Preliminary Report on a Novel Virtual Reality Perimeter Compared With Standard Automated Perimetry

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Precis: The VisuALL head-mounted perimetry in normal subjects and glaucoma patients had a moderate to strong correlation with the Humphrey Field Analyzer (HFA).

Purpose: Visual field testing has a vital role in diagnosing and managing glaucoma. The current clinical practice relies on large, table-based testing units. This study investigated the performance of a novel virtual reality head-mounted visual perimetry device (VisuALL), in normal and glaucoma patients.

Methods: This prospective observational study was conducted on 50 eyes of 25 healthy subjects (normal group) and 52 eyes of 26 patients with a controlled mild or moderate stage of glaucoma (glaucoma group). All participants had visual field testing with VisuALL and the HFA (24-2, Swedish Interactive Threshold Algorithm). The mean sensitivity of the whole visual field and each quadrant were compared between both machines and the receiver operating characteristic was used to compare the diagnostic abilities and the Bland-Altman plot to evaluate the agreement of the 2 perimeters.

Results: The global mean sensitivity of the Visu*ALL* and the HFA correlated significantly in both normal ($r=0.5$, $P=0.001$) and glaucoma ($r=0.8$, $P<0.001$) groups. The mean sensitivity of all quadrants also correlated significantly in both groups. The Visu*ALL* mean sensitivity had a greater (0.98) receiver operating characteristic curve than HFA (0.93) mean sensitivity ($P=0.06$) in discriminating normal versus glaucoma.

Conclusion: There was an excellent correlation between the VisuALL and the Standard Automated Perimetry in normal and glaucoma patients and VisuALL showing high diagnostic performance.

Key Words: glaucoma, visual field, perimetry, virtual reality, head-mounted device

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Automated perimetry is a noninvasive technique for evaluating pathology or dysfunction in the visual pathways. The Humphrey Field Analyzer (HFA; Carl Zeiss Meditec, Dublin, CA) and Octopus perimeter (Haag-Streit, Koeniz, Switzerland) are 2 examples of widely used automated perimeters. White-on-white Standard Automated Perimetry (SAP) is the most commonly used clinical tool for characterizing the level of visual loss of glaucoma and neurological diseases and for detecting the disease progression.[1]

The SAP requires maintenance of constant fixation for several minutes and conscious decision making in identification of near the threshold level stimuli.[2,3] In addition, it has a number of disadvantages including being stressful for debilitated, claustrophobic, ill, or elderly patients to keep their heads still in the perimeter bowl during the test. Patients with musculoskeletal problems and admitted patients in the hospital that are not able to position their head in the proper position for visual field testing may have unreliable, artifact laden results or be unable to take the test.

Several devices have been developed since the advent of the HFA and the Octopus perimeters, in an effort to improve the detection of visual field defects and make the test easier for patients.[4–6] Examples include the use of laptops and iPads.[7–9] These modalities bring portability, but lack of fixation monitoring methods and hardware standardization have been the limiting factors in their widespread use. In addition, specificity and sensitivity studies have been mixed.[7,8,10,11] The majority of these devices are composed of a head-mounted device (HMD) controlled by a laptop or a tablet.[8,12] The size and cost of current tabletop perimeters limit their use in screening efforts as well as clinical care in remote and rural settings. HMD perimeters may allow in-office, remote, and home visual field testing owing to their lower cost and portability and could promote a change in the screening protocol.

The aim of this study was to characterize a novel perimeter that includes an HMD with eye-tracking capabilities, to evaluate the age influence on the resultant retinal sensitivity, and to compare its results with the HFA.

METHODS

This prospective observational study was conducted at the Glaucoma Service of the Wills Eye Hospital from January to December 2019. The study was reviewed and approved by the Institutional Review Board of Wills Eye Hospital. Written informed consent was obtained from each subject before enrollment.

All participants underwent a comprehensive ophthalmologic examination, including a review of their medical history, visual acuity, a slit-lamp biomicroscopic examination of the anterior segment, examination of the retina and the optic nerve, tonometry with a calibrated Goldman applanation tonometer, and gonioscopy.

All participants were divided into 2 groups, healthy subjects (normal group) and glaucoma patients (glaucoma group). Twenty-five subjects (50 eyes) for the normal group were recruited among hospital personnel and volunteers with a normal evaluation of the retina and optic nerve, intraocular pressure (IOP) <21 mm Hg, and a normal

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Humphrey Visual Field (HVF). The glaucoma group consisted of 52 eyes of 26 patients with a controlled mild (mean deviation > −6 dB) or moderate and severe (mean deviation between −6 and −12 dB and < −12 dB, respectively) open-angle glaucoma[13]: glaucomatous appearance of the optic nerve (increased cup-to-disc ratio, rim thinning, and/or retinal nerve fiber layer defects indicative of glaucoma), and a reproducible (false positive, fixation loss, and false negative of ≤15%) abnormal SAP. IOP was not used as a glaucoma criterion.

Exclusion criteria were subjects with a history of any systemic or ophthalmic conditions affecting central vision, history of intraocular surgery (except uncomplicated cataract or keratorefractive surgery > 6 mo before testing), using any medication affecting vision or influencing reaction time, spherical refractive error > ± 5.00 and astigmatism > ± 2.00, best-corrected visual acuity < 20/30, a closed angle found on gonioscopy, and those unwilling and/or unable to participate.

All participants had visual field testing with HFA [24-2, Swedish Interactive Threshold Algorithm (SITA) Standard] and VisuALL (24, T algorithm). All HVFs were evaluated for various artifacts including eyelid, rim, fatigue, or learning effects artifacts, and visual field defects caused by a disease other than glaucoma (eg, neurological or retinal diseases); the eyes with such artifacts were excluded.

The VisuALL (Olleyes Inc. Summit, NJ) is a lightweight and portable device. The VisuALL does not require eye patching for testing, because each eye is stimulated by an individual screen and each screen is completely isolated from the fellow one. In addition, the screen is located only 60.5 mm in front of the eye which avoid overlap of the screens.

The patient does not need to maintain a particular head position and the headset is adjustable to optimize comfort for the patient. The headset is connected to a computing device and the data is saved on a shared cloud with access for eye-care providers. The VisuALL system is composed of 2 main parts of the hardware and software. The hardware includes 3 components: a HMD; a laptop, phone or tablet, and a Bluetooth connected handpiece (ie, response button). In Figure 1, the latest version of the device which could be connected to a tablet, cellphone, or laptop via Bluetooth is shown. The HMD weights 300 g with an organic light emitted diode display having a resolution of 3840×2160 pixels and a refresh rate of 75 Hz. The display is divided into 2 halves (one for each eye) with a resolution of 1920×2160 pixels on each half. The display size is 125.4×70.56 mm and when worn subtends a field of view up to 100 degrees. The screens are located at 60.5 mm from the eye. The HMD has 2 tracking systems, inertial measurement units consisting of gyroscopes and accelerometers, and infrared-based position tracking with 2 arrays of 6 infrared-based sensors. The HMD infrared cameras have a frame rate of 120 fps. The eye-tracking system has an accuracy of <1 degree. The eye-tracking system checks the gaze position before showing the stimulus to automatically adjust the location of the stimulus. If the fixation is appropriate, the test continues without variations. If the eye-tracking system detects an eccentric fixation, but still within central 15 degrees, the system readjusts the stimulus locations based on the new fixation point. If fixation is detected outside the central 15 degrees, the test stops and the device presents a signal requesting the patient to return to the central fixation target. The range of interpupillary distance covered by VisuALL is 54 to 71 mm which satisfies the majority of the tested subjects. Each monitor has a fixation target, patients with normal fusion and pupillary diameters in the covered range by VisuALL see only one fixation target. If the patient sees 2 fixation targets (pupillary diameter <52 or > 71 mm or lack of fusion), one monitor is turned off and each eye is tested separately. In our series, we did not have any patient requiring monocular testing.

The VisuALL thresholding algorithm T was used in this investigation. The testing characteristics are summarized in Table 1. The machine also has a suprathreshold strategy (SupraT) which in addition to checking the visual field, it provides the patient's reaction time at each tested point. Central 24-2 tests 50 locations over the central 24 degrees in a 6-degree grid pattern that straddles the horizontal and vertical midlines, that is, targets are located 3 degrees either side of the midlines. The blind spot is mapped at a location just a degree below the horizontal line.

FIGURE 1. The Visu*ALL* headset with the response button and the WebApp. Figure 1 can be viewed in color online at www.glaucomajournal.com.

TABLE 1. The Characteristics of the Strategies Employed in VisuALL and SITA-standard Strategy of Humphrey Visual Field

Parameters	VisuALL	HFA
Range (deg.)	24	24
Background illumination (cd/m^2)	3	10
Stimulus locations	50	52
Testing distance (cm)	Infinity	30
Stimulus source	Display	Projection
Stimulus size (deg.)	0.43	0.43
Stimulus duration (ms)	150	200
Stimulus intensity (cd/m^2)	Variable (3-120)	Variable (10-3183.1)
Interstimulus time (ms)	Random	Random
Gaze control (fixation losses)	Heijl-Krakau, Eye-tracking System	Heijl-Krakau, Video eye monitoring
False positive and negative (%)	0-100 (unexpected response)	0-100 (unexpected response)
Testing strategy	Full threshold	SITA Standard
Anchors	1/quadrant	1/quadrant
Refractive correction	Glasses/trial frame	Lens holder
Tutorial video	Yes	No
Fellow eye patched	No	Yes

HFA indicates Humphrey Field Analyzer; SITA, Swedish Interactive Threshold Algorithm.

Statistical Analysis

Descriptive statistics, which included means, SDs, frequencies, and percentages, were used to summarize all data. Tests for normality (Shapiro-Wilk) were carried out for each quantitative variable and appropriate parametric/nonparametric analyses were utilized. The Spearman correlation coefficient (r) between the VisuALL and the HFA parameters were computed for each eye and for each quadrant in the normal and glaucoma groups. The slope of the linear age versus sensitivity function was calculated. The receiver operating characteristic (ROC) curves were estimated for VisuALL and HVF mean retinal sensitivity (MS). The statistical analysis was performed on the right eye and left eyes separately and on both eyes. The same results were obtained, therefore only the results of the right and both eyes are presented. The Bland-Altman plots were used for assessment of the agreement of the 2 devices. P-values <0.05 were considered statistically significant. The statistical analysis was performed using SPSS, version 20.0 (IBM SPSS Statistics, Chicago, IL) and MedCalc software, version 15.00 (MedCalc Software, Ostend, Belgium).

TABLE 2. The Demographics of the Participants

	Normal Group	Glaucoma Group
Participants	25	26
Eyes	50	52
Age [mean (range)] (y)	53.96 (30-79)	66.04 (23-86)
Sex (% female)	68	50
Race		
White	52	50
African American	32	50
Hispanic	12	—
Asian	4	—

RESULTS

Of 55 patients who were enrolled in the study, 4 were excluded (2 of the normal were unable to take the visual field, 1 VisuALL and 1 HVF; and 2 did not met the inclusion criteria). A total of 102 eyes from 51 patients were included in the present study. The normal group consisted of 50 eyes and the glaucoma group consisted of 52 glaucomatous eyes, 36 eyes (69.23%) were classified as having mild, 13 (25%) eyes had moderate, and only 3 (5.77%) eyes had severe visual field defects. The types of the visual field defects were: nasal step 40%, arcuate scotoma 25%, paracentral scotoma 18.3%, combinations of defects 16.7%.

The demographic characteristics are presented in Table 2 and the clinical characteristics of all the participants are summarized in Table 3.

The testing time was longer on the VisuALL than the HFA for both the normal (6.13 vs. 4.77 min, $P=0.02$) and glaucoma groups (9.28 vs. 5.62 min, $P<0.001$). We noted a significant linear relationship between the age of subjects and the global MS. The MS decreased ~0.04 dB/year of age on both the VisuALL ($P=0.03$) (Fig. 2A) and the HFA ($P=0.04$) (Fig. 2B).

The correlation values for both groups for both eyes and right eyes are included in Table 4. The correlation and ROC curve of the left and right eyes were similar to the results of both eyes. Only the results of the right eye are presented. The global MS and each quadrant MS value correlated significantly between VisuALL and HFA.

The results of ROC curves are presented in Figure 3. The MS of the Visu*ALL* (0.98) had a greater ROC than HFA (0.93) MS but this was not significant ($P=0.06$). The Bland-Altman plots, Figure 4, showed a good agreement between the MS of the VisuALL and the HFA in both the normal and glaucoma groups.

DISCUSSION

In this study, we confirmed that the VisuALL successfully measures retina sensitivity in healthy subjects and glaucoma patients. We also found that the retinal sensitivity measured by the VisuALL, was similar to that of the HFA, and both are affected by the age of the individuals. Our study found that the VisuALL had a similar performance for thresholding as the HVF in healthy subjects and glaucoma patients. The MS of the whole visual field and all quadrants MS correlated significantly in both the normal and glaucoma groups. This study also confirmed that the VisuALL successfully discriminates healthy subjects from patients with glaucoma by MS. In our study, the diagnostic performance of the VisuALL was excellent which indicates a high discriminatory ability of the VisuALL in differentiating healthy from glaucomatous visual fields.

VisuALL has a lower peak brightness and lower background illumination than HFA. This may has contributed to the reduced correlation in the normal group compared with the glaucoma group in which presumably more eyes at more locations were tested to very low-intensity thresholds. This lower correlation in healthy individuals compared with glaucoma patients was also described by Morales et al[14] when comparing 2 different thresholding strategies of the Octopus perimeter. In addition, the Spearman correlation coefficient (a nonparametric equivalent of Pearson correlation coefficient) ranks the data of each device and computes the correlation

TABLE 3. The Clinical Examination Findings of the Normal and Glaucoma Groups

	Mean Deviation*	Pattern Standard Deviation*	Visual Acuity (Decimal)	IOP (mm Hg)	C/D Ratio
Normal group					
20-39	−0.94	1.41	1.04	13.40	0.26
40-49	−0.15	1.40	0.86	13.13	0.40
50-59	−0.80	2.00	0.99	14.60	0.32
60-69	0.48	1.52	0.89	13.80	0.20
70-80	−0.91	2.70	0.82	13.33	0.28
Glaucoma group					
Mild glaucoma	−2.73	2.77	0.85	17.33	0.66
Moderate glaucoma	−10.38	9.56	0.83	14.07	0.76

*The mean deviation and pattern standard deviation of the visual field.
C/D indicates cup-to-disc ratio; IOP, intraocular pressure.

between the ranks. Because both methods of VF testing showed high accuracy, and the glaucoma patients had different stages of the disease; the Spearman ranks were affected by the disease severity spectrum towards a higher correlation coefficient. This does not necessarily mean that the correlation between the devices was higher in the diseased eyes. The logical interpretation is that the 2 devices showed a significant correlation in both glaucomatous and normal eyes. Nonetheless, the overall agreement with HFA in the Bland-Altman analysis is good, with an MS difference of 0.25 dB.

Data from paired eyes are likely to be correlated and confound correlation analyses. We did the analysis on the right and left eyes separately, the correlation between the 2 devices were similar in statistical analysis on one or both eyes. Therefore, we reported the results of the right eye and both eyes. Use of both eyes data in asymmetric diseases is allowed and given the asymmetric visual field defect in the majority of glaucoma patients, using both eyes visual field data seems to be appropriate.[15]

Although structural imaging has improved significantly over the past decade, it is not yet ready to replace the functional testing in glaucoma detection and management. Several studies have shown that functional changes can precede structural change or vice versa. Therefore, all glaucoma patients including glaucoma suspects need to have visual field testing.[16,17] Despite the widespread use of automated perimetry, there are significant limitations. Standard units built for physicians' offices or hospitals are bulky, heavy, and expensive. These devices require dedicated office space and constant monitoring by technicians. Generally, patients dislike the tests, performance pressure, and difficulty understanding testing instructions.[3]

HMDs perimeters have the potential to reduce many of these burdens. The VisuALL efficiently controls the testing environment luminance. It does not require dedicated office space, and through internal videos and monitoring, approaches reduce the burden on technicians. Olleyes technology is user friendly, widening the population that can be screened and increasing the frequency at which visual fields can be tested on glaucoma patients to monitor glaucoma progression. The use of these devices is compatible with telemedicine in the detection of visual field defects, and the cloud-based architecture of the VisuALL is compatible with remote testing and monitoring.[18] VisuALL provided visual field measurements comparable to the SITA-standard thresholding strategy of HVF.

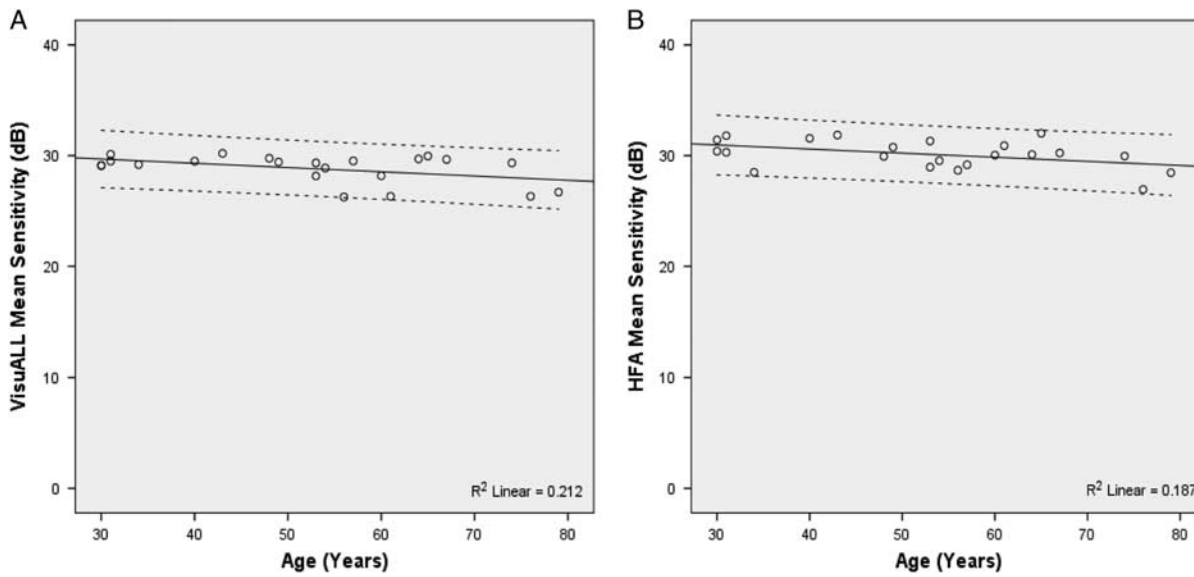

FIGURE 2. The VisuALL (A) and Humphrey (B) mean sensitivity dependence on age (the black line in the middle shows the predicted mean sensitivity). The dashed lines present the 95% confidence intervals. HFA indicates Humphrey Field Analyzer.

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TABLE 4. The Correlation (Spearman Correlation Coefficient) Between the Mean Sensitivity of the Normal and Glaucoma Groups

	Both Eyes		Right Eye	
Humphrey—VisuALL	**Normal Group**	**Glaucoma Group**	**Normal Group**	**Glaucoma Group**
Superior nasal quadrant	0.4 (0.004)	0.6 (<0.001)	0.4 (0.06)	0.6 (0.003)
Superior temporal quadrant	0.4 (0.01)	0.6 (<0.001)	0.4 (0.06)	0.6 (0.002)
Inferior nasal quadrant	0.3 (0.03)	0.8 (<0.001)	0.3 (0.2)	0.7 (<0.001)
Inferior temporal quadrant	0.5 (<0.001)	0.7 (<0.001)	0.4 (0.03)	0.6 (<0.001)
Superior hemifield	0.4 (0.005)	0.6 (<0.001)	0.4 (0.09)	0.6 (0.002)
Inferior hemifield	0.5 (<0.001)	0.8 (<0.001)	0.4 (0.05)	0.7 (<0.001)
Global	0.5 (0.001)	0.8 (<0.001)	0.4 (0.04)	0.7 (<0.001)

This device has its own advantages and limitations. Among the positive features, patients can be tested in virtually any position, and their head can be freely moved during the test without needing to stop the test. It improves the patient's comfort and may decrease the test-induced fatigue and improve testing patients with cervical or spinal disease, weight issues, and body habitus that makes positioning in a standard perimeter difficult. It also will allow visual field testing for hospitalized or bedridden patients. This new device offers the advantage of providing a printout almost similar to the HVF which is familiar to all ophthalmologists and optometrists (Fig. 5). The eye tracker permits strict control of the patient fixation during the whole test, similar to Octopus perimetry, which is potentially more accurate than HFA standard perimetry where fixation is checked occasionally during the test.

The patient can wear his or her own glasses during the test and there is no need for trial lens. Portable visual field tests have great potential in the delivery of good-quality vision care for glaucoma patients in situations where access to standard perimetry machines is difficult (rural/remote locations, developing countries, etc.) and for special situations when given patients are required to keep a social distance. Cleaning between patients involves simple wiping with alcohol.

The disadvantages of the VisuALL include those inhere to automated perimetry. Given the preset testing program of automated perimeters, patient cooperation and concentration are vital during the visual field examination. In addition, the machine does not have any follow-up analysis in the tested version. Although well-received by subjects in the current study, other subjects might not prefer the HMD device. We have not studied the device in claustrophobic patients. The VisuALL current strategy for checking the visual field is a full threshold which takes longer than the SITA-Standard, the most commonly used strategy by practitioners. In addition, this is the first report on the VisuALL and due to the lack of a normal database and frequency of seeing curve, the testing duration was longer. With further developments, the test duration will decrease. It is well known that flat screens used in perimetric devices create stimulus aberrations.[19] The VisuALL is not an exemption and a current research project intends to elucidate the extent and influence of those aberration specifically under the current optical system. Nevertheless, the effect of these kinds of aberration does not seems to significantly affect the overall correlations between bowl and screen perimetry like the one used in this study. The included patients in the current study had mainly mild or moderate glaucoma and due to the lower peak brightness and lower background illumination of the monitor the results may not apply to the patients with severe glaucoma and studies on severe glaucoma cases are required.

Evolving care paradigms are driving consideration of increased monitoring outside of the office. Remote monitoring of

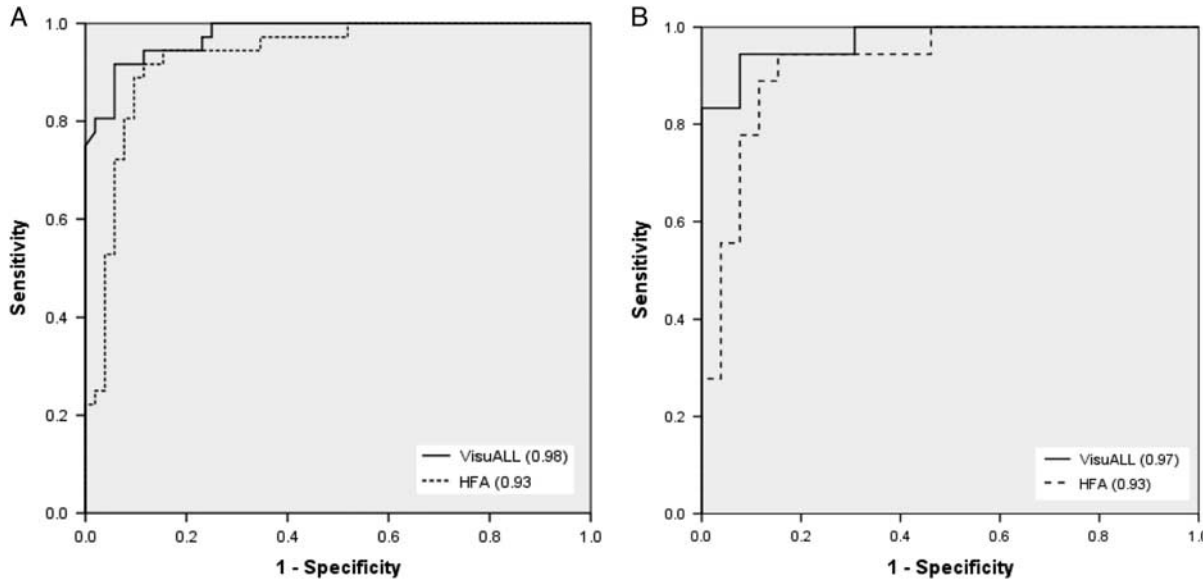

FIGURE 3. Receiver operating characteristic curve of the mean sensitivity of VisuALL and Humphrey Visual Field in both (A) and right eyes (B). HFA indicates Humphrey Field Analyzer.

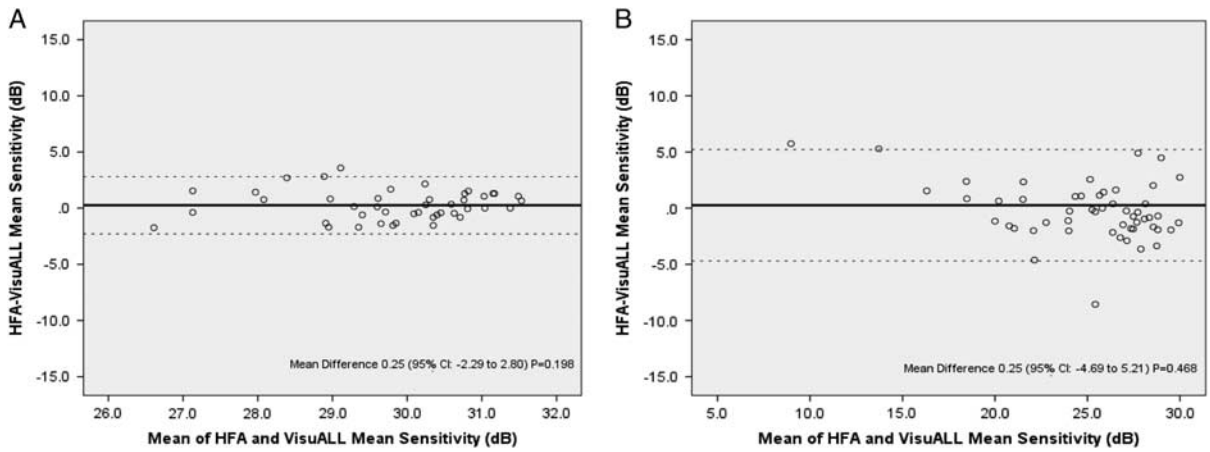

FIGURE 4. The Bland-Altman plots on the agreement between VisuALL and HFA in normal (A) and glaucoma groups (B). CI indicates confidence interval; HFA, Humphrey Field Analyzer.

IOP and perimetry has been reported, as well as cellphone-based fundus photographs.[20,21] Home-based visual field testing could become a reality, relieving both patients and clinicians of the burden of in-office testing and meeting changing patient expectations. In addition, because of the ease of use, it will allow for more frequent visual field testing, which can lead to a more rapid and confirmatory diagnosis of glaucoma progression.[22,23] If an HMD is used for in-office visual field testing, the visual field could be checked while the patients are seated in the waiting or examination room before being seen by their ophthalmologist.

In summary, we demonstrated in this study that the VisuALL perimeter successfully discriminates healthy subjects from glaucoma patients and correlates well with HVF, an established method of perimetry. These findings highlight the potential of a portable device in developing and performing measurements of visual function that can be easily and widely implemented either in the office or using telemetry. Additional studies on patient preference, repeat test performance, and clinical utility, and creating a normal database are underway.

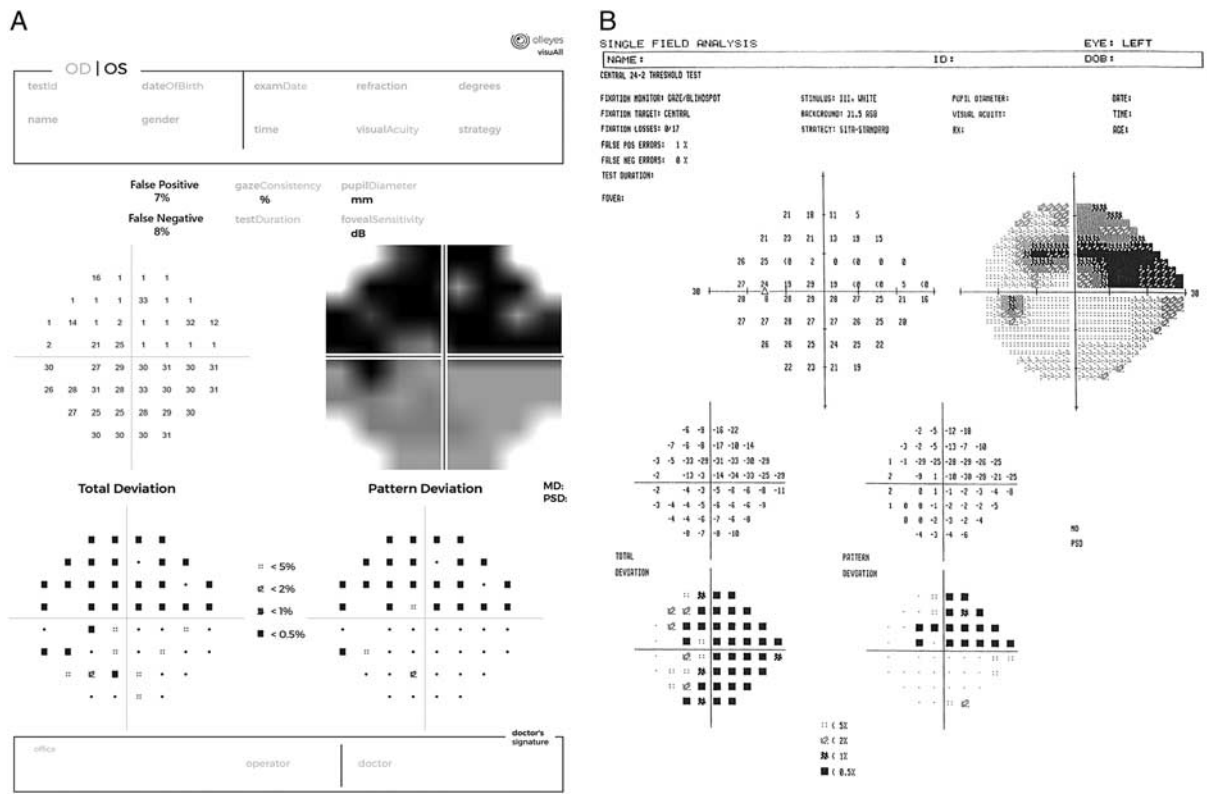

FIGURE 5. The printout of the VisuALL (A) and Humphrey Visual Field (B) in a patient with moderate glaucoma. MD indicates mean deviation; PSD, pattern standard deviation.

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