crHIT gain outputs can be used as normative data, as it most likely contains the true estimated value for 95% of the population in this sample.

Results

Normal distribution of data was tested using the K-S test, *p* values of $p > .05$, and kurtosis of normal distribution.

Pearson's and Spearman's Correlation

Pearson's correlation is used to investigate a linear relationship between "age" and "gender," and the crHIT gain outputs. It is chosen because "age" is a continuous variable measured on a ratio scale and "gender" is a binary variable (male = 1). Furthermore, Spearman's rank correlation coefficient is utilized for the variable "age group." Spearman's correlation allowed for the investigation of a monotonic relationship, that is, if the relationship is positive or negative.

The correlation coefficients reported in Table 2 indicate that age had a weak negative correlation. It can be seen that for right gain 1030°/s^2 (rho = −.25, p = .03) and left gain 1005°/s^2 (rho = −.24, p = .33), it appears significant with a negative correlation of approximately .25. Similarly, Spearman's correlation coefficient indicated some significant weak negative correlation between the age group and crHIT outputs for left gain, 1005°/s^2 (rho = −.274, p = .016). The relationship between gender and the crHIT gain output further indicated a negative correlation with no statistically significant relationship noted.

Table 2. Correlation between computerized rotational head impulse test (crHIT) and age, age group, and gender.

crHIT	Age group		Age		Gender (male = 1)	
	rho	*p*	rho	*p*	rho	*p*
Left gain (1030°/s^2)	−.191	.096	−.122	.290	−.012	.915
Right gain (1030°/s^2)	−.201	.079	−.250	.028	−.073	.525
Left gain (1005°/s^2)	−.274	.016	−.244	.033	−.040	.733
Right gain (1005°/s^2)	−.125	.278	−.175	.128	−.018	.878

Note. Spearman's correlation is used for age group. Pearson's correlation is used for age and gender. The COR function in the R software is used to compute the correlations and their significance levels.

Thus, there is evidence suggesting that a statistically significant relationship exists between the participants' age and crHIT gain output. However, for gender, no evidence was found of a relationship. Spearman's results revealed that there is a negative monatomic relationship between age group and crHIT gain outputs; however, it was only statistically significant in left gain, $1005°/s^2$.

Simple Linear Regression

Linear regression was carried out to further investigate the relationship between outputs of crHIT gain output and age, in years, of healthy participants in each decade age band of life from 10 to 80+. The results are reported in Table 3. The findings indicate a certain negative dependence of crHIT gain by age, right gain $1030°/s^2$ ($p = .028$), and left gain $1005°/s^2$ ($p = .033$), proposing a possible inverse linear relationship exists between variables. This suggests that as dependent variables (crHIT gain output), the independent variable (age) is predicted to decrease.

Table 3. Linear regression analysis.

Variable	Left gain ($1030°/s^2$)		Right gain ($1030°/s^2$)		Left gain ($1005°/s^2$)		Right gain ($1005°/s^2$)	
	Estimate	*p*	Estimate	*p*	Estimate	*p*	Estimate	*p*
Intercept	1.034	.000	1.018	.000	1.054	.000	1.034	.000
Age	−0.00039	.290	−0.00088	.028	−0.00085	.033	−0.00051	.128

Note. The lm function in the R software was used to estimate the regression.

Although a negative dependence exists between crHIT gain output and age, which is statistically significant, it is clinically insignificant. As can be seen with right gain 1030°/s^2, the coefficient is −.00088, which is statistically significant (p = .028); however, the slope is only minor. That is, that for every (additional) year, the crHIT gain decreases by 0.00088 units, and more specifically, gain will decrease 0.0088 units per 10 years. Hence, on average, gain output is around 1, indicating that the effect of age on the crHIT gain output is not clinically significant. Similar results were obtained for left gain, 1005°/s^2 (p = .033). It should be noted that a nonlinear (parabolic) relationship was also tested using a regression with two explanatory variables—age and squared age; however, no statistical evidence was found.

CIs (2.5th and 97.5th Percentiles)

As mentioned above, age and age group were statistically significant for right gain 1030°/s^2 and left gain 1005°/s^2; however, the clinical effect on crHIT gain was insignificant. Furthermore, no effect of gender on crHIT gain output was noted. This leads to the assumption that normative data can be calculated on the average for all data and age groups combined. The results are reported in Table 4. The 2.5th and 97.5th percentiles two-tailed CI was further utilized to determine the normative gain data values for all age decade bands, both protocols, with left and right gain combined. As seen in Table 4, for Protocol 1, 1030°/s^2, reference interval (RI) lower limit (2.5th) of 0.89 and upper limit (97.5th) of 1.11 were noted. The 90% CI for lower RI was 0.85–0.9, and the 90% CI for the upper RI was 1.11–1.18. Similarly, the RI lower limit (2.5th) of 0.91 and the upper limit (97.5th) of 1.14, with the 90% CI for lower RI of 0.86–0.92 and the 90% CI for upper RI of 1.13–1.16, were obtained for Protocol 2, 1005°/s^2. In using these limits, it can be expected that 90% of the population with normal lateral SCC functioning will have aVOR gain values that fall within this range.

Table 4. Computerized rotational head impulse test (crHIT): confidence intervals (CIs; 2.5th and 97.5th percentiles).

	RI lower limit, (2.5th)		RI upper limit (97.5th)		90% CI for lower limit RI		90% CI for upper limit RI		
Variable	**1030**	**1005**	**1030**	**1005**	**1030**	**1005**	**1030**	**1005**	***N***
Gain	0.89	0.91	1.11	1.14	0.85–0.9	0.86–0.92	1.11–1.18	1.13–1.16	77

Note. RI = reference interval.

Traces of data for reference can be seen below depicting the crHIT responses and working data. Figure 1 shows traces of horizontal eye position (blue and red lines) resulting from one crHIT acceleration stimulus of the rotational chair (black line). Leftward and rightward accelerations are shown in Figures 1A and 1B, respectively. The data were obtained from the 32-year-old male subject (Participant M051).

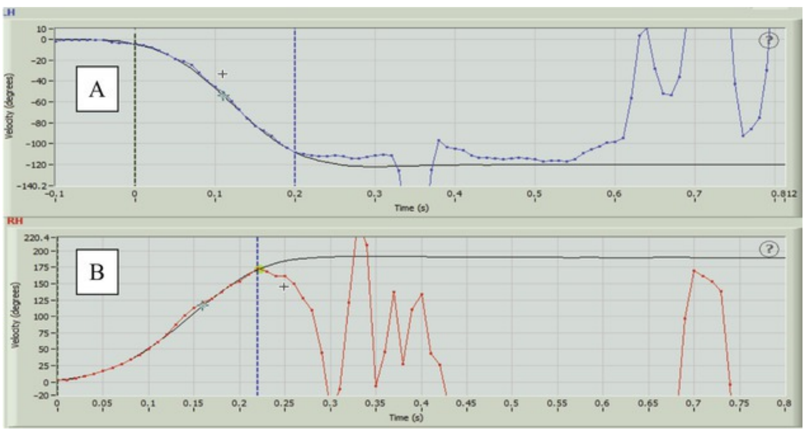

Figure 1. Leftward and rightward computerized rotational head impulse test (crHIT) trackings of horizontal eye movements during crHIT acceleration impulse.

Alt text: 2 graphs plot the velocity in degrees versus the time in seconds. In both graphs, a black line depicts the stimulus which is a rapid whole body ~~acceleration followed by a deceleration to a stop~~. A. In the first graph, a blue line represents traces of the inverted horizontal eye movement measured during rapid leftward acceleration. The blue line follows the black line during the rapid acceleration between 0.2 seconds. B. In the second graph, a red line represents the traces of the inverted horizontal eye movement during rapid rightward acceleration. The red line follows the black line between 0 and 0.23 seconds indicating an intact aVOR system.

Furthermore, we can see the working data obtained during a crHIT impulse from two participants, a 32-year-old man and an 83-year-old woman. Figure 2 shows traces of horizontal eye position (blue lines) resulting from one crHIT acceleration stimulus of the rotational chair (black line). Data from a 32-year-old man (Participant M051) and an 83-year-old woman (Participant M063) are depicted in (Figures 2A and 2B, respectively). Note the clarity of the eye position trace showing the initial velocity change reflecting the acceleration of the head, followed by the subsequent overt nystagmus once the acceleration ceases.

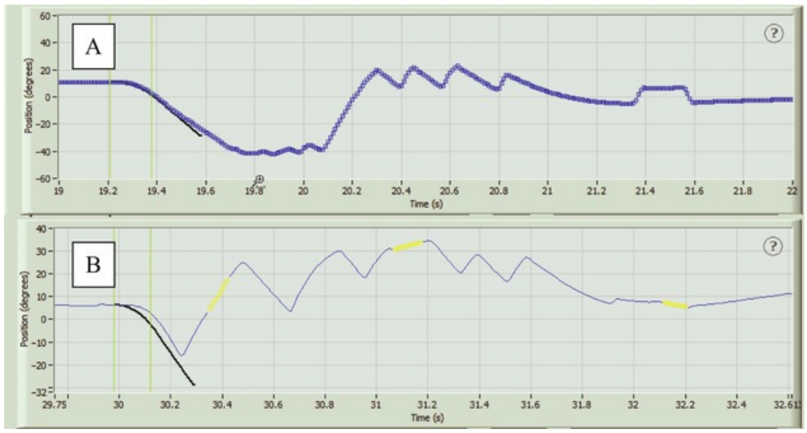

Figure 2. Leftward working data of eye trackings during a computerized rotational head impulse test acceleration impulse.

Alt text: 2 graphs record the values of the position in degrees with respect to the time in seconds. A. In the first graph, the data is captured from a 32 year old male. The black line represents the rapid leftward acceleration between 19.2 and 19.5 seconds. The blue line representing the horizontal eye tracings follows the black line between 19 and 19.5 seconds indicating the initial velocity change. The blue line then remains at negative 40 degrees between 19.6 and 20.1 seconds indicating that the acceleration has ceased. The blue line then fluctuates between negative 5 and 22 degrees for the remaining time reflecting the subsequent overt nystagmus following the deceleration to a stop. B. Data recorded for an 83 year-old female. Similarly, in the second graph, the black line represents a rapid leftward acceleration between 30 and 30.3 seconds. The blue line is very near to the black line between 20.75 and 30.2 seconds representing the horizontal eye tracings during the acceleration. The blue line then fluctuates between 4 and 35 degrees for the remaining values of time which reflects the subsequent ~~over~~ nystagmus ~~following the deceleration to a stop~~.

Discussion

The main aim of the study was to determine age-dependent normative values of aVOR gain for healthy participants in each decade age band of life: 10–19, 20–29, 30–39, 40–49, 50–59, 60–69, 70–79, and 80–89 years via crHIT using stationary targets. There has been limited research done on the crHIT since its introduction, with only one published article available. This justifies exploring the crHIT gain outputs in order to improve its clinical utility.

As well known, aging causes a degenerative effect within the vestibular system. Research has shown that an age-related decline in the functioning of the aVOR is associated with histopathological changes, which includes a progressive degeneration of hair cells, otoconia in otolith organs, and Scarpa's ganglion neuronal degeneration (Rauch et al., 2006). Using the 2.5th and 97.5th percentiles two-tailed CI test, a normative data range was obtained. The study revealed that the mean VOR gains for stationary targets are to occur within the range for lower limit RI of 0.85–0.9 and upper limit RI of 1.11–1.18 for Protocol 1 and between the lower limit RI of 0.86–0.92 and upper limit RI of 1.13–1.16 for Protocol 2. It can be predicted with 90% confidence that gain values measured by the crHIT, in healthy individuals without lateral SCC dysfunction, would occur within these ranges.

McGarvie et al. (2015) conducted a cross-sectional study with 91 healthy, community-dwelling participants aged 10–89 years (with about 10 participants per decade) to determine age-normative values of the vHIT. Their results indicated that the aVOR was age-independent since it remained consistent across the age groups. Gain values reported in their study were similar to the mean aVOR gain values reported by Bansal and Sinha (2016), which ranged from 0.9 to 1 in participants with normal hearing and SCC functioning. As previously mentioned, the aVOR gain values for the current study falls within a narrow range of 0.98–1.02, which agrees with the expected values of the vHIT as determined in the above studies (Bansal & Sinha, 2016; McGarvie et al., 2015).

Matio-Soler et al. (2015) evaluated the VOR gain across a sample of 212 healthy participants using the vHIT to assess lateral SCC function. Up to the age of 90 years, aVOR gain remained constant for low head impulse velocities, followed by a decrease thereafter. Similar results were reported by McGarvie et al. (2015), indicating that horizontal VOR gain for the youngest participants was closely clustered around 1.0 for low velocities, and a small decline was observed in VOR gain as the velocity increased. It was also reported that the average VOR gain across velocities in each decade age group was quite similar, with only a slight decline with age; however, it was not significant for the horizontal canal (McGarvie et al., 2015). Based on another study of age-dependent data for horizontal VOR gain with age and vHIT by Mossman et al. (2015), a decrease in horizontal VOR gain with age was noted. These changes were very minor with a decrease of 0.012 and 0.17 per decade as age increased. This decrease with age is similar to the results of this study, with a significant negative correlation and a minor decrease in aVOR gain output of 0.0088 per decade, which is consistent with the weak negative relationship found in this study that exists between aVOR and age, indicating that aVOR gain was clinically unaffected by age.

The decrease of vestibular receptor cells and main afferents with aging has been well documented and unexpected, as those structures do not regenerate (Iwasaki & Yamasoba, 2015; Rauch et al., 2006). Nevertheless, a large number of individuals who undoubtedly have such reductions yield vestibular test results that are, at least from the perspective of functionality, fairly normal. This is possibly due to an increased sensitivity of afferent nerve fibers or central mechanisms that maintain normal function despite reduced peripheral input (Jahn et al., 2003). This implies that the vestibular sensory regions can function reasonably well with a reduced amount of both sensory cells and nerve fibers (Jahn et al., 2003). The insignificant effect of age on VOR gain values we have shown is likely due to central compensation mechanisms. Researchers have proposed that age-related physiological vestibular losses are countered by compensatory mechanisms, thus maintaining the VOR in elderly individuals (Jahn et al., 2003; Li et al., 2015; McGarvie et al., 2015). The cerebellum regulates the oculomotor responses, and extensive research on the aVOR has demonstrated how crucial the cerebellum is for repairing the aVOR in the face of challenges (Zalewski, 2015). Age-related differences are usually subtle until they reach a level where both peripheral and central alterations can no longer be compensated and vestibular function deteriorates (Zalewski, 2015).

The only other published study of the crHIT was conducted by Furman et al. (2017) and compared data collected from the crHIT with data from calorics and the vHIT. In that study, it was demonstrated that the velocity method of data analysis for the crHIT yielded a sustainably higher lower limit compared to those used for the vHIT. This was likely due to the larger amount of usable data per trial for the lower variability of aVOR gain. According to this study, the horizontal crHIT is a clinically reliable assessment tool for measuring unilateral horizontal SCC function while overcoming many of the challenges of the manual vHIT. Some limitations of the crHIT are the need for a costly specialized rotational chair and the inability to transport the test equipment to the bedside (Furman et al., 2017). During our research, it was evident that older participants had difficulty getting into the chair than did the younger participants due to the elevation of the chair.

Conclusions

aVOR gain output of the crHIT, as measured directly by the eye movement response to a whole-body rotation, seems largely unaffected by gender. Despite a statistically significant relationship that exists with aVOR gain output age, the changes are minor, declining by 0.0088 units per 10 years, justifying the same normative data for all decade age bands. The normative aVOR gain values for crHIT have clinical value as they could provide clinicians with references for analyzing future patients' results, thereby aiding in the identification and diagnosis of patients with a lateral SCC dysfunction. Further research on the crHIT is currently being performed at the University of Pretoria, where data from the crHIT can be directly compared to those of the vHIT for patients with a vestibular hypofunction.

Data Availability Statement

The data obtained during the study are stored for a period of 15 years electronically and in the form of a hard copy. Hard copies are stored in a locked cupboard in the supervisor's office in the Communication Pathology building at the University of Pretoria. Electronic copies are password-protected, and the password is only known to the researcher and supervisors.

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