Repeatability of Online Circular Contrast Perimetry Compared to Standard Automated Perimetry

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Précis: Online circular contrast perimetry provides visual field assessment on any computer or tablet with no extra hardware. It has good test repeatability and reliability that is comparable with standard automated perimetry. It holds promise for use in disease screening and surveillance to expand the provision of glaucoma care.

Purpose: To evaluate the repeatability of online circular contrast perimetry (OCCP) compared to standard automated perimetry (SAP) in normal participants and patients with stable glaucoma over 18 weeks.

Methods: Thirty-six participants (13 normal controls and 23 patients with open angle glaucoma) were recruited. OCCP and SAP perimetry tests were performed twice at baseline, then at 6, 12, and 18 weeks. Global perimetric indices were compared between perimetry types and analyzed for short-term and intermediate-term repeatability.

Results: There were no statistically significant changes over time for both OCCP and SAP across all groups for mean deviation (MD), pattern standard deviation, and visual index/visual field index ($P > 0.05$). Test-retest intraclass correlation coefficients (ICCs) for OCCP MD were excellent at baseline (0.98, 95% CI: 0.89–0.99) and good at 18 weeks (0.88, 95% CI: 0.51–0.98). SAP test-retest ICCs were excellent at baseline (0.94, 95% CI: 0.70–0.99) and 18 weeks (0.97, 95% CI: 0.84–0.99). Inter-test ICCs were good, ranging from 0.84 to 0.87. OCCP testing time was shorter than SAP (5:29 ± 1:24 vs. 6:00 ± 1:05, $P < 0.001$). OCCP had similar false-positive (3.84 ± 3.32 vs. 3.66 ± 4.53, $P = 0.48$) but lower false-negative (0.73 ± 1.52 vs. 4.48 ± 5.00, $P < 0.001$) and fixation loss responses (0.91 ± 1.32 vs. 2.02 ± 2.17, $P < 0.001$).

Conclusions: OCCP allows visual field assessment on any computer screen with no additional hardware. It demonstrated good repeatability and reliability with similar performance indices to SAP in both the short term and intermediate term. OCCP has the potential to be utilized as a glaucoma screening and surveillance tool for in-clinic and at-home testing, expanding the provision of care.

Key Words: visual field test, perimetry, repeatability

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Glaucoma is a leading cause of irreversible blindness worldwide with a rising disease burden.[1] Early detection and lifelong monitoring remain integral to managing disease and preventing vision loss. Ensuring the availability of robust, cost-effective, and accessible screening and surveillance tools will be critical for healthcare services to meet the growing demands in the coming decades.[1,2]

Visual field (VF) testing is important for diagnosing and monitoring patients with glaucoma.[3] Once diagnosed, patients require ongoing monitoring for disease progression.[4] Most practices use standard automated perimetry (SAP) operated on dedicated clinic machines; the Humphrey Field Analyser (HFA) remains the clinical standard due to strong reliability and reproducibility.[3,5]

Current perimeter machines have many limitations including high equipment costs, operator dependence, and lack of portability; they are also time-consuming and can be associated with a poor user experience. Clinic perimeters are only available in hospitals or specialist eyecare clinics and patients are required to attend in-person. Unfortunately, resource-poor and rural communities often lack access to these services. Worldwide, eyecare clinics are becoming overburdened with high patient caseloads and are struggling to accommodate demand, with the potential consequences of delayed patient assessments, missed appointments, and loss to follow-up, with sight-threatening consequences.[6] This problem has been exacerbated by backlogs and wait-list blowouts related to recovery from the recent global COVID-19 pandemic.[7]

Shifting toward online perimetry technologies could be a viable solution to relieve the burden on health care providers while continuing to support patients. In recent years, perimetry has been developed on several devices including computers,[8] tablets,[9–12] smartphones,[13] and virtual reality headsets.[14,15] These devices offer patients the ability to undertake VF monitoring at home,[16–19] the advantages being: improved access to care, time and costs saved on in-person visits, greater flexibility, and the capacity for more frequent assessments. The added benefit of collecting more VF data between appointments is potentially identifying disease progression earlier, enabling prompt clinical decision-making.[20–22] In low-risk patients, this could be used to reduce the number of in-person appointments, helping to improve clinic flow, control waiting room numbers, and optimize the allocation of staff and resources. There is also potential to expand the delivery of care to remote and resource-limited areas. Finally, home-based testing in comfort on familiar devices might increase overall patient satisfaction given that a major drawback of clinic perimetry is the suboptimal patient experience; unfortunately, patients

find conventional perimetry machines uncomfortable, tiring, and anxiety-provoking.[23,24]

Online circular contrast perimetry (OCCP) is a validated perimetry application that offers VF testing on any computer, laptop, or tablet with an internet connection, and without additional hardware.[25] Its minimal hardware requirements make OCCP versatile, cost-effective, and easy to operate remotely, which is an advantage over other portable perimetry devices, therefore, offering a practical and affordable avenue for home perimetry. In a cohort study of both patients with glaucoma and healthy controls (n = 95 and n = 125), OCCP was found to have comparable diagnostic accuracy to both SAP and optical coherence tomography (OCT) scans of the retinal nerve fiber layer (RNFL) and macular ganglion cell complex.[26] It also provides an improved user experience that is favored by patients.[27] However, its short-term and intermediate-term repeatability remains unknown. Detecting disease progression is critically influenced by the frequency of testing and instrument variability[20,21]; therefore, understanding OCCP's stability over time is an important feasibility assessment.

The purpose of this study was to evaluate the perimetric findings of repeated OCCP against repeated SAP over 18 weeks in a cohort of normal participants and patients with stable glaucoma to determine its short-term and intermediate-term stability.

MATERIALS AND METHODS

We conducted a prospective, single-center study of 36 patients (60 eyes). The study was approved by the Royal Australian and New Zealand College of Ophthalmology Human Research and Ethics Committee (90.18), with local site governance, and was conducted as per the tenets outlined in the Declaration of Helsinki. All participants provided written informed consent before their participation.

Participants

Participants were recruited from patients who attend a subspecialty ophthalmology practice in Melbourne. Normal controls and patients with open angle glaucoma at various levels of disease severity were included.

The study's inclusion criteria were the ability to read and understand English fluently; provision of written, informed consent; open anterior chamber angles; logarithm of the minimum angle of resolution (logMAR) best-corrected visual acuity (BCVA) score ≤ 0.7 (for both glaucoma and control groups); adequate OCT image quality; and reliable SAP and OCCP test results.

The exclusion criteria were ocular pathology other than glaucoma (such as visually significant cataract defined by Lens Opacities Classification System III greater than Grade 2,[28] nonglaucomatous optic neuropathy, and retinal or macular pathology); systemic disease or medication that could affect glaucoma; secondary causes of glaucoma; angle abnormalities; recent ocular or laser surgery (within previous 3 months, with the exception of selective laser trabeculoplasty or peripheral iridotomy); papillary anomalies; ametropia $> \pm 5$ D; large peripapillary atrophy; neurological disorders; media opacities preventing good image scans; and unreliable SAP and OCCP tests.

Tests were considered unreliable based on the following traditional parameters: false negatives (FN) > 33%; false positives (FP) > 15%; and fixation losses (FL) > 20% (based on the Heij-Krakau method).[29] Tests were also evaluated for any artifactual interference including eyelid or rim artifacts, inattention, improper fixation, and fatigue; details of these methods are discussed elsewhere.[30] OCT scans with inappropriate centration, signal strength lower than 8/10, or segmentation errors were also excluded.

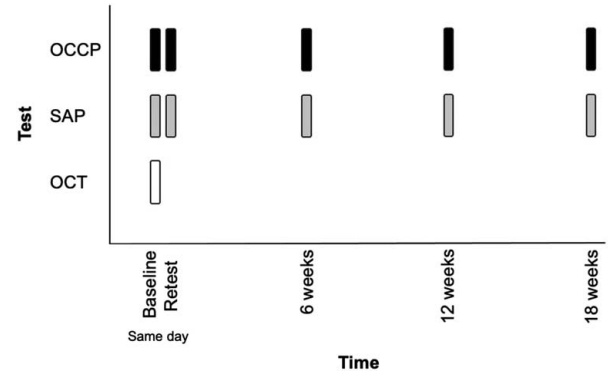

FIGURE 1. Testing strategy per eye over the study course for perimetric tests: standard automated perimetry (SAP), online circular contrast perimetry (OCCP), and optical coherence tomography (OCT) of the retinal nerve fiber layer and macular ganglion cell complex. Vertical bars represent one test.

Clinical Assessment

All participants were reviewed by the study's chief investigator to identify any factors that necessitated exclusion from the study. Participants then underwent a comprehensive ophthalmic examination to obtain baseline data including refractive correction for distance, BCVA, Cirrus OCT of the optic nerve head (ONH) and macula (Carl Zeiss Meditec Inc), central corneal thickness, and intraocular pressure (IOP) using the Goldmann applanation tonometer (Haag-Streit International).

Eyes were defined as glaucomatous based on the criteria outlined by the American Academy of Ophthalmology.[31] Control participants were defined as having normal IOP, RNFL thickness, ONH appearance, and SAP results, with no other ocular pathologies. Glaucoma subjects were defined as those with open angles on gonioscopy, with characteristic disc features and VF changes.

VF Assessment

Participants underwent VF testing with SAP using the HFA Swedish Interactive Threshold Algorithm (SITA) standard 24-2 test (Zeiss) and the OCCP test. Patients attending their scheduled review appointments were invited to participate. Recruited participants performed each perimetry test at baseline with a same-day retest, then once during scheduled reviews at 6, 12, and 18 weeks (Fig. 1). Before undergoing perimetric assessment, participants were briefed by the study's chief investigator and provided with detailed information about the study, each perimetry test, and test protocols, including their supervision by a trained orthoptist. During the first visit, participants completed the baseline SAP test, and then both OCCP tests (baseline and retest) and retest SAP were completed in a random order, with a 5-minute rest interval between each test. At subsequent follow-up visits, the order of SAP versus OCCP was randomized; simple randomization was used.[32] Each eye

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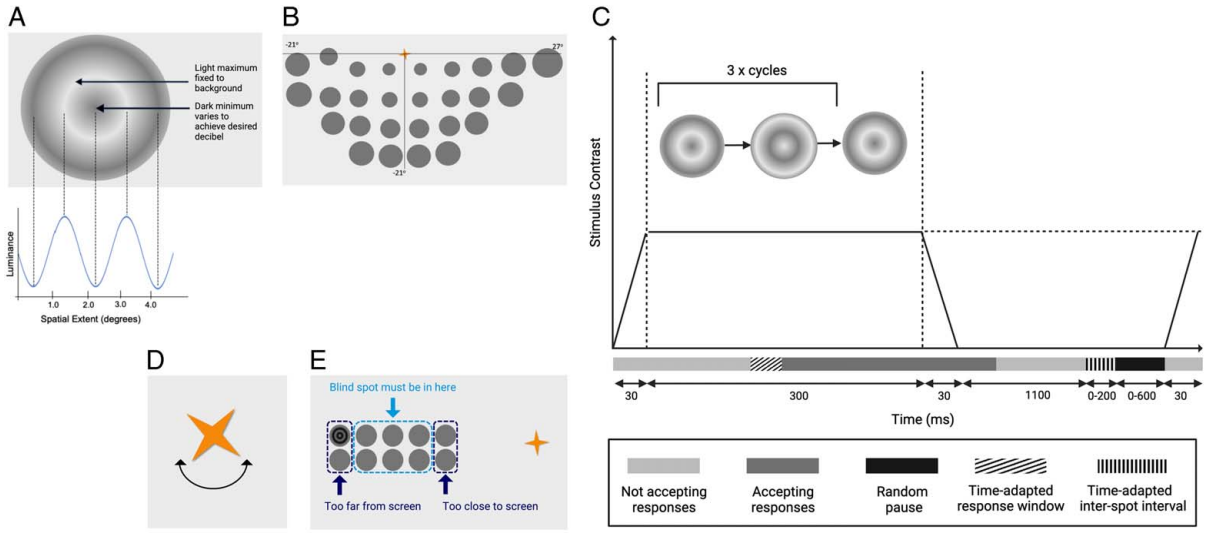

FIGURE 2. Online circular contrast perimetry test settings. (A) Flickering test target. (B) Map of inferior hemifield 24-2 perimetry loci testing. To test the superior hemifield, the fixation target later moves to the bottom of the screen. (C) Sequence of target presentation: targets appear for 3 counterphase flicker cycles lasting 360âms; the contrast is graded at the start/end of target presentation. Figure adapted from Alawa et al.[13] Adaptations are themselves works protected by copyright. So in order to publish this adaptation, authorization must be obtained both from the owner of the copyright in the original work and from the owner of copyright in the translation or adaptation. (D) Fixation target: spinning golden star. (E) Blind spot localization optimizes the user's viewing distance. (B, E) The dark gray homogeneous circles are a diagrammatic representation of where test targets may appear and are not present during the live test. Figure 2 can be viewed in color online at www.glaucomajournal.com.

was tested sequentially; however, due to feasibility constraints, some participants (n = 11) were only able to complete perimetry in 1 eye. When only 1 eye was chosen for patients with glaucoma, this was the eye with the worst mean deviation (MD), whereas for controls, 1 eye was chosen randomly.[32]

OCCP Application

The OCCP (Eyeonic) online application has been described in previous papers.[25–27] In essence, OCCP provides perimetry via the web browser to work on any computer. Participants are presented with circular flickering targets of alternating light and dark rings, which are 4.5 degrees of visual angle in size with 6 degrees of spatial separation (Fig. 2A). Similar to Pulsar perimetry (Haag-Streit International), targets maintain the same level of contrast throughout the spatial extent of the target, except for the peripheral edges to minimize light scatter and the inadvertent stimulation of ganglion cells.[33,34] Targets are also comparatively smaller in size (4.5 vs. 5 degrees), allowing for a more detailed mapping of the user's visual field loss.[33,34] OCCP assesses 52 loci over 24 degrees of peripheral vision (Fig. 2B). Each target flicker occurs for 60 ms over 3 on/off cycles, lasting a total of 360 ms. Like conventional FDP (Welch Allyn and Carl Zeiss Meditec), targets have sinusoidal contrast with spatial frequency of 0.55 cycles/degree and temporal counterphase flickering at 9 Hz.[35,36] The contrast is also ramped up and down linearly over 50 ms at the start and end of target presentations to prevent temporal transients and saccades (Fig. 2C).[37,38] In comparison to traditional FDP, where target bands vary around a mean of background luminance, OCCP's light rings were set to the background screen color (light gray), while the intensity of dark rings was varied to determine the appropriate contrast. This is similar to using a luminance pedestal flicker for stimulus decrements, which aims to minimize the number of grayscale colors in stimulus and background design for consistency of display parameters with gamma correction.[39]

Luminance output ranged from pure white (255, 255, 255), as 100% relative luminance percentage, to black (0, 0, 0) as 0%. Relative luminance was calculated for each 256-grayscale level, based on the Web Content Accessibility Guidelines standards for relative luminance calculation.[40] Contrast was calculated using the Michaelson formula by comparing the light band maximum and dark band minimum relative luminance of target rings.[41]

$$\text{Contrast} = (RL1–RL2)/(RL1 + RL2),$$

where RL1 is the light band maximum relative luminance and RL2 is the dark band minimum. Background screen luminance was set at 224 candela per square meter (cd/m^2) output. Contrast was then converted to relative decibels using the same method as FDP.[35]

$$\text{Relative decibel (rdB)} = -20 \log(\text{contrast}).$$

The dynamic range for target intensity was from 0 to 36 dB, which is consistent with the range employed in HFA and other perimetry devices for assisting human threshold estimates.[42] As described previously, the testing protocol of OCCP is similar to SITA, based on a priori probability density functions with a 4/2 dB staircase.

Participants were instructed to fixate on a continuous spinning golden star (4 degrees of visual angle), and then to click the mouse when a target appeared in their periphery (Fig. 2D). Our previous studies have shown that the use of a dynamic fixation target may help to improve concentration and reduce fixation losses.[26,27] FP responses were recorded where clicks occurred outside the accepted response window. Similar to SAP, FN responses were recorded when

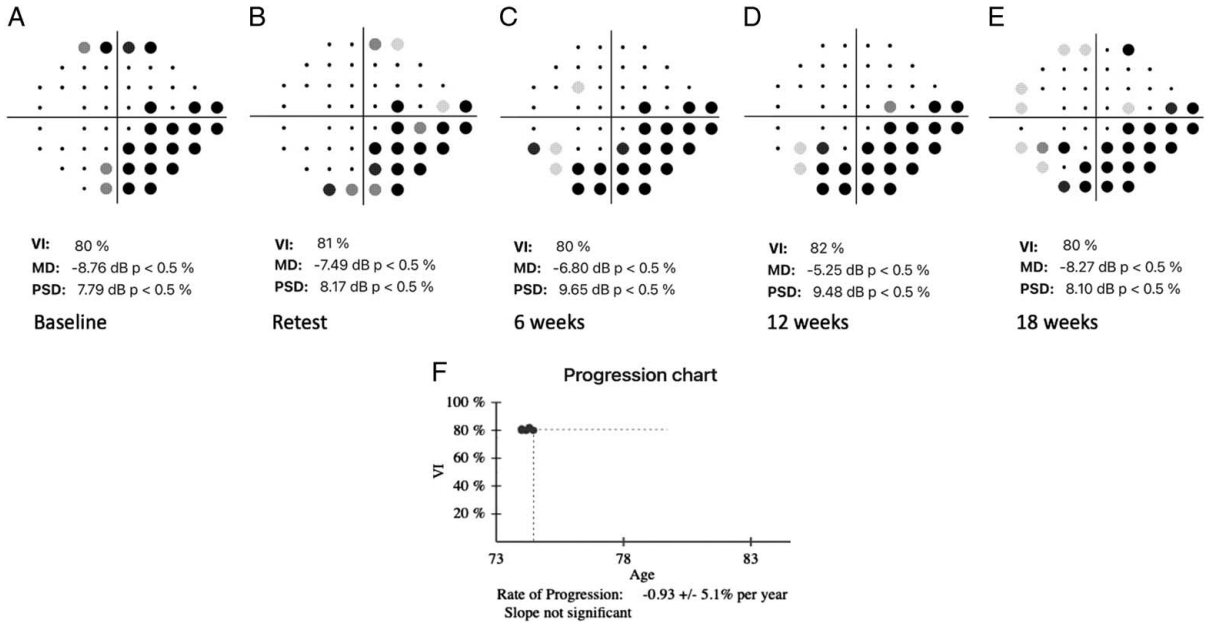

FIGURE 3. Online circular contrast perimetry progression analysis. (A–E) Sample left eye pattern deviation plots and global indices: mean deviation (MD), pattern standard deviation (PSD), and visual index (VI) for 1 patient with glaucoma over the study period. (F) Progression chart report for VI from the same patient over the study period.

participants failed to respond to stimuli at higher contrast in areas of normal threshold sensitivity and are described in further detail elsewhere.[25,26] To account for interuser variability, responses were time-adapted based on the user's previous response time; there were also inbuilt delays that occurred at random to prevent rhythmic responses.

Correct viewing distance is maintained by 3 mechanisms. First, the app advises users of the correct viewing distance to perform the test, which is based on the size of the computer monitor and calculated trigonometrically to ensure viewing angle consistency. Second, the user's blind spot is mapped by testing small areas on a 4×10-degree grid overlying the proposed blind spot, which was estimated at 15 degrees temporal and 0.5 degrees inferior (Fig. 2E). Third, the user's head position is monitored via a webcam, which links to the app's built facial detection (not recognition) software with a 1-second refresh rate using machine learning. No specialized head or neck supports were used. Deviations of facial position monitoring beyond 15% in 4 planes were detected and the test was paused while the user was instructed to adjust their position accordingly. OCCP's verbal instructions were pre-recorded and provided in English; however, several language options are available.

Testing Conditions

Testing was conducted in a controlled clinical setting and the environmental conditions were standardized, including the background noise, temperature, and ambient lighting. SAP was performed in a dedicated, quiet, darkened room. Testing for the OCCP application was performed at 1 site on 4 dedicated computers in quiet, undisturbed clinical rooms with the background lighting dimmed so that the main light source was the computer monitor. Each computer had a separate mouse, internet access, volume, and a webcam. All 4 monitors used were 24-inch screens of resolution 1920×1080 pixels. To ensure consistency of display across the monitors, screen calibration was performed using a SpyderX screen photometer (Datacolor); however, user-guided screen calibration is an inbuilt feature of OCCP. Gamma was set at 2.2 and white temperature at 6500 K. Participants were seated at a viewing distance of 50 cm (the correct viewing distance for this screen size) before the commencement of the test. Head position and height were optimized by the supervising orthoptist. All orthoptists had extensive experience in operating perimetry and had undergone additional training for administering OCCP to ensure the consistency of study protocols.

OCCP has several design features included specifically for home monitoring. Thorough pretest instructions are provided to establish the desired ambient noise and lighting, user positioning, correct eyewear, and mono-ocular occlusion. The app automatically recalibrates for every screen size, calculates the correct working distance, employs blind spot localization, and monitors the user with AI as discussed. After instructing the user to increase screen brightness manually, the app recalibrates itself automatically based on early test responses. In addition, presenting dark flickering test targets on a light gray background has shown greater resistance to variations in background lighting than conventional white-on-white perimetry.[35]

Main Outcome Parameters

MD was used as the primary outcome measure for determining test repeatability and for perimetry test comparisons. MD is a validated global endpoint used in similar studies to assess repeatability.[19,43] OCCP MD, pattern standard deviation (PSD), and visual index (VI) values were calculated from an established normative data set.[25] Secondary outcome measures were other perimetric parameters including PSD, VI/visual field index (VFI), reliability indices, and test duration. Progression analysis charts were also generated to monitor the trends in global indices over time (Fig. 3).

TABLE 1. Baseline Demographic Characteristics

Variables	Control group	Glaucoma group	*P*
Gender (F/M)	9/4	14/9	0.73
Number of eyes (R/L)	10/12	19/19	0.79
Disease severity: number (% eyes)			
Mild	—	21 (55.3)	—
Moderate	—	9 (23.7)	—
Severe	—	8 (21.1)	—
Abnormal ONH (% eyes)	0	100	—
Age (y)	68.54 ± 8.91	70.35 ± 8.88	0.40
log MAR visual acuity	0.02 ± 0.14	0.07 ± 0.12	0.07
Corrected IOP (mmâHg)	16.50 ± 5.21	14.21 ± 5.03	0.14
CCT (μm)	544.23 ± 52.84	551.13 ± 36.69	0.51
Spherical equivalent (D)	−0.58 ± 2.07	−0.61 ± 1.93	0.93
OCT RNFL			
MT (μm)	81.23 ± 9.11	67.05 ± 10.41	<0.0001
ST (μm)	97.55 ± 16.66	79.08 ± 14.82	0.0001
IT (μm)	100.95 ± 23.21	70.58 ± 14.82	<0.0001
VCDR	0.51 ± 0.21	0.68 ± 0.24	0.0011
OCT GCC			
MT (μm)	70.09 ± 13.37	65.24 ± 10.30	0.013
ST (μm)	69.86 ± 16.16	66.95 ± 10.83	0.048
IT (μm)	66.77 ± 16.27	61.74 ± 10.92	0.025
SAP			
MD	−1.06 ± 2.29	−7.40 ± 6.75	0.003
PSD	2.23 ± 1.37	6.61 ± 3.61	<0.0001
VFI	97.57 ± 3.27	81.18 ± 20.05	0.0079
OCCP			
MD	−0.43 ± 2.19	−7.18 ± 4.98	<0.0001
PSD	2.61 ± 1.46	5.58 ± 2.18	<0.0001
VI	96.75 ± 4.62	78.92 ± 17.50	0.0003

Values are presented as mean ± SD unless otherwise specified.

CCT indicates central corneal thickness; D, diopters; GCC, ganglion cell complex inner plexiform layer; IOP, intraocular pressure; IT, inferior thickness; MAR, minimal angle of resolution; MD, mean deviation; MT, mean thickness; OCCP, online circular contrast perimetry; OCT, optical coherence tomography; ONH, optic nerve head; PSD, pattern standard deviation; RNFL, retinal nerve fiber layer; SAP, standard automated perimetry; ST, superior thickness; VCDR, vertical cup disc ratio; VI, visual index; VFI, visual field index.

Statistical Analysis

Data were analyzed using Statistical Package for Social Sciences (SPSS, Inc.) and Real Statistics in Excel 2016 (Microsoft 365). Statistical significance was set at $P < 0.05$, with adjustment by the Bonferroni method. Normality was assessed using the Shapiro-Wilks statistic. Mixed linear models were used to determine the significant predictors of global indices.[44]

Baseline demographic and clinical data were compared between control and glaucoma groups using *t* tests to identify paired differences or Mann-Whitney *U* analysis of ranks for nonparametric data.

Global indices and reliability parameters were assessed for change over time for both OCCP and SAP. Intraclass correlation coefficients (ICCs) were calculated to assess intertest reliability and were defined as poor (<0.5), moderate (0.5–0.75), good (0.75–0.9), or excellent (≥ 0.90).[45] Collinearity was quantified using Pearson's correlation with simple linear regression and 95% CIs. Bland-Altman plots were generated to evaluate the 95% limits of agreement (LoA) to compare MD values obtained at baseline against subsequent retests and to compare OCCP against SAP.

RESULTS

Thirty-six participants (60 eyes) were recruited into the study, of which 35 (58 eyes, 97.2%) attended all test sessions. Table 1 presents the demographic and clinical data from the 36 recruited participants. One participant was excluded from the cohort for the subsequent analyses for failing to attend the follow-up test appointments. One other participant with glaucoma began with both eyes included, but during the course, 1 eye was excluded as it was found to have unstable glaucoma and required glaucoma filtration surgery; however, the other eye achieved full follow-up.

Figure 4 presents the global perimetric and reliability indices for OCCP and SAP (A–E). No statistically significant changes over time were observed for both OCCP and SAP across all groups for MD, PSD, and VI/VFI (Figs. 4A–C). Control participants performed perimetry faster than patients with glaucomas in both OCCP and SAP (Fig. 4D, $P < 0.001$). Across all time points, OCCP testing time was shorter than SAP (5:29 ± 1:24 vs. 6:00 ± 1:05, $P < 0.001$). OCCP FP responses were not statistically different from SAP (3.84 ± 3.33 vs. 3.66 ± 4.52, $P = 0.48$); however, FN rates were lower (0.73 ± 1.52 vs. 4.48 ± 5.00, $P < 0.001$), as were FL responses (0.91 ± 1.32 vs. 2.02 ± 2.17, $P < 0.001$, Fig. 4E).

Table 2 presents the intratest change in MD values over time with corresponding ICCs, Bland-Altman bias, and limits of agreement for both OCCP and SAP. ICCs evaluating immediate repeatability of MD (baseline vs. same-day retest) were excellent for both OCCP (0.98, 95% CI: 0.89–0.99) and SAP (0.94, 95% CI: 0.70–0.99), while ICCs evaluating 18-week versus baseline MD were good for OCCP (0.88, 95% CI: 0.51–0.98) and excellent for SAP (0.97, 95% CI: 0.84–0.99). On comparing OCCP to SAP at each time point, a good level of concordance was observed for MD across all test sessions, with ICCs ranging from 0.84 to 0.87 and bias ranging from 0.13 to 1.72.

Figure 5 presents the linear regression correlation curves and Bland-Altman plots for test-retest data for each perimeter's MD. Figures 5A, B, E, and F compare the baseline to same-day retest, and Figures 5C, D, G, and H compare the baseline to 18 weeks. For baseline versus same-day retest, OCCP MD had a retest bias of −0.31 (LoA: −2.49 to 1.85, Fig. 5A) and correlation coefficient of 0.98 (95% CI: 0.91–1.00, Fig. 5E) that were similar to the SAP MD retest bias of −0.07 (LoA: −4.31 to 4.18, Fig. 5B) and a correlation coefficient of 0.94 (95% CI: 0.82–1.00, Fig. 5F). For baseline versus 18 weeks, OCCP MD had a retest bias of 0.87 (LoA: −4.05 to 5.78, Fig. 5C) and a correlation coefficient of 0.89 (95% CI: 0.75–0.99, Fig. 5G) while SAP MD had a retest bias of 0.23 (LoA: −2.96 to 3.42, Fig. 5D) and a correlation coefficient of 0.97 (95% CI: 0.92–1.00, Fig. 5H). Figure 6 presents the linear regression correlation for MD between OCCP and SAP averaged over all test sessions, which also showed a high level of concordance between the 2 tests ($r = 0.93$, 95% CI: 0.68−0.83).

DISCUSSION

In the coming years, online and portable perimetry devices are anticipated to expand the delivery of glaucoma care worldwide, with the benefits of earlier disease detection,

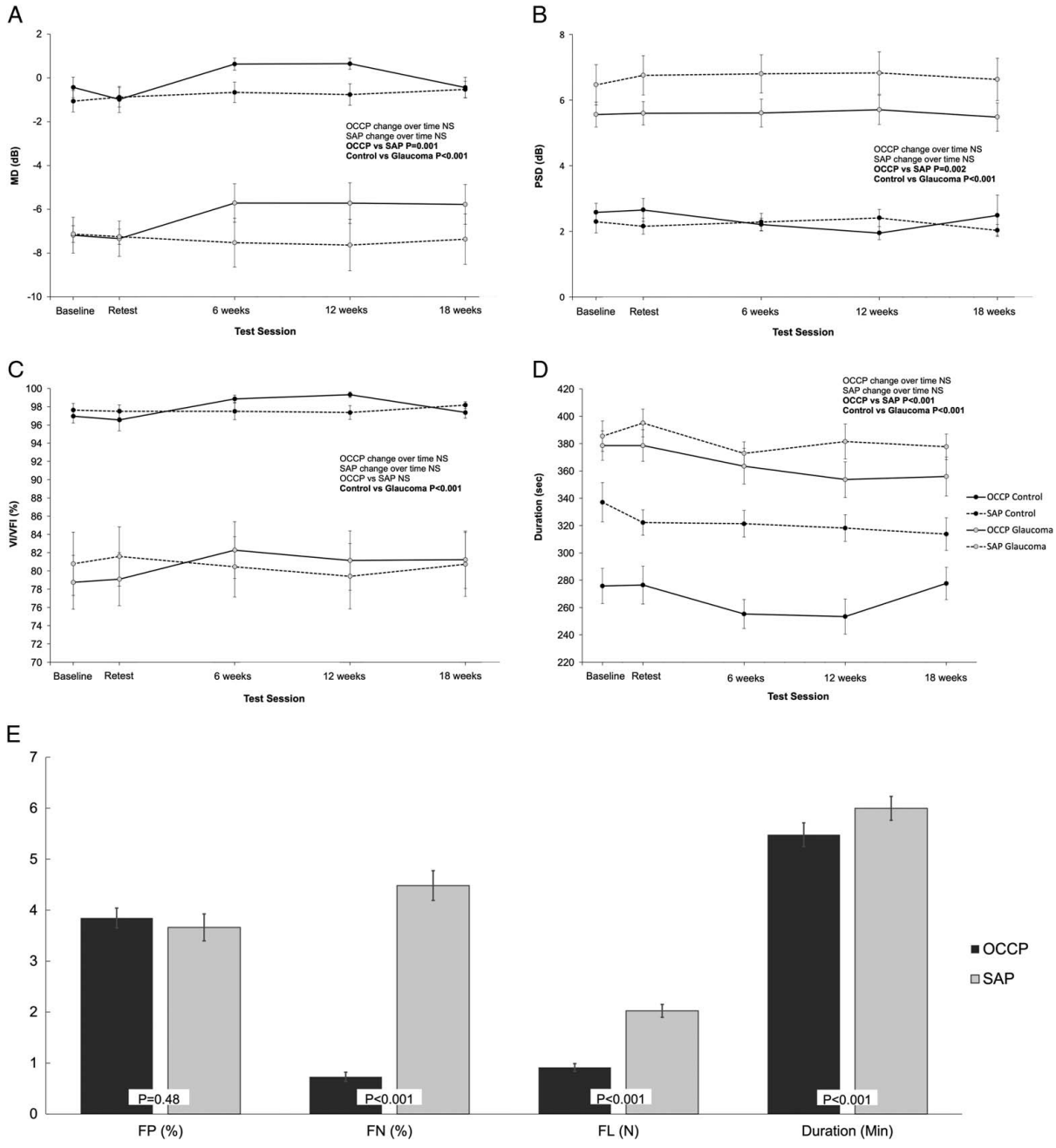

FIGURE 4. Global perimetric indices for online circular contrast perimetry (OCCP) versus standard automated perimetry (SAP). (A–D) Parameters are presented over multiple time points. (A) Mean deviation (MD). (B) Pattern standard deviation (PSD). (C) Visual index/visual field index (VI/VFI). (D) Test duration. OCCP is represented by a solid line, SAP is represented by a dotted line, black-colored circles represent controls, and gray-colored circles represent glaucomatous eyes. (E) Reliability indices and test durations from the combined cohort averaged over all tests. FL indicates fixation loss; FN, false negative; FP, false positive. Error bars represent standard errors.

improved surveillance outcomes, greater patient satisfaction, and lower health care costs.[46] The advantage of OCCP compared to other portable devices is the versatility for different hardware devices and the improved user experience. By reducing the cost and improving the accessibility of perimetry, OCCP facilitates the delivery of affordable home perimetry.

This is the first study evaluating the repeatability of OCCP in a cohort of normal participants and glaucoma subjects. Our findings demonstrate that OCCP has strong immediate test-retest repeatability and good intermediate-term repeatability. While the repeatability of OCCP was not as high as SAP, the ICCs for OCCP ranged from good to excellent, while the ICCs for SAP were all excellent. In addition, the 95% limits of agreement from the Bland-Altman plots for SAP were ~25%−30% lower than for OCCP. However, ICCs for agreement between OCCP and SAP were good at all testing intervals. OCCP's lower

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TABLE 2. Comparison of OCCP and SAP Short-term and Intermediate-term Repeatability

Test	MD (dB)	ICC (95% CI)	Bland-Altman bias (dB)	Bland-Altman 95% LoA (dB)
OCCP repeatability				
Baseline	−4.62 ± 5.28			
Retest (same day as baseline)	−4.93 ± 5.19	0.98 (0.89, 0.99)	−0.31	−2.49, 1.85
6 weeks	−3.31 ± 5.22	0.86 (0.53, 0.98)	1.31	−3.51, 6.14
12 weeks	−3.31 ± 5.41	0.87 (0.55, 0.98)	1.32	−3.46, 6.10
18 weeks	−3.75 ± 5.18	0.88 (0.51, 0.98)	0.87	−4.05, 5.78
SAP repeatability				
Baseline	−5.00 ± 6.29			
Retest (same day as baseline)	−5.06 ± 6.09	0.94 (0.70, 0.99)	−0.07	−4.31, 4.18
6 weeks	−4.91 ± 6.28	0.96 (0.81, 0.99)	0.09	−3.43, 3.61
12 weeks	−5.02 ± 6.64	0.96 (0.82, 0.99)	−0.02	−3.51, 3.46
18 weeks	−4.77 ± 6.45	0.97 (0.84, 0.99)	0.23	−2.96, -3.42
OCCP vs. SAP				
Baseline test	—	0.84 (0.36, 0.97)	0.38	−6.12, 6.87
Retest (same day as baseline)	—	0.85 (0.38, 0.97)	0.13	−6.06, 6.33
6 weeks	—	0.84 (0.46, 0.97)	1.60	−4.16, 7.37
12 weeks	—	0.86 (0.52, 0.98)	1.72	−3.90, 7.33
18 weeks	—	0.87 (0.49, 0.98)	1.02	−4.64, 6.68

MD reported as mean ± SD.
ICC indicates intraclass correlation coefficient; LoA, 95% limits of agreement; MD, mean deviation.

repeatability as compared to SAP also needs to be considered in terms of its utility and other advantages: reduced costs, improved user experience, potential for more frequent at-home testing, and improved portability.[26] OCCP was performed slightly faster than SAP, which is an observable trend in the previous studies.[26,27] Even moderately faster testing time may reduce the length of clinic appointments over multiple visits, improve patient satisfaction, and increase compliance with in-clinic and home testing.[17] There were also no significant differences for the other perimetric parameters including VI/VFI and PSD, consistent with previous studies.[26,27] Overall, OCCP provides robust and clinically useful results and highlights its potential as a glaucoma screening and surveillance tool to complement existing community perimetry, with the potential for home monitoring. Findings are also consistent with the previous studies[8,10,17,37,43] and other perimetry devices.[37]

Both OCCP and SAP demonstrated excellent short-term retest variability. By the nature of the recruitment process on day zero, SAP was performed first and the other 3 tests were performed in a random order; therefore, the baseline-retest sessions for OCCP may have been performed more closely together temporally as compared to the baseline-retest for SAP, potentially introducing further bias. Several factors may explain the lower intermediate retest repeatability of OCCP. Compared with SAP, OCCP introduces several variables associated with personal device-based testing: such as differences in screen size, brightness, color tone, increased flexibility in head positioning, and the need to move the fixation target. There are also various

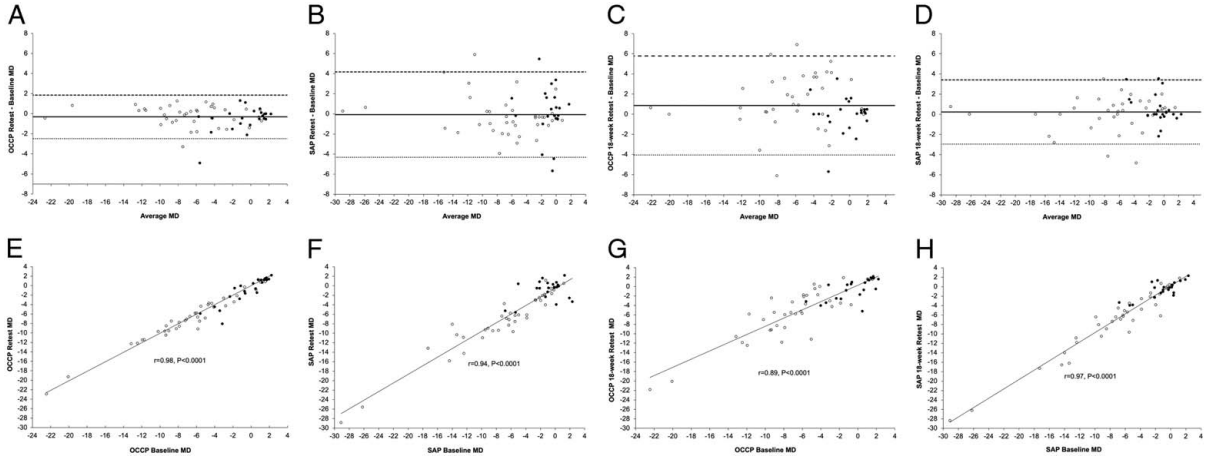

FIGURE 5. Bland-Altman plots (A–D) and linear regression curves (E–H) of same-device repeatability of mean deviation (MD). For Bland-Altman plots, immediate test-retest repeatability is shown for online circular contrast perimetry (OCCP) (A) and standard automated perimetry (SAP) (B), while baseline/18-week repeatability is shown for OCCP (C) and SAP (D). For linear regression curves, immediate test-retest repeatability is shown for OCCP (E) and SAP (F) while baseline/18-week repeatability is shown for OCCP (G) and SAP (H). For Bland-Altman plots, the continuous horizontal line represents the mean differences (bias) between tests, and dashed and dotted horizontal lines represent the 95% limits of agreement (Bias ±1.96SD). Black-colored circles represent controls and white colored circles represent glaucomatous eyes.

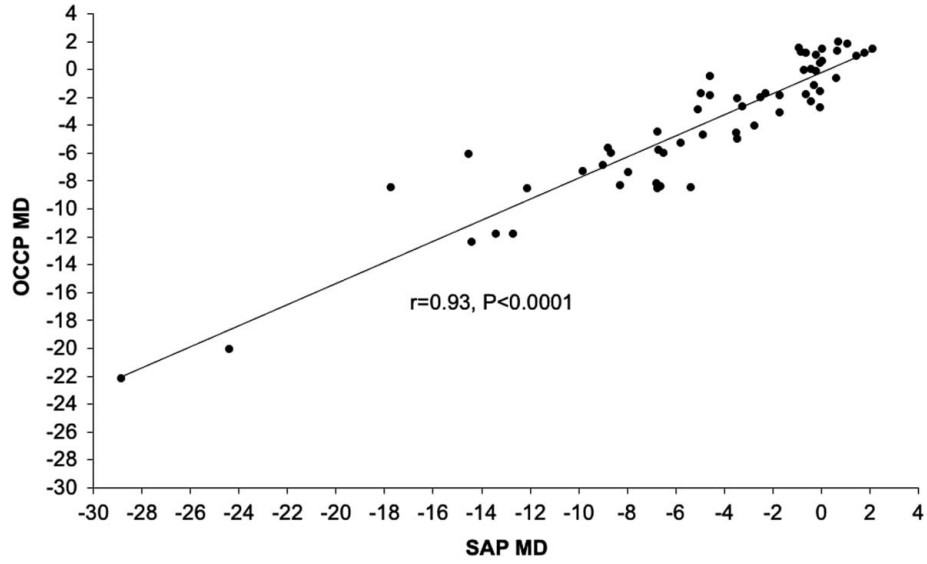

FIGURE 6. Linear regression curve for mean deviation (MD) from the combined cohort averaged over all tests for online circular contrast perimetry (OCCP) versus standard automated perimetry (SAP).

unfamiliar aspects of online perimetry for patients and staff including login processes, new instructions, responding to the cues from the facial monitoring system, and using a mouse instead of the perimetry clicker; these differences can make the test more challenging for the user, potentially increasing performance variability over time. However, there are simple modifications to OCCP's code that can reduce the intermediate-term variability without sacrificing its sensitivity to detect glaucomatous progression. These include expanding pretest instructions, providing an interactive demonstration test version for practice before commencing the real test, adding a space bar option for target detection, optimizing the blind spot localization algorithm, and reducing the flicker speed to increase the test stability despite small changes in retinal adaptation.[35] Ongoing testing, software optimizations, and refinements to OCCP's user interface are expected to further improve its usability, diagnostic accuracy, and repeatability.

Compared to SAP, OCCP had similar FP rates but lower FN and FL responses. By constantly rotating on the same spot, the spinning gold star may be a more interesting (and hence easier) target on which to maintain fixation compared to a fixed LED light. The difference in FL may also be facilitated by the inbuilt verbal cues, feedback sounds, and facial detection software that detects head position. For instance, when a fixation loss is detected, the test tells the user "Look at the star," applying immediate corrective procedures. Our previous user-experience study found that these were valued features and helped participants concentrate[27]; however, some users might find additional sounds and commentary distracting. This may also impact performance given that reliability can be influenced by the quality of perimetric instructions.[47] The limitations of the traditional reliability criteria used in this study are well-recognized[48,49]; however, consistent with our previous studies, our view is that it is important to use orthodox metrics when evaluating new devices.[26,27] In both perimetry-naïve and experienced patients, test reliability parameters can be influenced by the patient's visual function.[47] False negatives correlate strongly with disease severity and may reflect a true inability to perceive stimuli.[48] In this study, participants with very poor visual acuity (LogMAR >0.7) were excluded to mitigate the possible confounding effects of severe visual impairment. Conversely, higher MD scores are associated with high FP responses, though with a small clinical effect.[50–52] FL responses can be influenced by positional changes, inattention, and blind spot mis-mapping; however, FL purportedly has a limited impact on overall test reliability.[53] Increasing the yield of perimetry testing has led to Phu and Kalloniatis[54] exploring a "front-loading approach" by having patients perform multiple tests per clinic visit and then selecting the test with the highest reliability. Increased testing also has the added benefit of reducing the time to detect VF changes,[54] with the main disadvantage being longer appointment times. In a home-monitoring scenario, where patients are less impacted by the logistical challenges of in-person clinic appointments, this may be a possible strategy. However, the lack of trained supervisors and added environmental distractions in the home environment may lead to a greater number of tests with suboptimal reliability scores,[17] and clinicians should consider this trade-off with the benefits of increased frequency of testing at home to detect progression earlier.[50] Appropriate patient counseling and thorough pretest instructions will be critical for home perimetry. Patients also need to be motivated, physically able, and have access to a personal device with internet access.[26] Suitability for home monitoring and establishing desired testing frequency would likely be determined on an individual basis by considering the relevant patient factors and logistics. Research is currently underway evaluating the useability and accuracy of OCCP testing in an unsupervised home environment. Home perimetry has a myriad of potential applications including expanding screening programs, increasing disease monitoring in select patients, reducing clinic visits, and can be applied to other eye diseases.[17] However it also presents new challenges—will patients be willing/able to perform home perimetry, and at what frequency? Also, will funders be willing to pay for more frequent tests?

Retest variability is an established limitation of perimetry that can delay disease diagnosis and compromise the detection of disease progression.[55,56] Even with low variability, patients experiencing rapid disease progression of MD (–2âdB/y) require at least 2 examinations annually to detect such change with 80% power in 2.5 years.[21] In patients with moderate progression of MD (–0.5âdB/y) and moderate test variability, changes are only detected over 6.5 years with biannual assessments.[21] Current guidelines recommend a high frequency of VF assessments in the months following diagnosis given the challenges associated with accurately detecting sensitivity changes with conventional perimetry.[21,31] This study's findings demonstrate that OCCP has acceptable retest variability that is similar to SAP with mildly lower ICCs and wider 95% LoA on the Bland-Altman plots. The additional data from increasing testing frequency will hopefully be used to substantiate disease progression trends and help guide management where appropriate. The accuracy and quality of visual field measurements are critically important. However, the potential implications of an increase in the mean square error of the individual test on progression sensitivity can be mitigated by increasing testing frequency, and this has been found in studies evaluating similar portable perimetry devices.[17,19]

Several factors have been linked to performance variability including patient inattention, fatigue, and small fixational eye movements during testing,[57] those intrinsic to the visual system such as cortical adaptions, and external factors including defect severity,[58,59] environmental changes, technician experience, time of day, season, patient anxiety, and poor concentration.[60–62] For portable perimetry devices, supplying patients with additional equipment supports such as a chin rest or viewing hood has been suggested to promote correct positioning and focus[17]; however, the extra hardware is a barrier to widespread acceptance in the home environment. Instead, OCCP uses a combination of detection of the blind spot and machine learning to monitor the head position during the test. To maximize test accuracy and usability, a 15% deviation in face position monitoring is permitted, although whether fluctuations are inappropriately high and increase test variability can be explored in future studies. However, participants performing OCCP appeared to maintain acceptable levels of concentration. Performance variability also increases with worsening disease severity and SAP is known to be less reliable at detecting sensitivity changes with field defects below 15−19âdB.[63] The loss of retinal ganglion cells leads to areas of spatial undersampling that causes an aliasing effect, in which higher frequencies are measured as lower frequencies, distorting the VF.[64] Spatial undersampling also leads to greater variability with increasing eccentricity, particularly with severe peripheral defects.[64] FDP tends to be less affected by the effects of both increasing disease severity and eccentricity,[62] as the use of achromatic gratings for measuring sampling-limited resolution acuity provides an excellent estimation of magnocellular ganglion cell density, particularly in the peripheral fields.[65] A larger target size employed in OCCP may help to mitigate the effects of spatial undersampling and defect depth.[64,66] Although there is the risk of an oversampling effect masking areas of declining sensitivity, in our previous cohort study, OCCP demonstrated strong diagnostic accuracy in distinguishing normal from glaucomatous eyes across a spectrum of disease severities with increasing eccentricity.[26]

Repeated attempts over time may increase perimetric sensitivity through a learning effect, leading to improvements in test performance[67]. Procedural learning is a prominent cause of retest variability in perimetry testing.[37,61,67–71] Repeat testing has been associated with improvements in perimetry results, test reliability scores, and faster test times.[67] In patients with glaucoma, this may underestimate VF loss and mask disease progression resulting in delayed treatment.[21] The magnitude of the learning effects varies between studies, likely because of the different cohort demographics, perimetry device settings, technician expertise, and testing environments.[67] Historically, the learning effect in SAP tends to be greatest between the first and second tests and more variable in subsequent tests.[70,71] In this study, a trend toward higher MD scores was observed with OCCP possibly indicating a learning effect; however, this was not statistically significant. Addressing the issue of procedural learning has led some investigators to recommend a training session or sample VF test demonstration to prime participants before testing,[67] though whether this eliminates the learning effect remains controversial.

A limitation of this study is the smaller cohort size and recruitment of participants from a single, subspecialty ophthalmology practice. While a larger cohort might have reduced the 95% limits of agreement on Bland-Altman plots, the size was sufficient to generate meaningful ICCs and allow for comparison between the perimetry devices. Participation becomes more onerous when patients are requested to attend clinic more frequently than their clinical care dictates. This cohort was motivated to participate, and this led to the study having a very low attrition rate. Assessing OCCP among other patient groups such as a multisite study or a home-monitoring study would provide useful insights into its uptake, performance, repeatability, and potential applications more broadly. Data for a home-monitoring study are currently being collected. This study was performed in a controlled clinical setting and with trained supervisors who were available to thoroughly monitor patients and brief them about the purpose of the study—this may have introduced bias. Furthermore, the repeatability of OCCP on different device types, including tablets, also requires assessment, as does its implementation across different cultures and health care settings with varying levels of resourcing. Another limitation is the shorter timeframe of the study. Given the implications of disease progression on retest variability, it would be useful to extend the follow-up time in a future study to better characterize OCCP's long-term repeatability in glaucoma subjects of a wide range of severity levels and critically evaluate its ability to reliably detect disease progression. In the future, OCCP should also be compared against the newer HFA systems such as SITA Faster and the other perimetry devices. Finally, although MD provides a robust global estimate of VF, there may be regional variations that are not reflected by the MD statistic; although not assessed in this study, OCCP has previously shown strong point-wise sensitivity regional correlation with SAP.[26]

OCCP demonstrates good retest repeatability and reliability in both the short and intermediate settings and strongly correlates with SAP. Its improved user experience, short testing time, low retest variability, and minimal hardware requirements are added advantages. In summary, OCCP holds promise as a novel perimetry tool to be utilized both in eyecare clinics and at home for disease screening and surveillance, hopefully expanding the provision of glaucoma care and improving patient outcomes.

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