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Effects of device on video head impulse test (vHIT) gain

Kristen L. Janky¹, Jessie N. Patterson², Neil T. Shepard³, Megan LA Thomas¹, and Julie A. Honaker^{2,4}

¹Boys Town National Research Hospital, Department of Audiology, Omaha, NE 68131

²University of Nebraska-Lincoln, Department of Special Education and Communication Disorders, Lincoln, NE

³Mayo Clinic – Rochester, MN

⁴Cleveland Clinic, Cleveland, OH

INTRODUCTION

The video head impulse test (vHIT) allows examiners to objectively assess the vestibulo-ocular reflex (VOR) during head impulses in the plane of each semicircular canal (horizontal, anterior, and posterior). The purpose of the VOR is to maintain steady vision during head movement by initiating a reflexive eye movement that is equal and opposite that of head movement. During vHIT, a head worn gyro-meter measures angular head velocity and an infrared camera measures angular eye velocity during each head impulse. In the event of abnormal VOR function, vHIT identifies both overt and covert corrective reset saccades (i.e., corrective reset saccades that occur after and during the head impulse, respectively), indicating abnormal VOR function and the inability to maintain steady vision during head movement [MacDougall et al., 2009]. Advantages of vHIT over other clinical vestibular measures of canal function (e.g., calorics, rotary chair) are that it provides information regarding individual canal function, is quick to administer, and does not induce dizziness; however, its relationship to other tests of canal function suggest that vHIT is not a replacement to, but adjunctive to other tests of vestibular function [MacDougall et al., 2009; McGarvie et al., 2015a; McCaslin et al., 2014; Bell et al., 2015; McCaslin et al., 2015].

The most common outcome parameter reported with vHIT is VOR gain. VOR gain is calculated as the ratio of eye velocity to head velocity. While numerous vHIT devices are available commercially, gain is not calculated uniformly. To our knowledge, no study to-date has compared vHIT gain collected from different commercially available vHIT systems, which is necessary when comparing studies that have used different devices. Therefore, in the current study, three different vHIT devices were compared, with each calculating vHIT

Kristen L. Janky, PhD, Corresponding Author, Boys Town National Research Hospital, 555 N. 30th St. Omaha, NE 68131, Phone: 402-498-6535, Fax: 402-452-5015, kristen.janky@boystown.org.

Conflicts of Interest:

KLJ provided consulting for Otometrics regarding the clinical use of vestibular evoked myogenic potential testing and video head impulse testing (vHIT) during this time frame.

Boys Town National Research Hospital was a beta site for the Interacoustics EyeSeeCam.

University of Nebraska Lincoln (JAH lab) was a beta site for MicroMedical vHIT system and Key opinion site with GN Otometrics.

gain using a different method: 1) instantaneous gain, 2) area under the curve gain, and 3) position gain. For instantaneous gain, gain is calculated by dividing eye velocity by head velocity at a discrete point in time after the initiation of the head impulse (Figure 1A). For area under the curve gain, gain is calculated by averaging instantaneous gain (eye velocity divided by head velocity at every point; cumulative gain) across the duration of the head impulse (zero crossing point; Figure 1B, shown by dotted lines). Reset saccades interfere with gain calculations using area under the curve by artificially inflating the gain; therefore, gain is calculated on de-saccaded waveforms (reset saccade removed; Figure 1B, removal of the reset saccade shown by black shading). For position gain, gain is calculated by dividing the total eye rotation (in degrees) by total head rotation (in degrees) from the time the head impulse is initiated to the zero crossing, when normal, or to the start of a corrective reset saccade, when abnormal (Figure 1C, shown by dashed lines). This is effectively the same as measuring area under the curve, but with a different stopping point. It is unknown if these different devices, utilizing different methods of gain calculation, yield similar gain values for individuals with normal and abnormal vestibular function.

While other tests of vestibular function have demonstrated vulnerability to aging, minimal effect of age has been documented with respect to vHIT gain [McGarvie et al., 2015b;Matino-Soler et al., 2015;Davalos-Bichara and Agrawal, 2014;Mossman et al., 2015]. Age has been shown to have little effect on vHIT gain until the 8th or 9th decade of life [Davalos-Bichara and Agrawal, 2014;Matino-Soler et al., 2015;McGarvie et al., 2015b;Mossman et al., 2015], but this work has not been replicated and evaluated with all devices. Therefore, a second aim of the current study was to evaluate the effect of age on vHIT gain for each vHIT device and gain algorithm.

We hypothesize no significant differences in lateral canal angular gain values among three commercial vHIT devices, each utilizing a different VOR gain algorithm; however, subtle differences may occur, which could affect clinical performance or the comparison of data obtained with different devices. Therefore, using three commercially available vHIT devices the purpose of the present study was three-fold, to compare: 1) horizontal canal vHIT gain among devices in normal control subjects; 2) the effects of age on vHIT gain for each device in normal control subjects; and 3) the clinical performance of horizontal canal vHIT gain among devices for differentiating normal versus abnormal vestibular function.

MATERIALS & METHODS

Study population

Control sample—Sixty-one normal control adult subjects (mean age: 49, range 20–78, 25 males, 10 subjects per decade) participated in the study. By case history, all control subjects denied significant hearing loss or history of dizziness, imbalance or other neurologic complaints.

Patient sample—Eleven adults with unilateral or bilateral vestibular loss (mean age: 52.3, range 32 – 79, 2 males) also participated. Unilateral vestibular loss was diagnosed by caloric weakness (> 30%). Bilateral vestibular loss was diagnosed by reduced sinusoidal harmonic acceleration rotary chair gains across the frequency spectrum up to 0.32 Hz. Of the 11 adults

with vestibular loss, 3 had bilateral loss (6 ears affected) and 8 had unilateral loss (4 left and 4 right ears affected, mean caloric weakness: 70%, range: 43 – 91) for a total of 14 ears affected with vestibular loss.

Informed consent was obtained from all subjects for testing approved by the Institutional Review Boards at Boys Town National Research Hospital and the University of Nebraska-Lincoln.

Video Head Impulse Test (vHIT)

vHIT was administered using three different devices/algorithms, randomized in order for each subject on the same day: 1) Impulse (Otometrics, Schaumburg, IL; monocular eye recording, right eye only, using area under the curve gain; software version: 1.2), 2) EyeSeeCam (Interacoustics, Denmark; monocular eye recording, left eye only, using instantaneous gain; software version: 1.1.1), and 3) VisualEyes (MicroMedical, Chatham, IL, binocular eye recording, using position gain; software version: 8.11A). All head impulses were completed by 3 examiners (KLJ, JAH, JP). For any given subject, the same examiner completed vHIT for each device. Each device was calibrated according to manufacture recommendations. For each vHIT, subjects were seated 1 meter from a visual target mounted at eye level on the wall. The examiner stood behind the participant, placed hands on the participant's chin and delivered randomized (timing and direction) head impulses (100 to 250°/s peak head velocity) in the plane of the horizontal semicircular canal. Each manufacturer utilized different criteria for the number of impulses required. Interacoustics, EyeSeeCam had no criteria, so testing was stopped when approximately 20 head impulses were acquired for each side, Otopetrics, Impulse required 20 acceptable head impulses for each side, and MicroMedical, VisualEyes required 10 acceptable head impulses for each side. The outcome parameter was gain, which was calculated differently for each device: A) Instantaneous gain (Figure 1A; Interacoustics, EyeSeeCam); B) Area under the curve (Figure 1B; Otopetrics, Impulse), C) Position gain (Figure 1C; MicroMedical, VisualEyes). Of note, vHIT gains utilizing position gain were automatically rounded by the software.

Statistical Analyses

Either a paired samples t-test or a within-groups ANOVA was completed to evaluate the effects of impulse side (rightward versus leftward) on vHIT gain for each device/algorithm. Correlations were calculated to investigate the relationship between vHIT gain and age. A within-groups ANOVA was completed to evaluate mean differences in vHIT gain between the three devices/algorithms. All post hoc analyses used Tukey's procedure. To determine clinical accuracy of the different devices/algorithms for detecting vestibular loss (control vs patient sample with significant caloric weakness), Receiver Operating Characteristic (ROC) curves and Area under the ROC curve (AUC) were calculated, where an area of 1 represents a perfect separation of controls from patients and an area of 0.5 represents a test with poor diagnostic accuracy.

RESULTS

The effects of vHIT device/algorithm and age on horizontal canal vHIT gain in normal control subjects

(1) Instantaneous gain

For instantaneous gain (measured using the left eye, Interacoustics EyeSeeCam), gain was calculated for rightward and leftward head impulses as the median value at 3 latencies: 40, 60, and 80 ms after the initiation of the head impulse, shown in Table 1. A within-groups ANOVA was completed with impulse side (rightward versus leftward) and latency (40, 60, and 80 ms) as the within-subjects factors. There was a main effect of impulse side ($F(1, 60) = 19.34, p < .001$), with significantly higher mean gain for leftward (0.99) compared to rightward (0.94) head impulses. When interpreting the simple effects, as shown by an asterisk (*) in Table 1, mean gain was significantly higher in the eye ipsilateral to the direction of head impulse for 40 and 60 ms. There was also a main effect of latency ($F(2, 120) = 22.86, p < .001$), with gain significantly increasing as the latency increased from 40 ms (.91) to 60 ms (.97) to 80 ms (1.01). There was a significant interaction between impulse side and latency ($F(2, 120) = 3.442, p = .04$), with differences in gain being more pronounced between the latencies for rightward compared to leftward head impulses. Age was weakly correlated with mean vHIT gain at 40 ms ($r = .27, p = .037$), but not correlated at 60 ($r = .18, p = .16$) or 80 ms ($r = .14, p = .3$).

(2) Area under the curve gain

For area under the curve gain (measured using the right eye, Otometrics Impulse), gain for rightward and leftward head impulses are shown in Table 1. Data from one subject was dropped as gains were greater than 3 SDs from the mean (1.39 and 1.2 for right and left vHIT respectively), suggesting possible calibration error [Mantokoudis et al., 2015]. A paired samples t-test was completed comparing rightward and leftward head impulses. Significantly higher mean gain was noted for rightward (0.99) versus leftward (0.92) head impulses ($t = 8.19, p < .001$), as denoted by an asterisk in Table 1. There was no significant correlation between age and mean vHIT gain ($r = -.17, p = .19$).

(3) Position gain

For position gain (using both eyes simultaneously, MicroMedical VisualEyes), gain for rightward and leftward head impulses are shown in Table 1. A within-groups ANOVA was completed with impulse side and eye (right versus left) as the within-subjects factors. In 10 subjects, data was only available for either the right or left eye; therefore, this data was not included in the repeated measures analysis. There was no main effect of impulse side ($F(1, 51) = 1.24, p = .27$) or eye ($F(1, 51) = 0.01, p = .92$); however, there was a significant interaction between impulse side and eye ($F(1, 51) = 52.63, p < .001$). When interpreting the simple effects, as shown by an asterisk (*) in Table 1, mean gain was significantly higher in the eye ipsilateral to the direction of head impulse. Age was not significantly correlated with vHIT gain for eye (right: $r = .09, p = .49$; left: $r = .09, p = .49$).

There was no relationship between vHIT gain and age in the normal control subjects for any of the three devices/algorithms, with the exception of instantaneous gain at 40 ms. However, vHIT gain was significantly larger in the ipsilateral direction of the eye used to measure gain. Because vHIT was measured with different eyes for different devices, gain in response to rightward and leftward head impulses was averaged for each device to eliminate this directional bias; the normal control average values are shown in the third row of Table 1. When comparing vHIT gain across devices/algorithms, gain values with the least variability (i.e., smallest standard deviation) were used. Therefore, a within-groups ANOVA using mean [SD] gain for area under the curve (0.95 [0.09]), mean gain at 80 ms for instantaneous gain (1.01 [0.1]), and mean gain for the right eye for position gain (1.05 [0.12]), was calculated to evaluate for differences between devices/algorithms. There was a significant main effect for device/algorithm ($F(2, 110) = 20.25, p < .001$); post hoc analysis revealed that area under the curve gain was significantly lower than instantaneous gain at 80 ms ($p < .001$) and position gain ($p < .001$), and that instantaneous gain at 80 ms was significantly lower than position gain ($p = .02$), Table 1, Figure 2.

The effect of vHIT device/algorithm for differentiating normal versus abnormal vestibular function:

Abnormal vHIT gain was defined as being lower than 2 SD from the normal control average (Table 1). Example vHIT waveforms of a subject with left vestibular loss are shown in Figure 3 for each device/algorithm. vHIT gain from the normal control group and gain from the *affected* ear of the vestibular group were plotted in Figure 4; as shown, of the 14 ears affected with vestibular loss, ears were classified similarly on all devices/algorithms as having normal vHIT gain versus abnormal vHIT gain, with the exception of instantaneous gain at 40 ms, where 1 subject with abnormal gain for all other devices/algorithms demonstrated overlap with the normal control group. It should be noted that data from 3/14 ears for instantaneous gain was lost due to software failure; therefore, data from 11/14 ears is reported for instantaneous gain. These results suggest that in spite of the statistically significant mean differences in vHIT gain between devices/algorithms and the significant directional bias (significantly larger vHIT gain in the ipsilateral direction of the eye used to measure gain) classification of *normal* versus *abnormal* gain is consistent across devices/algorithms with the exception of instantaneous gain at 40 ms.

A within-groups ANOVA was calculated to evaluate differences in mean gain between devices/algorithms in the ears with abnormal vHIT gain: mean [SD] gain for area under the curve (0.32 [0.1]), mean gain at 80 ms for instantaneous gain (0.32 [0.18]), and mean gain for the right eye for position gain (0.49 [0.13]). There was a significant main effect for device/algorithm ($F(2, 16) = 4.39, p = .03$); post hoc analysis revealed that position gain was significantly larger than both area under the curve and instantaneous gain at 80 ms. There was no significant difference between area under the curve and instantaneous gain at 80 ms, Table 1.

ROC curves and AUC were calculated between the vestibular (abnormal caloric weakness) and normal control groups for each of the devices/algorithms, Table 2. While these AUC

values suggest good agreement among devices/algorithms, the data also highlight a discrepancy between caloric and vHIT results given the AUC values < 1.0 .

DISCUSSION

A variety of vHIT devices are available commercially; however, gain is not calculated uniformly among devices. Thus, the purpose of this study was to examine vHIT gain across a wide age range and investigate the clinical performance of three different vHIT devices, each utilizing a different VOR gain algorithm, for identifying peripheral vestibular system dysfunction.

Regardless of device/algorithm, there were no significant relationships between vHIT gain and age in the normal control subjects up to 78 years. This finding is consistent with others. Age related decrements in vHIT VOR gain have been noted in normal control populations in the 8th or 9th decade of life [Matino-Soler et al., 2015;Davalos-Bichara and Agrawal, 2014;McGarvie et al., 2015b;Mossman et al., 2015]; however, we did not perform vHIT on subjects greater than 78 years. The lack of age related changes on VOR gain is in contrast to anatomic and physiologic data that show the onset of age effects before the sixth and seventh decades via histological studies documenting physiological reductions in receptor function [Engstrom et al., 1974;Rosenhall, 1973] and the vulnerability of other tests of vestibular function to age [Agrawal et al., 2012;Janky and Shepard, 2009;Taylor et al., 2012]. However, McGarvie et al. (2015) suggest the cerebellum is instrumental in VOR repair and could be responsible for overcoming the effects of age in vHIT.

vHIT gains were significantly larger in the ipsilateral direction of the eye used to measure gain. While some investigators report symmetrical mean gain between right and left sides in normal control populations [Weber et al., 2008a], a similar directional bias has been reported [McGarvie et al., 2015b;Yip et al., 2016;Weber et al., 2008b;Matino-Soler et al., 2015]. The difference in VOR gains between right and leftward impulses has been attributed to the “demand” placed on each eye during head rotation; for instance, when gain is measured over the right eye, rightward head rotations result in larger right eye verses left eye rotations to maintain steady gaze (i.e., larger demand) and vice versa for leftward rotations [McGarvie et al., 2015b]. This directional bias has also been attributed to differences in the neural pathway between the ipsilateral and contralateral rectus muscles [Weber et al., 2008b]. Results of the current study are consistent with these suggestions, and this pattern of findings remained consistent regardless of the eye used to measure vHIT gain. In spite of this directional bias, there were no differences in the ROC AUC values between devices/algorithms for identifying individuals with vHIT gain abnormalities. These findings suggest that each device/algorithm performs equally well at discriminating between normal versus abnormal vHIT gain and that the inter-ocular difference due to camera placement does not affect clinical performance, with the exception of instantaneous gain at 40 ms.

In the current study instantaneous gain was calculated at 40, 60, and 80 ms after the initiation of the head impulse, according to manufacturer specification. Findings suggest there is an effect of latency on the clinical accuracy of vHIT gain and that 60 and 80 ms are the preferred latencies for detection of abnormal vHIT gain.

Mean vHIT gains were also significantly different among devices/algorithms. In normal control subjects, area under the curve gain was significantly lower than instantaneous gain and position gain, and instantaneous gain was significantly lower than position gain. In subjects with vestibular loss, position gain was significantly higher than both instantaneous gain and area under the curve gain. These findings suggest that while each device/algorithm performs equally well at discriminating normal versus abnormal VOR function, care should be taken when making direct comparisons of gain obtained with different devices.

Lastly, we examined the clinical performance of vHIT for identifying peripheral vestibular system dysfunction. All devices/algorithms performed equally well at identifying subjects with a significant caloric weakness; however, there was a disassociation between the caloric test and vHIT given the AUC values < 1.0 . Several theories have been posed for the disassociation between vHIT gain and caloric asymmetry. One factor is the difference in stimulus frequency of the vHIT and caloric test. The caloric stimulus is a low frequency assessment of vestibular function, while vHIT is a high frequency assessment [McCaslin et al., 2014; Blodow et al., 2015]. A second factor is the extent of physiologic involvement in specific patient populations. Several theories have been postulated with respect to Meniere's disease. One theory is that the membranous labyrinth becomes distended throughout the course of Meniere's disease, increasing volume of the labyrinth [McGarvie et al., 2015a]. This disrupts the convective flow of endolymph during caloric stimulation, thus resulting in a caloric weakness, yet normal vHIT [McGarvie et al., 2015a]. A second theory, is that Meniere's disease may selectively impair type I versus type II hair cells [Tsuji et al., 2000]. Further understanding of this discrepancy is beyond the scope of this manuscript; however, our findings suggest this discrepancy is tied to physiologic factors and not related to device/algorithm. Interestingly, in our 11 vestibular patients, 4 demonstrated normal vHIT gain; of those, 2 were diagnosed with definite Meniere's disease, 1 with probable Meniere's disease, and 1 with unspecified vestibular dysfunction [Lopez-Escamez et al., 2016].

Examiner related factors could also account for this disassociation. vHIT gain reductions are more likely to occur as head acceleration increases [Weber et al., 2008a]. Therefore, head velocities that exceed $150^{\circ}/s$ are recommended [McGarvie et al., 2015b]. One limitation of the current study is that 2 of the 3 vHIT devices did not provide mean head velocity as an outcome parameter; this data was only available upon data export. The Impulse (Otometrics) device provides mean head velocity data, which was $158^{\circ}/s$ for rightward head impulses and $166^{\circ}/s$ for leftward impulses. Data was exported from the EyeSeeCam (Interacoustics) and noted to be $177^{\circ}/s$ overall. While mean head velocity data was unavailable for export from the Visual Eyes (MicroMedical) device, their algorithm does not accept head impulses less than $150^{\circ}/s$ suggesting velocities to be within a similar range. For the Interacoustics EyeSeeCam and Otopetrics Impulse, head velocities that fell below $150^{\circ}/s$ were included in the final mean gain calculation; however, specific cut-off values can now be set in all of the devices due to updated software versions not available at the time of data collection. It is unknown if the inclusion of head velocities less than $150^{\circ}/s$ affects test interpretation.

Some additional limitations of the current study are that our normal control population did not extend beyond 80 years, which has been documented as a critical age where vHIT abnormalities related to age begin to surface [Matino-Soler et al., 2015; Davalos-Bichara and

Agrawal, 2014;McGarvie et al., 2015b]. We also had a small number of individuals with vestibular loss who completed vHIT on all 3 devices. Additionally, differences between the three commercial vHIT devices extend beyond their gain algorithms. Each vHIT device differs in their resolution, sampling rate, filtering, and calibration, among other factors; therefore, differences between the devices cannot be attributed solely to differences in gain algorithm. One noteworthy difference is the calculation of position gain where vHIT gains were automatically rounded by the software. This difference is evident when analyzing the raw data in Figures 2 and 4, which demonstrate gain values in factors of 0.05. Comparison of these three commercial devices was also not compared against the gold standard coil system. Previous findings suggest good agreement between vHIT and coils; although, this has not been replicated with various devices/algorithms [MacDougall et al., 2009].

Conclusion

Our data support that there is not an effect of age on vHIT gain up to 78 years, regardless of the device/algorithm used to calculate gain. There was a consistent directional bias, with vHIT gain being significantly larger in the ipsilateral direction of the eye used to measure gain; however, clinical performance for identifying vestibular involvement was not significantly affected. vHIT gain is significantly different between devices, suggesting that care should be taken when making direct comparisons of absolute gain values from these devices/algorithms.

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Figure 1.

Reduced eye velocity, which would produce reduced gain, with a covert reset saccade is depicted in the top panel with corresponding head velocity shown in the bottom panel during a head impulse for 3 types of gain algorithms: A) Instantaneous gain (Interacoustics EyeSeeCam): calculated by dividing eye velocity by head velocity at a discrete point in time; B) Area under the curve gain (Otometrics, Impulse): calculated by averaging instantaneous gain across the entire duration of the head impulse, not including any covert saccade (dotted line); and C) position gain (MicroMedical VisualEyes): calculated by dividing the total eye rotation (in degrees) by total head rotation (in degrees) from the time the head impulse is initiated to the start of a corrective reset saccade (hashed line).

Figure 2.

Mean (rightward and leftward impulses) vHIT gain in the normal control subjects for each algorithm: PG: Position Gain, IG: Instantaneous Gain, AG: Area Under the Curve Gain; Mean vHIT gain shown by horizontal bar.

Figure 3.

Example vHIT waveforms in 1 subject with left vestibular loss for each device/algorithm: A) Instantaneous gain (gain = .54), B) Area under the curve gain (gain = .45), and C) position gain (gain = .4). For each segment, time is along the x-axis and eye and head velocity are along the y-axis. Arrows notate corrective reset saccades.

Figure 4.

VHIT gain in the normal control and vestibular loss groups across devices. Of note, vHIT gains utilizing position gain are automatically rounded by the software. PG = position gain, IG = Instantaneous gain, AUC = area under the curve gain, R = right, L = left, 40, 60, and 80 correspond to the ms at with the instantaneous gain was measured.

Table 1

Mean vHIT Gain Values

Mean vHIT GAIN	AUC		Instantaneous Gain				Position Gain	
	Right Eye	Left Eye	Left Eye 40 ms	Left Eye 60 ms	Left Eye 80 ms	Right Eye	Left Eye	Left Eye
Normal Control Rightward	0.99* [0.09]	0.89 [0.18]	0.94 [0.14]	0.94 [0.14]	1.0 [0.11]	1.08* [0.13]	1.01 [0.14]	1.01 [0.14]
Normal Control Leftward	0.92 [0.07]	0.94* [0.18]	1.0* [0.1]	1.0* [0.1]	1.01 [0.09]	1.02 [0.13]	1.09* [0.14]	1.09* [0.14]
Normal Control Average	0.95 [0.09]	0.91 [0.18]	0.97 [0.13]	0.97 [0.13]	1.01 [0.10]	1.05 [0.12]	1.04 [0.13]	1.04 [0.13]
Vestibular Affected Ear	0.32 [0.1]	0.31 [0.18]	0.25 [0.14]	0.25 [0.14]	0.32 [0.18]	0.49 [0.13]	0.46 [0.13]	0.46 [0.13]

Mean [SD] vHIT gain values for rightward, leftward, and overall (right and left combined) head impulses utilizing Area Under the Curve (AUC), Instantaneous Gain, and Position gain.

* denotes significantly higher gain value compared to contralateral impulse

Table 2

ROC AUC Values

	Position Gain		Instantaneous Gain			AUC
	Right Eye	Left Eye	Left Eye 40 ms	Left Eye 60 ms	Left Eye 80 ms	
ROC AUC VALUES	Rightward	0.899	0.870	0.862	0.849	0.945
	Leftward	0.857	0.920	0.876	0.841	0.885

ROC AUC values close to 1.0 = diagnostic accuracy in identifying peripheral vestibular loss, ROC AUC values close to 0.5 = poor diagnostic accuracy.