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GlauCUTU: Virtual Reality Visual Field Test

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Abstract— **This study proposed a virtual reality (VR) head-mounted visual field (VF) test system, or also known as the GlauCUTU VF test, for a reaction time (RT) perimetry with moving visual stimuli that progressively increase in intensity. The test entailed 24-2 VF protocol and was examined on 2 study groups, controls with normal fields and subjects with glaucoma. To collect reaction times, participants were urged to respond to the stimulus by pressing on the clicker as fast as possible. Performance of the GlauCUTU VF test was compared to the gold standard Humphrey Visual Field Analyzer (HFA). The HFA showed a significant difference between the GlauCUTU and HFA with mean duration of 254.41 and 609, respectively [$t(16) = 15.273$, $p<0.05$]. Likewise, our system also effectively differentiated glaucomatous eyes from normal eyes for the left eye and right eye, respectively. When compared to the HFA, the GlauCUTU test produced a significantly shorter average test duration by 354 seconds which reduced test-induced eye fatigue. The portable and inexpensive GlauCUTU perimetry system proves to be a promising method for increasing accessibility to glaucoma screening.**

Clinical relevance- **GlauCUTU, an automated head-mounted VR perimetry device for VF test, is portable, cost-effective, and suitable for low resource settings. Unlike the conventional HFA test, GlauCUTU VF test reports in terms of subjects RT which is reportedly higher in glaucoma patients.**

I. INTRODUCTION

Glaucoma optic neuropathy, a leading cause of irreversible blindness, affects approximately 60 million people worldwide which is expected to almost double by 2040 [1]. The disease causes permanent vision loss through damage of the retinal ganglion cells and retinal nerve fibers at the optic nerve head (ONH) [2], [3]. Fortunately, blindness from glaucoma can be prevented with early detection stressing the importance of screening [1]. Even though Thailand has an average of 1.52 ophthalmologist per 100,000 persons, many rural areas do not have access to any ophthalmologists or ophthalmic tools [4]. Consequently, people affected by glaucoma do not receive medical attention until their disease has advanced.

Manifestations of glaucoma include high intraocular pressure, visual field defects, and structural changes of the ONH such as increased cup to disc ratio (CDR); therefore, screening includes intraocular pressure measurement with tonometry, ONH examination with fundus imaging or optical coherence tomography (OCT) and visual field (VF) test using the Humphrey Field Analyser (HFA) [5]. As an essential part of screening and diagnosis, perimetry can reveal glaucomatous VF changes such as nasal step defect, temporal wedge VF loss, arcuate defect delineated by a comma-shaped extension from the blind spot, tunnel vision, severe VF defect with a crescent-shape sparing in temporal area and complete VF loss [6]. The current gold standard for assessing VF defects is the HFA which is an essential tool for diagnosis and monitoring of multiple ophthalmic and neurologic diseases including glaucoma [7], [8]. During the test, participants react to the visual stimulus presented on a 2D plane up to 30 temporally and nasally by pressing on a button. The HFA device is large, expensive, and non-portable limiting its use in rural areas and with elderly, disabled or immobile patients [9].

On the contrary, VR glasses are portable and cost-effective devices that can be comfortably adjusted on the patient's head without requiring them to maintain a particular head position [10]. Furthermore, this new technology enables the option of hands-free testing via the visual grasp mode in which the subject's responses are collected by tracking eye movements instead of pressing a button [11]. With VR glasses, patients tolerated the VF test well with minimal fixation losses and reduced test-induced fatigue [7]. Moreover, the VR method can also potentially increase accessibility to glaucoma screening in low resource countries, such as Thailand, and in the elderly and disabled population. However, commercially available VR glasses are not widely used as they are created for gaming purposes with a small display at low resolution, whereas custom made VR glasses with larger display screens have higher costs and no standardization [10].

Over the years, various perimetry tools have been used to identify VF defects. In the kinetic perimetry method, the examiner assesses VF by using a mechanical arm to control moving visual stimuli of different sizes and brightness [7], [12]. As a result, the manual kinetic perimetry requires an experienced examiner and the results are difficult to standardize and compare between different operators [12], [13]. Unlike the manual kinetic perimetry, the automated static perimetry is not examiner-dependent and produces more standardized results [12]. The static perimetry is employed in modern standard automated perimetry (SAP) devices such as the HFA (Zeiss Humphrey Systems, Dublin, Calif) [12], [14]. SAP utilizes targets of various brightness located within the central 30 degrees of the VF which increases sensitivity in detecting VF defects [7], [12]. However, static perimetry entails higher subject concentration as several minutes of fixation on the

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target is required. Hence, the subject's alertness and reaction to the visual stimuli can lead to variability and fluctuation within the same assessment or between examinations [7]. Static perimetry also has decreased efficacy in localizing complex lesions in the peripheral field and characterizing pathologies in the occipital lobe [12].

The frequency-doubling technology (FDT) [15] and color-on-color or short-wavelength automated perimetry (SWAP) [16] were introduced to enhance efficacy of glaucoma detection. The latest technological advancement in VF testing, head-mounted virtual reality (VR) device, is an alternative to the conventional VF tools. The VR modality is suitable for low resource settings and the elderly, bedridden and disabled population as they provide a portable, convenient, cheaper and more comfortable option [7], [10], [17]. Various studies on virtual perimetry produced results comparable to those of HFA and also demonstrated participants preference and acceptance of the VR device [7]–[10]. Tsapakis *et al.* created an automated perimetry test using a commercially available VR device, Trust EXOS 3D VR glasses, and a smartphone. Although comparison between the proposed method and the HFA in glaucoma patients indicated high correlation coefficient, there was a significant difference between mean values due to the different perimeters [10].

Another modality created by Wroblewski *et al.* is a compact, head-mounted and eye-tracking VR perimeter known as VirtualEye [7]. The method also included a visual grasp mode which did not require manual input from participants. The results showed agreement of VF measurements between the VisualEye test in both manual and visual grasp modes and the HFA test [7]. Mees *et al.* introduced a head-mounted VR perimetry device known as the C3 fields analyzer which was moderately effective at recognizing glaucoma patients, but the VF deficits did not match the HFA [8]. Most recently, Nanti and Lenoci compared between the virtual reality visual field testing with the BOLT strategy and the HFA 24-2 SITA standard protocol and concluded that both devices are similar but the virtual perimetry had a shorter test duration by 2.4 minutes and was more cost-effective [17]. Despite the growing interest in clinical use of VR in perimetry, the modality still has several limitations.

Our main goal is to develop an automated head-mounted VR perimetry device that is portable, cost-effective and suitable for low resource countries such as Thailand. Unlike the conventional HFA test, our VF test reports in terms of subject's reaction time (RT) which is reportedly higher in glaucoma patients when compared to normal subjects [18], [19]. Hence, we propose a novel VR technology for glaucoma detection that is comparable to the gold standard HFA.

The main contributions of this paper are as follows:

1) A portable and inexpensive virtual perimetry method with comparable performances to the Humphrey perimetry test is proposed as an alternative tool for glaucoma screening in low resource settings.

2) Novel software features including increasing intensity of stimulus and reaction time measurement are incorporated to reduce total test time while maintaining reliability of results.

3) A reaction time perimetry which incorporates the strategy of increasing stimulus intensity is utilized for detection of visual field defects.

4) Addition of average reaction time detection during VF testing to determine false-negative and false-positive points which will be re-examined to enhance accuracy.

The remainder of this paper is organized as follows: Section II explains the materials and methods for the proposed VR perimetry tool. Section III and IV show results, and discussion and conclusion. Section V and VI contain acknowledgements and future work, respectively.

II. MATERIALS AND METHODS

A. Study Group

The Chulalongkorn Institutional Review Board (No. 715/61) approved the protocol for this study and all subjects signed informed consent statements. Patients who attended King Chulalongkorn Memorial Hospitals out-patient ophthalmology clinic underwent prospective evaluation. Subjects were selected according to medical records and invited to participate in this study. Subjects were classified into 2 groups: glaucoma and control. A total of 17 subjects were enrolled in the study providing 34 eyes. There were 12 eyes from 6 glaucoma patients, 3 males and 3 females, with an average age of 70 ± 5.4 years. The glaucomatous eyes were grouped based on severity: 6 eyes with mild defect, 3 eyes with moderate defect, and 3 eyes with severe defect. The other group consists of 22 eyes from 11 non-glaucoma patients with a mean age of 41.18 ± 16.72 years.

The inclusion criteria were 18 years of age or older, having a diagnosis of primary glaucoma using Hodapp-Parrish-Anderson criteria along with visual field defects detected by SAP (Humphrey visual field analyzer, Carl Zeiss Meditec, Dublin, CA) within the previous 3 months for the glaucoma study group [14], [20], having normal intraocular pressure and no evidence of glaucomatous optic neuropathy with normal visual field reported by SAP according to Hodapp-Parrish-Anderson criteria within the past 3 months for the control group [20], no known history or clinical manifestations of neurological or psychological disorders, and having best reported visual acuity (VA) of 20/70 or better. Patient exclusion criteria included those with other non-glaucomatous diseases that can cause visual field defects and subjects receiving medications that affect the nervous system such as haloperidol and diazepam.

B. Hardware Features

The novel technology of 3D printing enables rapid and reliable production of medical equipment that can be personalized for each patient's specific physiology and so this technology can assist in monitoring of disease progression and response to treatment [21]. With 3D printing, we created a VR headset using widely available materials. Due to its low cost and reproducibility, our creation provides a portable and inexpensive alternative to standard VF tests and can

potentially increase accessibility to glaucoma screening in Thailand. Our perimetry VR headset utilizes two separate liquid crystal display (LCD) systems to provide the subject with a binocular view and enables adequate positioning which will increase the subject's view of the visual field plane, thereby reducing lens rim artifact (LRA) which can mimic nasal step scotoma seen in glaucoma [10].

The system reduces distortion from ambient light as each module includes a convex lens and a monitor display that can be adjusted to fit each individual eye. For the display screen, we chose LCD over Organic Light Emitting Diode (OLED) due to the lower costs and benefits of backlighting that increases visual comfort which may reduce test-induced eye fatigue [22]. The contrast ratio or ratio between the brightest white and the darkest black produced by the Sharp LCD module no LS029B3SX02 was quantified with the Extech EA31 EasyView Light Meter [10]. The EA31 EasyView Light Meter has a maximum resolution of 0.01 Fc/Lux [23] with a calibration certificate CAL03035-20 from Industrial Calibration Co., Ltd [24]. To measure the light level, we enclosed the lens and light meter's photo sensor dome with a truncated cone that is cut in half longitudinally and coated with Black 3.0, a non-reflective color, from Stuart Semple's studio to reduce reflectance from within and outside the cone [25], [26].

The distance between the LCD screen and the lens was 63 millimeters (mm) which is within the minimum and maximum focal length of the lens, while the distance between the lens and photo sensor dome is approximately 150 mm which is equivalent to the distance between the lens and subject's eye. Luminance of display screen is quantified by initially measuring the lowest light level and increasing by increments of 5 step Red Green Blue (RGB) using our Python code on library OpenCV 0.4.3 and results reveal that the display screen has a contrast range of 0–36.69 dB. Our VR perimetry test is portable, easy to set up and ready to use within 5 minutes. The proposed module consists of a VR headset, a Nvidia Jetson Nano microcontroller, a clicker, a portable screen of display size 15.6" and a keyboard and mouse set shown in Fig. 1. The clicker weighs around 40 grams and can be held comfortably with indentations designed for finger engagement. The VR headset weighs approximately 350 grams and can be tightly mounted with the adjustable straps to appropriately fit each subject's head. The test reports real-time results as well as parameters such as stimulus presentation rate, fixation loss, and false negative loss that can demonstrate test reliability.

C. Software Features

The software entails manual detection of the blind spot by placing a target at the physiological blind spot which is approximately 15 degrees temporal to fixation, and relocating the point until the participant can no longer visualize it [9]. The field of vision is measured in terms of degrees from the reference point which is the participant's blind spot. The proposed algorithm, known as GlauCUTU, is a research collaboration between the Department of Ophthalmology, Faculty of Medicine, Chulalongkorn University and the Center of Excellence in Intelligence Informatics, Speech, and Language Technology, and Service Innovation (CILS), Faculty of Engineering, Thammasat University. Our algorithm differs from the standard full threshold algorithm in HFA in that the GlauCUTU strategy increases intensity of the test point by 0–255 and the response latency is analyzed to increase threshold sensitivity.

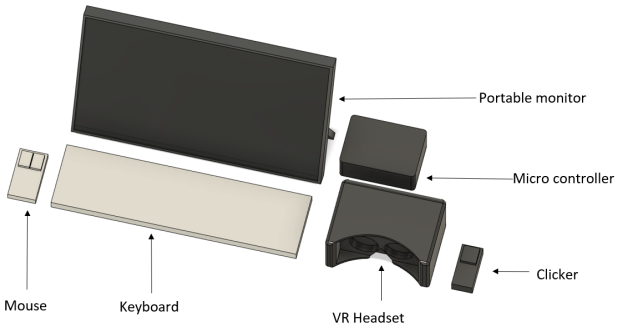

Fig. 1: Portable GlauCUTU perimetry system.

While in the full threshold test, the initial test point is projected at a given intensity and the next stimulus is adjusted 4 dB darker or brighter if there was positive response or no response, respectively, and once there is an opposite response, the increments of 4 dB is replaced by 2 dB in the opposite direction [7]. The threshold, which represents retinal sensitivity, is determined by the minimum intensity detected in the last point. The GlauCUTU test uses the 24-2 Swedish Interactive Thresholding Algorithm (SITA) strategy which is the most common HFA protocol for measuring VF [8], [27]. The 24-2 strategy examines 54 points that are 6 degrees apart and 12 of those points are located in the central 10 degrees of fixation [28].

During the VF testing, the subject was instructed to immediately press the clicker upon seeing the visual stimulus on the LCD screen which requires constant fixation and concentration. In this study, subjects were urged to respond rapidly so we chose to use the term "reaction time" [29]. We incorporated an additional test that intermittently appeared during the perimetry to compute an average RT and also enhance attention. The frequency in which the reaction test appeared was derived from the ratio of number of clicks from the subject to number of stimuli in the test. This latency analysis can validate results by providing information on the false-positive and false-negative points [29]. If the test reports an RT that is longer than the average RT which can either indicate a VF defect or loss of concentration, those defective VF areas will be tested again for accuracy of results. Furthermore, the test utilizes a moving target which can also capture the subject's attention. The stimulus presentation rate can be adjusted to allow time for the participant to focus on the target. The test enables adjustable parameters such as stimulus presentation time, stimulus brightness and background luminance to make the test suitable for each subject.

Unlike the conventional bracketing strategy that increases

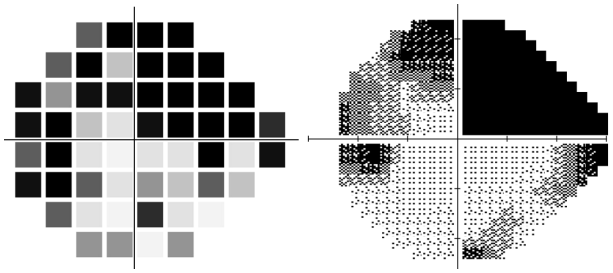

Fig. 2: examples of GlauCUTU perimetry and HFA test results.

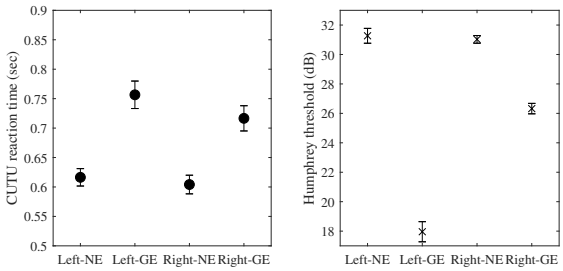

Fig. 3: ANOVA results of GlauCUTU reaction time and HFA sensitivities from 2 study groups: normal eye (NE) and glaucomatous eye (GE).

test point intensity by 4 dB then decreases it by 2 dB, our software incorporates the technique of brightening test points which reduces number of presentations and test time for both eyes and thus, enhancing precision of results [30]. Total test time can vary from 5–7 minutes with test duration of 3–5 minutes and calibration time of 2–3 minutes, depending on the subject. The test duration mainly depends on the subject's visual function. For instance, the duration is lengthened if there are many defective points that are inconsistent with the average RT. A longer test time can be due to visual field defects or a slower reaction. Duration of each subject's visual fixation is compensated by adjusting stimulus presentation time to enable the eyes to align with the new target. Upon completion of the VF test, the software assembles a report similar to those of the HFA as shown in Fig. 2.

D. Experimental Procedure

Each participant underwent the standard HFA and the GlauCUTU test at least 30 minutes apart within the same day in a randomized order. When problems occurred during the test that required retesting, subjects were given approximately a 15-minute break. The HFA test was executed based on standard protocol, while the GlauCUTU test was performed as follows. The VF test which contains a VR headset, clicker, Jetson Nano microcontroller, portable monitor, mouse, keyboard, signal cable and power adaptor was configured. The subject underwent history taking for information pertinent to the study and his or her pupillary distance was measured. The VR headset was positioned appropriately to avoid LRA and was adjusted to match the subject's pupillary distance. Subjects were allowed to wear their own glasses underneath the headset for refractive correction.

Software parameters such as background luminance, stimulus presentation time and fixation errors were selected. Each subjects blind spot was detected by projecting stimuli at expected blind spot locations until the subject no longer sees the stimulus. Then each subject underwent a trial of the perimetry system to make him or her acquainted with the process and to also collect the average RT. Prior to testing, the participant was instructed to immediately press on the clicker every time they see a visual stimulus. The examiner initiated the test and analyzed the reported fixation error, false negative error, false positive error. If those values were higher than the accepted values, the subject was required to repeat the test with a 15-minute break. The test results were reported in an electronic file.

III. EXPERIMENTAL RESULTS

Both the GlauCUTU VR perimetry and HFA employed the 24-2 VF protocol and also tested on 2 study groups, people with normal visual fields and glaucoma patients with visual field defects. The difference between the two tests was that the GlauCUTU test measured results in terms of the subject's RT, while HFA does so using participants reported threshold value. In our study, the mean RTs of the left and right eyes were 0.7565 ± 0.0119 and 0.7166 ± 0.0109 seconds in the glaucoma group, respectively [$F(1,52) = 98.98$, $p<0.05$]. The significant differences were also shown in the control group which were 0.6164 ± 0.0075 and 0.6041 ± 0.0081 seconds, respectively [$F(1,52) = 68.43$, $p<0.05$]. Similarly, the HFA results revealed that the glaucoma group has a significantly lower mean sensitivity than the control group. In the HFA test, the mean sensitivities for the left and right eyes were 17.9591 ± 0.3487 and 26.2329 ± 0.1810 dB [$F(1,52) = 942.67$, $p<0.05$], and 31.2693 ± 0.2575 and 31.0274 ± 0.1337 dB [$F(1,52) = 437.1$, $p<0.05$] for the glaucoma and control group, respectively. All 17 subjects recruited in this study produced reliable HFA results that can be used for interpretation. GlauCUTU test time for both eyes is approximately 254.41 seconds which is significantly lower than the duration of 24-2 SITA protocol for HFA of around 609 seconds ($p<0.05$) [$t(16) = 15.273$, $p<0.05$].

IV. DISCUSSION AND CONCLUSION

We have developed a portable, head-mounted automated perimetry that can potentially increase accessibility to glaucoma screening in rural areas. The benefits of a head-mounted VR perimetry system are the portability, the ease of configuration, and the ability to adjust the headset in a way that comfortably fits each subject's head. Proper placement of the VR glasses will reduce test-induced eye fatigue and LRA, and also maintain fixation which will increase test reliability [10], [31]. At the end of the test, all participants expressed that the head-mounted VR system was more comfortable and imposed less eye strain than the standard HFA test. Furthermore, we have introduced the novel concept of incorporating average RT tests into the

perimetry test to enhance concentration and also detect false-positive and false-negative results which will lead to repeated testing of those suspicious points.

RT to a visual stimulus represents the processing times of stimulus perception, neural conduction, and motor response and thus, can indicate real-world visual function [18], [32]. RT perimetry can be used to differentiate between glaucoma patients and normal subjects [32], as people with visual field defects have longer RTs than those with normal visual fields [18], [19], [33]. In a study by Westcott *et al.*, response times in glaucoma patients were significantly prolonged with a mean delay of 0.2 seconds when compared to those of the controls [18]. They used the term response time which can indicate that the subjects were not instructed to immediately respond to the stimuli which may lead to higher RT [29]. Furthermore, our study may not be directly compared to the study from Westcott *et al.* because they employed the bracketing strategy which is different from our strategy.

Although Wall *et al.* found no significant difference between RTs of glaucoma patients and normal subjects, there was a prolongation of about 0.09 seconds in the RTs of 4 out of 10 glaucoma patients when compared to normal subjects [19]. Our study showed that the mean RT of glaucoma patients were significantly longer than those of control subjects, with a mean delay of 0.135 seconds. To ensure that the RT are a reliable indicator of visual field defects, we informed subjects, prior to testing, to respond to the stimuli as quickly as possible and we created an average RT test to validate that a slower RT resulted from visual field defects rather than from loss of fixation or concentration, or a delay in pressing the clicker. Even though we urged our subjects to respond as quickly as possible to the stimuli, our average RT in the glaucoma group is still longer than those of the glaucoma group in the studies of Wall *et al.* and Westcott *et al.*, which support the prolonged RTs in glaucoma patients. However, our study provides preliminary results and hence, we plan to recruit more participants in our future work.

Although the GlauCUTU VR perimetry and the standard HFA utilized different perimetry techniques, they share the same purpose of detecting VF loss. While the HFA utilizes the bracketing strategy to measure retinal sensitivity threshold, the GlauCUTU test employs a different strategy by increasing the luminance from lowest to highest to measure RT. The glaucoma subjects had significantly lower mean sensitivities and higher average RTs when compared to those of normal controls in the HFA and GlauCUTU test, respectively. It can be concluded that both tests are effective in differentiating between glaucoma patients and normal subjects. When compared to the HFA, the GlauCUTU has a shorter test duration which enhances precision and reduces eye fatigue [30]. Moreover, we utilized a moving fixation target that can maintain subjects fixation and concentration and also reduce the fatigue effect which is the progressive decline of visual performance due to prolonged exposure to static contrast levels [30], [34].

Wroblewski *et al* designed a VR headset VF testing system to conduct the 24–2 HFA exam and reported agreements in VF measurement with the HFA [7]. Similarly, our study validates the concept of utilizing VR headsets for VF testing and is the first to demonstrate the use of RT perimetry using a head-mounted display. Similarly, the advantage of our RT perimetry over Nanti and Lenoci's cost-effective and portable VR perimetry device is the shorter test duration that is almost 6 minutes shorter than HFA while their test was 2.4 minutes shorter than the HFA [17]. The FDT VR visual field testing designed by Alawa *et al.* powered by a smartphone. Despite its low cost, the FDT VF test is limited by the commercial screen with the C–20 testing pattern which tests sixteen $10^\circ \times 10^\circ$ targets and one central 5° diameter circle in the central 20° of the visual field. Meanwhile, our system incorporates the 24–2 VF protocol which tests a wider field [35].

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VI. FUTURE WORK

In the future, we are planning to recruit more participants for this study to increase the reliability of our results. We aim to incorporate the head-mounted VR perimetry into glaucoma detection in Thailand. Moreover, we are going to integrate this work with our optic disc and cup segmentation network model for glaucoma detection. All in all, our main goal is to increase the accessibility to glaucoma screening in Thailand in hopes of reducing irreversible blindness resulting from glaucoma.

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