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Development of a Prototype Video Head Impulse Test System Using an iPhone for Screening of Peripheral Vestibular Dysfunction

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Keywords

iPhone · Application · Video head impulse test · EyeSeeCam · Vestibular neuritis

Abstract

Introduction: Head impulse, nystagmus, and test of skew (HINTS) is more accurate for the early diagnosis of occipital fossa stroke than magnetic resonance imaging. However, the head impulse test (HIT) is relatively challenging to perform, as it is subjective. Herein, we developed a prototype video HIT (vHIT) system using an iPhone (Apple, Cupertino, CA, USA) that is compact, easy to operate, and analyzable by our iPhone application. ***Methods:*** The iPhone-vHIT and a vHIT using EyeSeeCam (Interacoustics, Eden Prairie, NM, USA) were performed on a healthy man in his 30s and on a patient with vestibular neuritis who visited the Mejiro University Ear Institute Clinic. For the iPhone-vHIT, eye movements were detected by analyzing high-speed videos captured using an iPhone camera, and head movements were followed using an iPhone gyro sensor. An iPhone fixation brace was used to capture the video without any blurring. ***Results:*** The iPhone-vHIT system obtained vHIT waveforms similar to those of the EyeSeeCam-vHIT system in the healthy man and the patient with vestibular neuritis. The iPhone-vHIT system effectively detected the reduced vestibulo-ocular reflex gain in patients with vestibular neuritis. The iPhone-vHIT system at 120 frames per second was less sensitive to catch-up saccades than the EyeSeeCam. ***Conclusion:*** vHIT systems using a smartphone have been reported but are currently unavailable. At present, the iPhone-vHIT application in this study is the only available smartphone-based vHIT system for screening of peripheral vestibular dysfunction. We believe that the prototype iPhone-vHIT with a high-speed camera will be clinically used to perform the vHIT, even though it only examines the lateral semicircular canal.

Introduction

In the USA, 4.4 million patients with acute vestibular syndrome (AVS) visit the emergency department each year, and AVS is missed in approximately 10,000 cases because many patients show no obvious focal neurologic symptoms [1]. Head impulse, nystagmus, and test of skew (HINTS) is a combination test comprising the head impulse test (HIT), nystagmus test, and test of skew. This technique is considered to be more accurate than magnetic resonance imaging in the diagnosis of early-onset central vascular disease in AVS [2]. Video-oculography (VOG)-HINTS, in which the HIT is replaced with a video HIT (vHIT), making it recordable and reducing interobserver variability, can help in the diagnosis of AVS, and its widespread use is expected to improve AVS care [1, 3].

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The vHIT systems available in Japan are the EyeSeeCam and ICS impulse. Both models connect goggles equipped with a high-speed camera and gyro sensor to a PC via a universal serial bus cable, allowing the PC to process the data [4]. Recently, smartphones have become increasingly sophisticated, and many models have built-in high-speed cameras and gyro sensors, which provide the performance required by vHIT systems. Thus, we developed a prototype vHIT system using an iPhone (Apple, Cupertino, CA, USA). The commercially available vHIT system is expensive, and only a few facilities are currently using it. Parker et al. reported the development of a vHIT application (eyePhone) designed for the iPhone platform. Although eyePhone can contribute to the widespread use of the vHIT and help improve medical care for AVS, its introduction in clinical practice will take several years, as it is not currently available for use [5]. Our iPhone-vHIT system can be used solely with an iPhone (with self-made goggles), is compact, and can be easily applied in general emergency and outpatient clinics. This study demonstrated the lateral semicircular vHIT results of the iPhone-vHIT system with those of the EyeSeeCam-vHIT system (Interacoustics, Eden Prairie, NM) in a healthy participant and a patient with vestibular neuritis.

Materials and Methods

iPhone-vHIT System

Our vHIT system uses an iPhone fixed in front of the eye to capture high-speed videos of eye movements during the HIT, simultaneously saving data from the iPhone's in-built gyro sensor. At the end of the HIT, the saved high-speed video and gyro sensor data were analyzed to display the vHIT results. The iPhone-vHIT system can analyze both horizontal and vertical eye movements; however, only horizontal movements related to the lateral semicircular canals were examined in this study.

Analysis of Eye Rotation

The pupil and iris are difficult to distinguish on color imaging due to the similarities in color. However, the pupil and iris can be distinguished on infrared imaging because the pupil and iris absorb infrared light differently [6]. In the commercially available vHIT system, pupil movement is measured by shining infrared illumination on the eyeball and capturing pupil movement with a high-speed infrared camera. iPhone cameras have an infrared filter and therefore cannot capture infrared images; as such, it was impossible to measure pupil movement using our iPhone-vHIT system, which analyzes the movement of light spots reflected from the cornea owing to the iPhone's light-emitting diode (LED) flash illumination. This is known as the corneal reflex method [6]. The cornea acts as a convex lens, creating a virtual bright image. Because the radius of the curvature of the cornea is smaller than that of the eyeball, the direction of reflection of LED illumination changes as the eyeball rotates. Hence, the virtual corneal reflex image moves in the direction of the eye movement relative to the head (Fig. 1). This image of the LED illumination is small; thus, it is not hidden by the eyelid and its boundaries are clear. Therefore, detecting the image of the LED illumination is easy. OpenCV (Intel Corporation, Santa Clara, CA, USA), a free image processing software, was used to process the images.

The LED illumination was too bright on the iPod Touch (Apple); hence, two sheets of copy paper were attached to the LED illumination area to adjust the amount of light. The more recent iPhone 12 mini model allowed for fine control of light intensity, eliminating the need to cover the LED with a piece of paper.

Analysis of Head Rotation

The iPhone's in-built gyro sensor data were saved every 10 ms during the HIT, and the head rotation speed was analyzed using these data. If a change in velocity was assessed and determined to be the starting point of head rotation, the head rotation velocity and eye rotation velocity for 500 ms from that starting point were displayed as the vHIT waveform.

Calibration

When recording the vHIT, the participants were first asked to fixate their eyes on a single point 1.0 m ahead for calibration and rotate their heads approximately 20° to the left and right several times at a speed that does not cause vestibulo-ocular reflex (VOR) effects before performing the vHIT. Calibration was performed by matching the waveforms of the eye and head rotation velocities during calibration. As a time lag of approximately 10 ms occurred between the start of recording and the start of gyro sensor data acquisition, this lag was also adjusted. This procedure is shown in Figure 2. The calibration was performed for each inspection. The VOR gain values were displayed as the ratio of eye rotation velocity to head rotation velocity at 60 ms from the start of head rotation, just as the EyeSeeCam obtains the VOR gain value.

Goggles for iPhone Fixation

When the head rotates during the vHIT, the iPhone fixed in front of the eyeball may shift if it is not fixed sufficiently. Thus, we fabricated lightweight iPhone fixation goggles using a three-dimensional (3D) printer that used a sunglass frame and a rubber band to shoot videos with minimal misalignment. The goggles are shown in Figure 3. The size of the 3D-printed goggle is fixed and not changed to fit each individual. The 3D data of the goggles and information on how to simply construct them are available on the web at https://www.kuroda33.com/jibika/vHIT96da_en.php#goggles.

We used lightweight goggles and the lightest available iPhone (iPod touch) to obtain the video and gyro data with minimal misalignment. However, even with this combination, the combined weight was 132 g (goggles: 44 g and iPod touch: 88 g), which is twice as much as the weight of the market-available vHIT system (ICS Impulse [Otometrics, San Carlos, CA, USA]: 60 g, EyeSeeCam: 72 g).

iPhone Camera Performance and Weight

All iPhone models released after the iPhone 6s in 2015 are capable of high-speed shooting at 240 frames per second (fps). Among these models, the lightweight first-generation iPhone SE (113 g) and iPhone 12 mini (133 g) were suitable for iPhone-vHIT

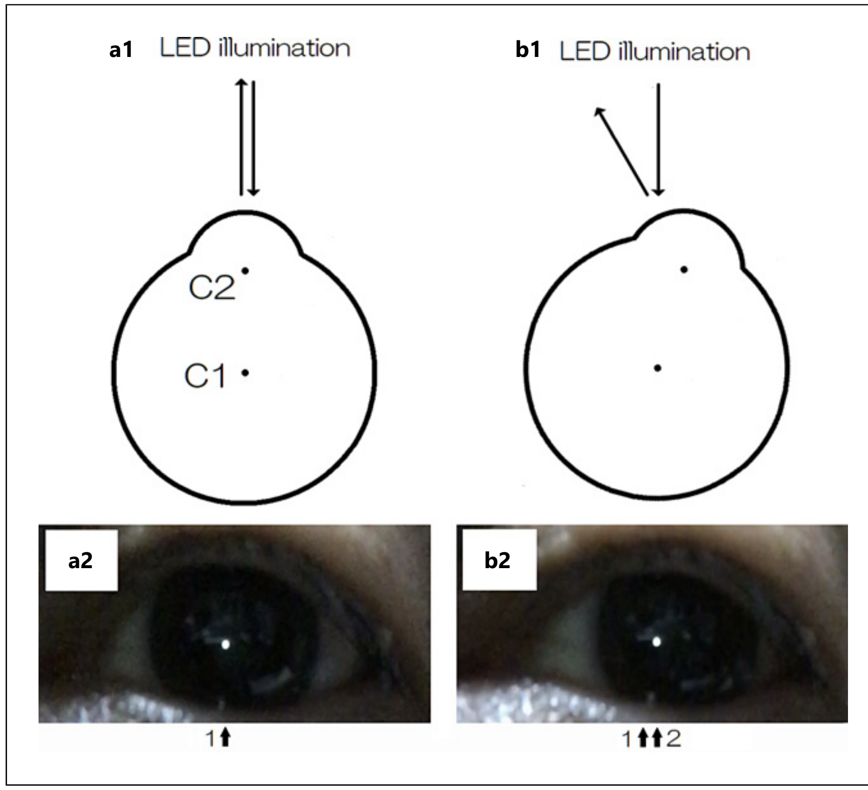

Fig. 1. Corneal reflex method. C1, center of curvature of the eyeball; C2, center of curvature of the cornea. **a1** The direction of reflection of LED lighting when viewed from the front. **b1** The direction of reflection of LED illumination when the eyeball is rotated. **a2** The position of the imaginary image of LED illumination in the frontal view (arrow 1). **b2** The position of the imaginary image of LED illumination when the eye is rotated. The position of the imaginary image has moved from arrow 1 to arrow 2.

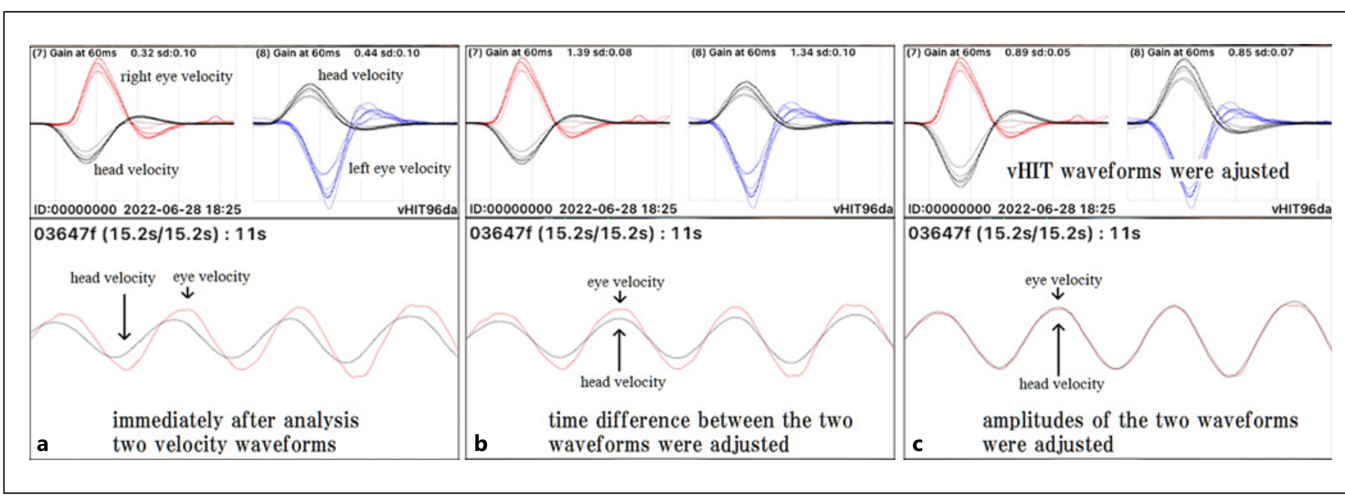

Fig. 2. Calibration procedures. Immediately after the analysis (**a**); where the time difference between the eye and head rotation velocity waveforms was adjusted (**b**); where the amplitudes of the two waveforms and vHIT waveforms were adjusted (**c**).

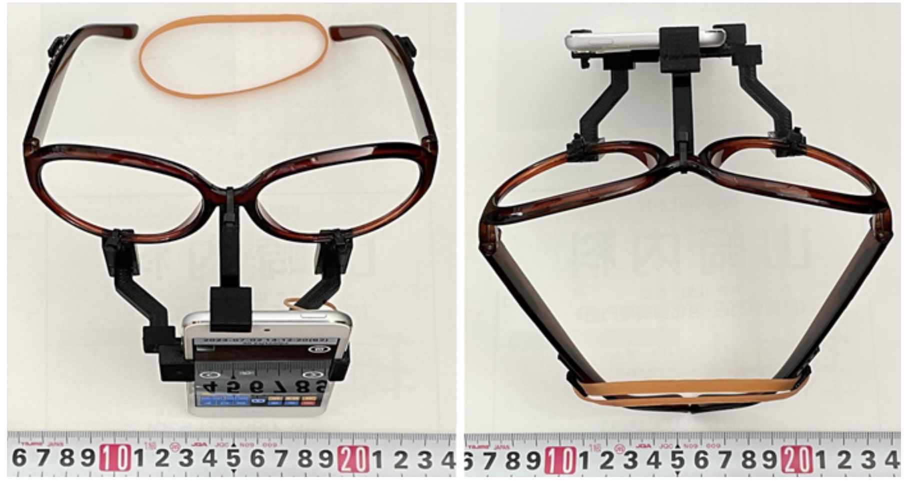

Fig. 3. Goggles used to hold the iPhone on the participant's head.

use. The iPod Touch (seventh generation), which eliminated the phone function from the iPhone, could only shoot at 120 fps but was by far the lightest, at only 88 g. Therefore, we used the iPod Touch in this study, considering the speed of its in-built central processing unit, fps value of its camera, and its low weight.

Use of the iPhone-vHIT System

The operating procedures of the iPhone-vHIT are shown in Figure 4. The procedure can be summarized as follows: (a) fix the iPhone with the vHIT application installed in front of the participant's eye. Tap the camera button in the lower right corner to start the camera and tap the start recording button to initiate the recording. (b) For calibration, instruct the participants to stare at a single point and move their head approximately 20° to the left or right side and then perform the vHIT. Gyro data are acquired simultaneously with the high-speed imaging of the eye. Tap the stop button to terminate the recording. (c) The first frame of the recorded video is shown, and the green frame is placed on the reflection point of the iPhone's LED illumination. Tap the analyze button. (d) The movement of the reflection point in the video and the stored gyro data are analyzed and graphed, and the vHIT waveform is displayed.

Software Availability

The iPhone-vHIT application was registered as a free application in the Apple Store under the name "vHIT96da" and can be downloaded by anyone. The website below provides information and videos on how to install and use the application as well as the 3D data of the fixation goggles and information on how to make them: https://www.kuroda33.com/jibika/vHIT96da_en.php.

Results

The EyeSeeCam-vHIT results for a healthy male participant in his 30s are shown in Figure 5 a1; the right VOG gains at 60 ms from the start of head rotation were 0.96, and the left VOG gains were 0.98. His iPhone-vHIT results are shown in Figure 5 a2; the right VOG gains were 0.98, and the left VOG gains were 1.14. The vHIT traces of the two systems were visually similar in terms of VOG gain.

The results of the patient with right vestibular neuritis, a woman in her 40s who was admitted to a nearby clinic after being rushed to the emergency room with severe vertigo, are shown in Figure 5 b1 and b2. Two weeks after the onset, she visited our clinic and underwent vHIT tests and a caloric test. The caloric test showed right canal paresis (100%). The right VOG gains of the EyeSeeCam-vHIT were 0.13, and the left VOG gains were 0.87 (Fig. 5 b1). Regarding her iPhone-vHIT results, the right VOG gains were 0.25, and the left VOG gains were 1.31 (Fig. 5 b2). The right VOR gains were smaller than the left ones in both the iPhone-vHIT and EyeSeeCam-vHIT. The ratio of the right to left VOR gains was 0.15 (0.13/0.87) in the EyeSeeCam-vHIT and 0.19 (0.25/1.31) in the iPhone-vHIT, showing the same trend. The right VOR response was accompanied by distinct catch-up saccades in the EyeSeeCam-vHIT, but the right VOR response was accompanied by only a slight catch-up saccade in the iPhone-vHIT system. The EyeSeeCam video was taken at 240 fps, whereas that of the iPhone-vHIT was taken at 120 fps; thus, the iPhone-vHIT system may not have picked up the catch-up saccades well.

Discussion

In 1988, during which the VOR was observed with the naked eye, the HIT was reported as a functional test of semicircular canals [7]. The vHIT, which uses a high-speed camera with VOG, was introduced in 2008 [8]. The

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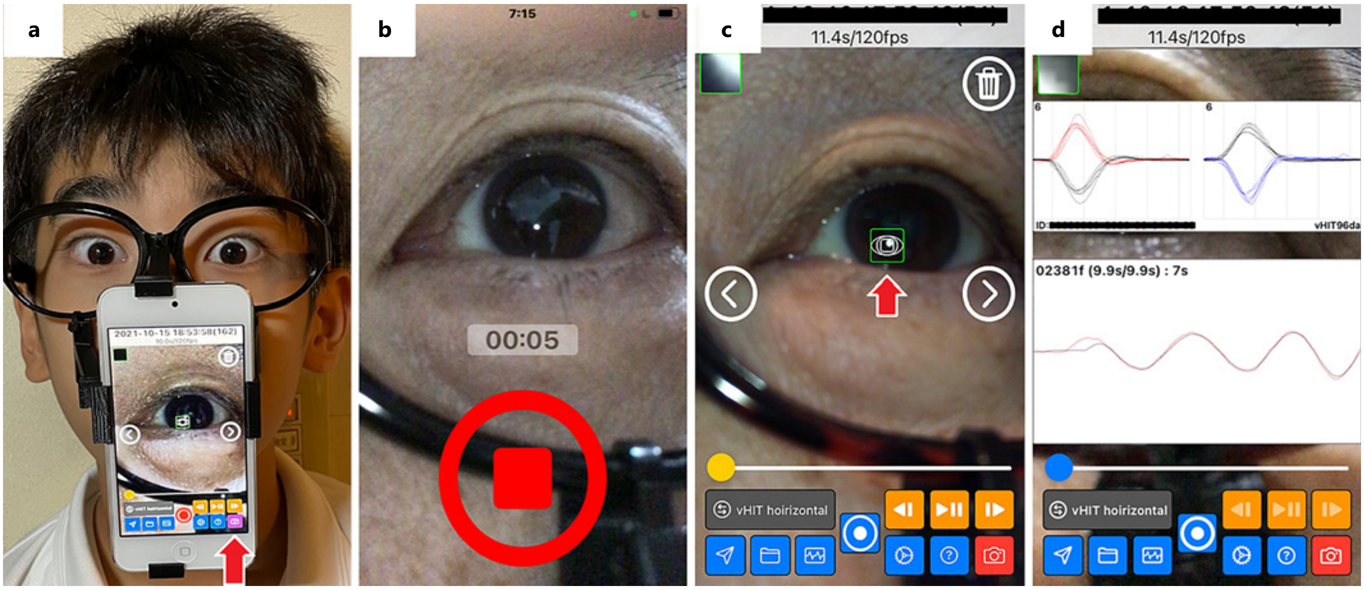

Fig. 4. iPhone-vHIT operating procedures. **a** Fix the iPhone in front of the participant's eye. Tap the camera button in the lower right corner. **b** The iPhone is recording eye movement and gyro data. Perform the vHIT. **c** Move the green frame on the reflection point of the iPhone's LED illumination and tap the analyze button. **d** The vHIT waveform is displayed.

vHIT reflects an improvement in the HIT, in that it can observe detailed VOR that cannot be captured by the naked eye, and the results can be stored as objective data. These devices are installed in facilities specializing in dizziness and large hospitals. However, as it requires costly medical equipment, it is not yet widely used in emergency rooms and general clinics.

In this study, we developed and reported a prototype iPhone-vHIT system that uses the iPhone's high-speed camera and in-built gyro sensor. In the system, we replace the data processing PC function with the iPhone's iOS. Since the entire vHIT system is contained in an iPhone, the weight of the system is 132 g (goggles: 44 g and iPod touch: 88 g), which is heavier than commercially available vHIT systems (ICS impulse: 60 g, EyeSeeCam: 88 g). Therefore, more attention should be paid to the slippage of goggles during testing of this iPhone-vHIT system compared to the commercial vHIT systems. Parker et al. reported a vHIT application (eyePhone) that uses the iPhone's Augmented Reality Kit (ARKit) system [5], which can only handle 60-fps videos. It appears that an additional PC was used for the analysis, as implied by the following information provided in the ARKit system description: "The data from ARKit were recorded and exported out of the phone for visualization and analysis in MATLAB." In contrast, our iPhone-vHIT system has the advantage of being able to handle 120–240-fps videos and analyze the VOR directly via the iPhone application. MEME (JINS, Inc., Tokyo, Japan) are wearable eyeglasses with a gyro sensor that can measure electronystagmography data. Data are transmitted to a smartphone via Bluetooth, analyzed, and displayed in real time. Ushio et al. [9] used the MEME for the HIT and compared it with the EyeSeeCam's vHIT; they discovered that it was useful as a qualitative HIT.

VOG-HINTS, a modification of HINTS in which the HIT is replaced by vHIT, allows for more accurate diagnosis of AVS than HINT. VOG-HINTS is also called eye electrocardiography, as its role in the diagnosis of AVS is analogous to that of electrocardiography in the diagnosis of myocardial infarction. The widespread use of vHIT is expected to significantly improve the accuracy of the initial diagnosis and subsequent treatment of AVS [2, 3]. McDowell et al. stated that HIT or vHIT is underutilized, being applied in only 31 of 642 cases (5%) indicated for AVS care in the emergency department, and that physicians treating AVS need to recognize the importance of HIT and vHIT to apply them [10].

We developed an iPhone-vHIT system. Compared with commercially available vHIT systems, the iPhone-vHIT system is inexpensive, compact, and can be used by simply adding fixation goggles to an iPhone. It is easy to operate and can be easily introduced in emergency departments, thus allowing for more widespread use of the vHIT and reducing the rate of misdiagnosis of AVS.

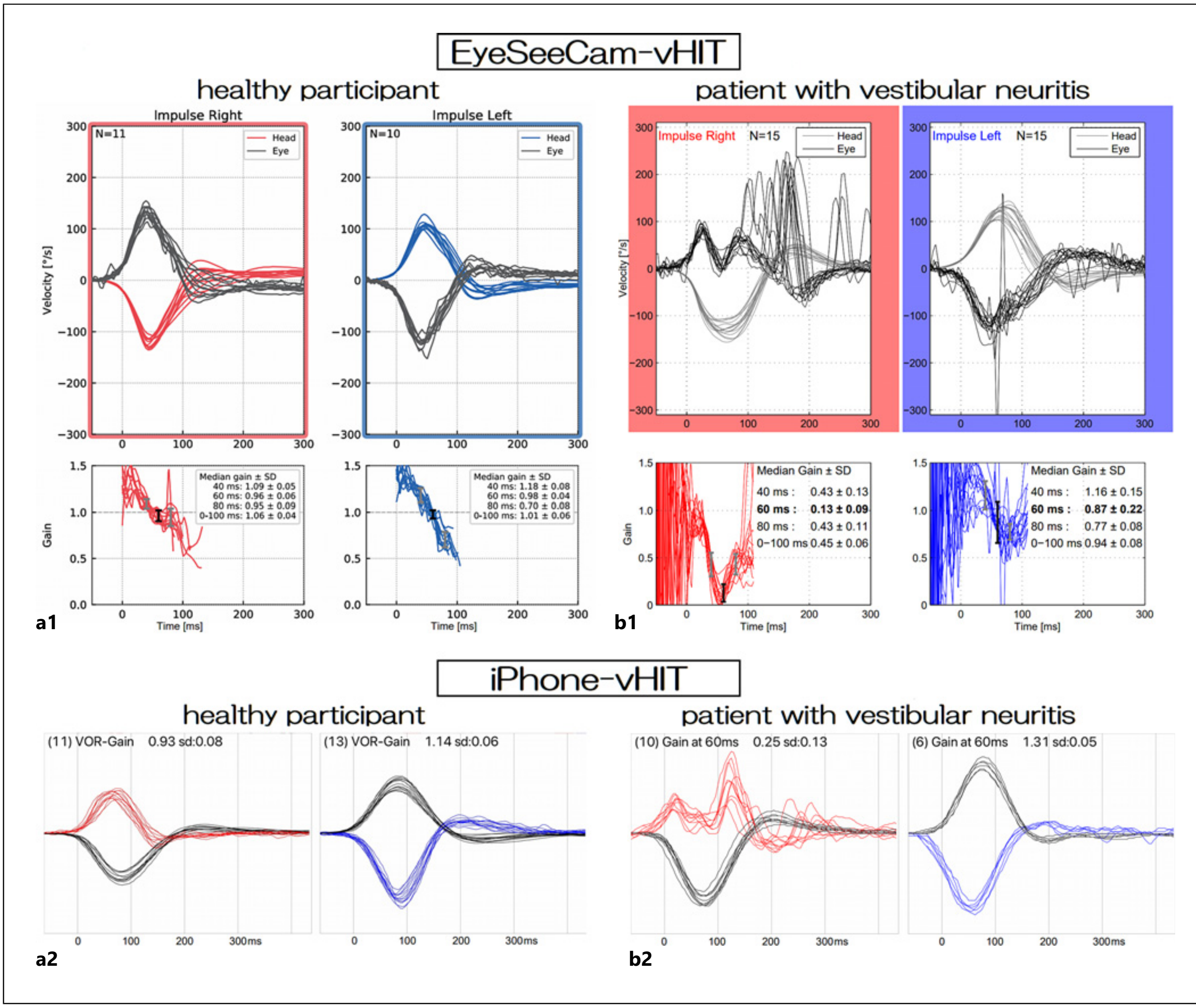

Fig. 5. vHIT results. **a1** The eye and head velocity during the HIT of the healthy participant as measured by the EyeSeeCam. The right VOR gain at 60 ms is 0.96, whereas the left VOR gain is 0.98. **a2** The eye and head velocity during the HIT of the healthy participant as measured by the iPhone-vHIT. The right VOR gain at 60 ms is 0.93, whereas the left VOR gain is 1.14. **b1** The eye and head velocity during the HIT of the patient with right vestibular neuritis as measured by the EyeSeeCam. The right VOR gain at 60 ms is 0.13, whereas the left VOR gain is 0.87. The right VOR response is inadequate and accompanied by distinct catch-up saccades. **b2** The eye and head velocity during the HIT of the patient with right vestibular neuritis as measured by the iPhone-vHIT. The right VOR gain at 60 ms is 0.25, whereas the left VOR gain is 1.31. The right VOR response is inadequate, but the catch-up saccades do not occur to the same degree as in **b1**.

Limitations and Next Steps

The number of participants was small in this report; thus, the system should be tested with more participants and include statistical analyses. As iPhones become lighter and more capable of processing data, the weight burden on patients will decrease, and the detection rate of the catch-up saccades will improve. As the goggles holding the iPhone in place are heavy, rotation of the head up and down is likely to shift the position of the goggles. To reliably perform the iPhone-vHIT test in an emergency medical setting, the goggles may need to be more securely fastened, and we should consider modifying the 3D-printed goggles to be more securely fastened or adapting goggles that are not 3D printed.

Conclusion

The iPhone-vHIT system reported in this study showed qualitatively and visually equivalent results compared to the commercially available vHIT. More cases and statistical procedures need to be added in the future regarding the VOR gain. Our iPhone-vHIT does not require another PC for analysis, allowing for the widespread use of vHIT and possibly helping in reducing the rate of AVS misdiagnosis. The vHIT systems using an iPhone and a wearable device have been reported, but they are not currently available for public use. We believe this is the first vHIT application using a smartphone or wearable device that can be used by the public.

Acknowledgment

We thank Yumi Dobashi, the clinical laboratory technician of the Mejiro University Ear Institute Clinic, for her assistance in performing the head impulse test.

Statement of Ethics

The study protocol was reviewed and approved by the Mejiro University Medical Research Ethics Review Committee, approval number 21medicine-022. Written informed consent was obtained from all participants for publication of the details of their medical case and any accompanying images.

Conflict of Interest Statement

The authors have no conflicts of interest to declare.

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Author Contributions

T.K. and K.K. programed the iPhone-vHIT application. T.K. wrote the first draft and revisions of the manuscript. H.F. designed the work, reviewed, and edited the manuscript.

Data Availability Statement

The iPhone-vHIT application (vHIT96da) can be downloaded from the following page of Apple Store: https://apps.apple.com/usa/app/vhit96da/id1369699678. The following website provides information and videos on how to install and use the application as well as the 3D data of the fixation goggles and information on how to make them: https://www.kuroda33.com/jibika/vHIT96da_en.php. Further enquiry can be directed to the corresponding author.

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