Online Circular Contrast Perimetry: Validity and Repeatability of Home Performance

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Precis: Online Circular Contrast Perimetry (OCCP) offers clinically validated threshold perimetry to patients via a web application from their own devices. This study evaluates the feasibility, repeatability, and reliability of OCCP when performed in unsupervised home environments.

Purpose: To evaluate the feasibility, repeatability, and reliability of online circular contrast perimetry (OCCP) when performed in unsupervised home environments on personal devices.

Patients and Methods: A total of 55 participants (20 control and 35 open angle glaucoma patients) were recruited. Participants underwent baseline visual field testing using OCCP in a clinical setting, followed by weekly unsupervised home tests over 6 weeks on their personal computers. An online survey was completed afterwards. Global perimetric indices and reliability indices were compared between clinic-based and home-based tests and analyzed to assess the repeatability and reliability of OCCP at home. Rasch analysis assessed the psychometric properties of the survey and intergroup variability.

Results: No statistically significant differences were found in mean deviation (MD), pattern standard deviation (PSD), or visual index values between home and clinic tests ($P > 0.05$), and these values did not significantly alter over the 6 weekly at-home tests. OCCP false positive and fixation loss responses were statistically higher at home compared with baseline ($P = 0.002$ and $P = 0.001$). Test-retest intraclass correlation coefficients for OCCP home use compared with in-clinic for MD ranged from 0.90 to 0.93, and for PSD ranged from 0.81 to 0.85. Bland-Altman analysis for MD revealed zero test-retest bias with limits of agreement ranging from ± 5.28 to ± 5.83 dB across the 6 weeks. The survey indicated high user satisfaction; however, Rasch analysis revealed suboptimal precision and targeting.

Conclusions: OCCP retains a similar diagnostic accuracy and repeatability in home environments on personal devices compared with clinic-based environments and has the potential to be utilized as a remote tool for glaucoma screening and surveillance.

Key Words: online perimetry, glaucoma, home perimetry, visual field testing

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Glaucoma is the leading cause of irreversible preventable blindness worldwide.[1,2] Because it is asymptomatic until advanced stages, glaucoma can remain undetected in early or moderate stages, with the proportion of undiagnosed cases reaching 50% in the developed world and 90% in the developing world.[3,4] Early detection and regular surveillance are imperative for preventing blindness and monitoring the rate of disease progression.[4,5]

Visual field (VF) testing with a standard automated perimeter (SAP) is the current clinical standard for diagnosis and monitoring of glaucoma.[6] However, SAP has several disadvantages, including the high costs of perimetry machines, their specific calibration requirements, and the limited availability of trained staff. Therefore, perimetry is often only available in specialty ophthalmology clinics, potentially contributing to the lower rates of glaucoma detection, particularly in low-resource and remote areas.[7–9] In better-resourced health care settings, remote monitoring and telehealth via online applications with at-home testing are attractive due to the increasing demands and growing costs associated with chronic disease management. SAP is further well recognized to be an uncomfortable and anxiety-provoking experience,[10] which may be improved with a user-friendly online perimetry application.[11–14] Virtual reality systems can provide VF testing on a dedicated headset; however, such devices have additional hardware costs, reducing their affordability and accessibility.[15]

Online circular contrast perimetry (OCCP, Eyeonic, Melbourne), has been developed to provide perimetry services on any computer or tablet without additional hardware. OCCP offers patients the option of perimetry at home, via an online application that works on any computer or tablet. Online perimetry via personal devices has many potential advantages, including improved access to perimetry in rural or resource-limited areas, home-based perimetry, significant cost-saving benefits in perimetric hardware, cheaper health care delivery for health care funders, a more enjoyable user experience for patients, reduced travel time, potentially lower costs and environmental impact, and data integration within electronic medical records for improved data-sharing efficiency.[16–18]

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A normative database for central 24-degree and 10-degree OCCP has been established.[19,20] Studies comparing OCCP to SAP have shown favorable results, with similar perimetric outcomes and diagnostic accuracy in distinguishing glaucoma patients from controls, as well as an improved user experience.[21,22] The repeatability and reliability of OCCP have been validated further in a clinic setting.[23] At-home testing is a critical advantage of device-independent perimetry, but this has not been critically evaluated for OCCP.

This study aimed to assess the repeatability and reliability of OCCP when performed at home in unsupervised conditions, assessing its potential utility as a tool for remote monitoring and early detection of glaucoma through at-home use. It builds upon previous validation studies that have demonstrated that OCCP produces sensitivity thresholds comparable to SAP when tested under clinical conditions, as well as a similar test-retest repeatability to SAP.[21,23]

METHODS

Ethics

The study complies with the Declaration of Helsinki. All subjects provided informed written consent before participating. Ethics approval was obtained from the Royal Australian and New Zealand College of Ophthalmology Human Research and Ethics Committee, with local site governance.

Study Population

Participants were recruited consecutively from patients who attended ophthalmology practices across Melbourne, Sydney, and Wellington. The population included normal controls and patients with glaucoma of varying disease severity.

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

The definition of glaucoma was based on the American Academy of Ophthalmology criteria.[24] Control participants had normal IOP, retinal nerve fiber layer (RNFL) thickness, optic nerve head (ONH) appearance, and SAP results, with no other ocular pathologies. Glaucoma subjects were defined as those with characteristic disc features and VF changes. Appropriate hardware was defined as either a laptop or desktop computer, with a webcam and a flat viewing screen.

The exclusion criteria included: ocular pathology other than glaucoma (eg, visually significant cataract defined by Lens Opacities Classification System III greater than Grade 2[25]; non-glaucomatous optic neuropathy, retinal or macular pathology); systemic disease or medication that could affect visual fields; ocular surgery within the previous 3 months; papillary anomalies; ametropia $> \pm 5$ dioptres; large peripapillary atrophy; neurological disorders; media opacities preventing good image scans; unreliable SAP and OCCP tests.

Traditional parameters were used to determine if tests were considered unreliable based on the following: false negatives (FN) $> 33\%$; false positives (FP) $> 15\%$; fixation losses (FL) $> 20\%$; FL were detected using the Heijl-Krakau method.[26] Tests were also evaluated for any artifactual interference, including eyelid or lens holder rim artifacts, improper fixation, fatigue, and inattention.[27] Participants with unreliable SAP results were excluded to establish a baseline comparison for evaluating OCCP in-clinic and at-home reliability. This ensures that the observed reliability of OCCP reflects its inherent accuracy rather than confounding factors. OCT scans with inappropriate centration, segmentation errors, or signal strength lower than 8/10 were excluded.

Assessment of Clinical Parameters

Following recruitment, subjects were clinically assessed by investigators of the study. BCVA was collected, intraocular pressure was measured using a Goldmann applanation tonometer (GAT; Haag-Streit International, Bern, Switzerland), and central corneal thickness (CCT) via a Pachmate hand-held pachymeter (DGH Technology, Exton, PA, USA). Cirrus or Spectralis OCT of the ONH and macula (Carl Zeiss Meditec Inc., Dublin, CA and Heidelberg Engineering, Heidelberg, Germany) was performed. Participants underwent VF testing with SAP using the HFA Swedish Interactive Threshold Algorithm (SITA) standard 24-2 test (Zeiss).

Online Circular Contrast Perimetry

A full description of the OCCP methodology of perimetry has been outlined previously.[19,21,22] The 24-degree protocol evaluates 52 loci spanning 24 degrees of peripheral vision by presenting users with circular flicking targets characterized by concentric alternating dark and light rings, each measuring 3.5 degrees of visual angle with 6 degrees of spatial separation (Figs. 1A, B).[19] These targets share similarities with Pulsar Perimetry (Haag-Streit International) and High Pass Resolution Perimetry (HighTech Vision); however, they maintain consistent contrast with respect to their maximum and minimum luminance peaks and troughs across their spatial extent (Fig. 1A), with slight reduction at the peripheral edges to minimize light scatter and unintended stimulation of ganglion cells.[28–31] In addition, OCCP targets are smaller than those used in Pulsar perimetry (3.5 vs. 5 degrees). The size of the targets increases with increasing eccentricity to maintain a consistent size of viewing angle on a flat screen, and to allow similar normal sensitivity thresholds across different loci. To account for the angular eccentricity introduced by the flat computer screen compared with a Ganzfeld bowl, trigonometry is used to adjust the placement of test loci relative to the fixation target.

Targets consist of concentric sinusoidal contrast rings (Fig. 1A). The bright peaks have the same luminance as the background monitor, while the dark troughs are adjusted to determine the difficulty level of the target. On flicker, these targets alternate with their inverse image (with dark troughs replacing bright peaks, and vice versa). Each target flicker for 3 counterphase cycles each lasting 60 milliseconds, totaling 360 milliseconds. In the JavaScript code, the window request Animation Frame object with a timestamp callback allows for synchronization of target presentations with the display's refresh cycle, improving timing consistency. This minimizes variability to hardware-specific temporal properties, such as pixel response times or display overdrive algorithms. Like conventional FDP (Welch Allyn,

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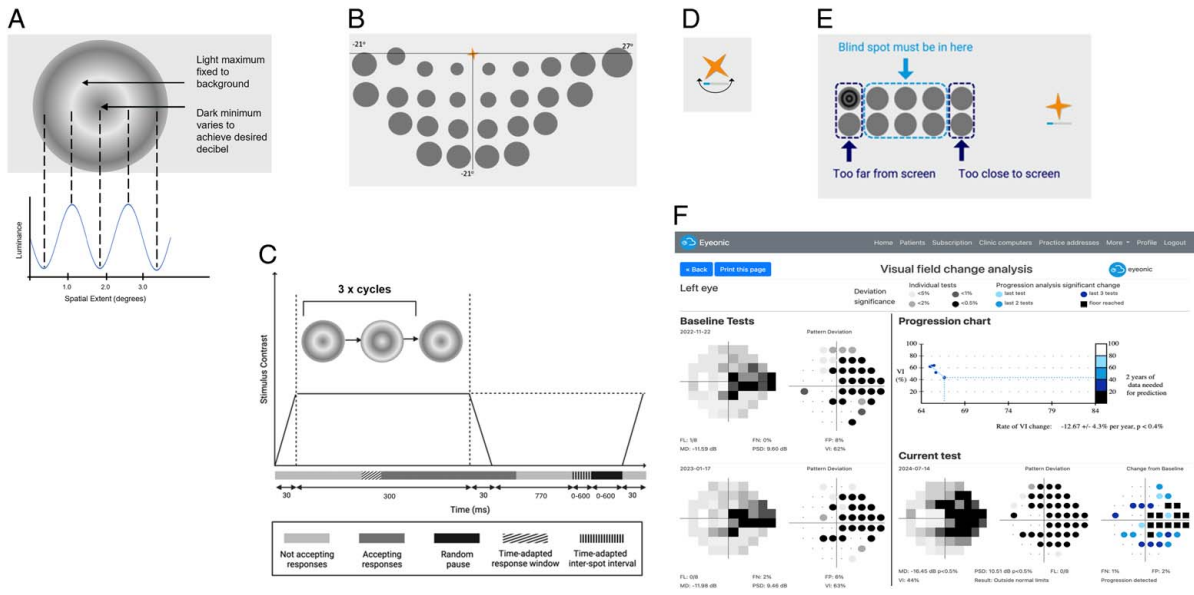

FIGURE 1. Online circular contrast perimetry test settings. A, Flickering test target. B, Map of inferior hemifield 24-degree perimetry loci testing. To test the superior hemifield, the fixation target later moves to the bottom of the screen. The size of test targets projected on the screen has a magnification factor that increases with eccentricity. C, Sequence of target presentation: targets appear for 3 counterphase flicker cycles lasting 360 miliseconds; contrast is graded at the start/end of target presentation. Figure adapted from Meyerov et al.[21,22] D, Fixation target: spinning golden star. E, Blind spot localization optimizes the user's viewing distance. B and E, The dark gray homogenous circles are a diagrammatic representation of where test targets may appear and are not present during the live test. F, Example of printout that the clinician will receive for change analysis. Figure 1 can be viewed in color online at www.glaucomajournal.com.

Skaneateles, N.Y., and Carl Zeiss Meditec, Dublin, CA), targets have sinusoidal contrast with a spatial frequency of 0.55 cycles/degree but have a slower temporal counterphase flickering (at 8.3 Hz compared with 18 Hz for FDT). A slower flickering rate maximizes consistency despite varying illumination levels.[32,33]

Contrast is ramped up and down at the beginning and end of target presentations, respectively (Fig. 1C).[34,35] Unlike FDP, in which light and dark bands vary around a mean of background luminance, for OCCP target dark-band color was varied to achieve the desired contrast while light-band color was fixed to the light gray background, similar to a luminance pedestal flicker for stimulus decrements.[36] This is so that the number of grayscale levels used in the stimulus and background design is minimized to maintain consistency across display parameters with different gamma corrections. The assumption in FDP—that the background is the mean of the light and dark bands—may not hold true on modern screens and tablets without extensive precalibration.

The Web Content Accessibility Guidelines standards allocate a relative luminance for each 256-grayscale level.[37]

The app has been designed to provide consistency despite variations in screen intensity. The background color is set to a light gray tone, and users are instructed to increase their screen brightness to 75% before commencing the test. This corresponds to a relative luminance of 220 cd/m^2; however, absolute luminance will vary among screens. This background was selected so that effects of pupil size, background lighting, and lens yellowing on retinal illumination can be minimized.[38]

By comparing peaks and troughs of targets, contrast can be used to calculate relative contrast via the Michelson formula[39]:

$$\text{Contrast} = (RL_1 - RL_2)/(RL_1 + RL_2)$$

where RL_1 is the light band maximum relative luminance and RL_2 is the dark band minimum. Similar to FDP, contrast was converted to relative decibels:[32]

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

The dynamic range of sample spot intensity ranges from 0 to 38 rdB; this range is comparable to those used in other perimetry methods such as SAP. It is important to note that SAP employs Weber contrast rather than Michelson and prior comparison studies have established that OCCP thresholds are systematically higher by approximately 1.02 log units (95% CI: 0.95–1.08) and require this conversion factor to be applied for direct comparison.[12,21,40]

Participants are asked to fixate on a continuously spinning golden star (4 degrees of visual angle, Fig. 1D) chosen to enhance fixation stability.[19] Previous studies have found that OCCP has comparable or lower fixation loss rates to SAP in a clinic and, home environment, across different monitors, and that participants appraise the target as high in ease of maintaining gaze (Supplemental Table 1, Supplemental Digital Content 1, http://links.lww.com/IJG/B47).[20,22,23,41–44] They are instructed to click their mouse when a target appears in their peripheral vision. False positives are recorded when the click falls outside of the accepted response window. False negatives are determined by a similar method utilized in SAP.[45] Fixation losses are assessed using the Heijl-Krakau method, with small (0.5 degree) stimuli to ensure that they remain within the physiological blind spot.[19,46]

OCCP uses a Bayesian thresholding strategy analogous to modern SITA-type approaches. For each locus, age-matched a priori probability density functions (PDFs) define expected sensitivity and variance, based on preacquired normative data.[19,20] Thresholding proceeds on a 4/2 dB staircase with an iterative maximum a posteriori update after each response, which runs in real-time to assess when testing can stop at each point, based on a SD threshold being reached.[47] Two reversals are required at primary test points, after which only a single reversal is required for termination at each point.

To account for differences in user response time to stimuli, the interval between stimuli presentations was adapted based on previous user responses, to ensure that the test proceeded at a suitable pace for the individual. The interstimulus interval utilized in OCCP ranges from 800 msec to 2 seconds (Fig. 1C). An in-built random delay was introduced between stimuli to prevent rhythmic responses.[48]

Thorough pretest instructions are provided to establish the correct environmental conditions, including ambient noise and lighting, user positioning, correct eyewear, and monocular occlusion. Guidance is provided throughout by preprogrammed verbal instructions recorded in multiple different language options.

Accurate viewing distance is maintained without a brace by 3 mechanisms used in combination. Firstly, the application calculates and advises the user on the appropriate viewing distance by detecting the screen size in pixels of the device used. This ensures that the user maintains a consistent viewing angle throughout the test, and that the targets are placed at the correct position and size to ensure a consistent viewing angle. Secondly, at the beginning of the test, the user's blind spot is mapped out with small (0.5 degree) targets within a 4×10-degree grid (Fig. 1E). If the blind spot is detected too far from fixation, users are instructed to move closer to the screen; on the contrary, if the blind spot is detected too close to fixation, the user is instructed to move backwards so that the correct visual angle may be maintained for consistent testing results. If the blind spot is not located within the initial grid, it is searched for further laterally in case the user is positioned even further back from the monitor screen than anticipated. Thirdly, the computer's webcam also provides continuous monitoring of head position throughout the test with a one-second refresh rate by using machine learning (ML) for facial detection (not recognition). Deviations of head movement of up to 15% are permitted before the test pauses and asks the user to reposition to the starting position. Head position monitoring is independent of the process of fixation loss assessment described above. When used together, the 3 mechanisms maintain head position within an error rate of less than 1%.[49]

The usage of dark flickering targets on a light gray background as previously described provides increased resistance to changes in background lighting.[32] The properties of the test, including target size, spatial frequency, background luminance, and flicker rate have all been carefully chosen to maximize testing consistency despite differences in computer screen output displays, gamma function, and testing environments.[38] These parameters have been chosen based on a critical review of the literature, our initial pilot work, and subsequent refinement based on use in our previous publications.[19,50–52] Furthermore, in acknowledgment of persistent variations among screens, the app undergoes an internal calibration process based on early responses, and, if available, information from prior tests performed, either on that screen, or by that patient on another screen.

OCCP VF Assessment

Recruited participants first performed the OCCP test in each eye twice at the clinic to establish a baseline with a same-day retest, then once per week at home over 6 weeks followed by a feedback survey. Before undergoing perimetric assessment, participants were provided with detailed information about the study and the OCCP test, including their supervision by a trained orthoptist during the baseline test. No physical constraints or specialized equipment was used to support head position. Each eye was tested sequentially, and participants wore their usual near correction during testing, including reading glasses, bifocal, or progressive lenses where applicable. Corrective refraction and near addition used during OCCP were recorded (Table 2).

Within the clinic, participants completed the OCCP test with standardized monitors, including a screen size of 24 inches diagonally (Dell, TX), white temperature at 6500 K, gamma set at 2.2, and resolution of 1920×1080 pixels. This yielded a viewing distance of 50 cm. Environmental standardization included a dark room with lighting solely from the computer monitor and minimal background. All monitors were cleaned before use.[11]

All participants were educated by the trained orthoptist on how to set up and perform the test independently. Because of the ease of self-setup and clear messaging within the application, the time for this was minimal and the uptake relatively quick by the patients, with a shorter setup time than SAP. When the tests were completed at home, environmental and monitor conditions were not standardized, beyond the participants' prior instructions. Participants were sent weekly reminder emails to complete home testing for OCCP, with a link that directly transferred them to the OCCP website. Phone and email support was available from the research team.

Feedback Survey

The survey, based on similar studies evaluating OCCP in an Australian cohort and other home perimetry devices, was designed by the chief investigator to capture the experience of home perimetry.[22,53] It contained 9 questions, regarding home perimetry experience (Table 1). Three additional questions related to the participant's preference for either test, their opinion of remote perimetry, and their opinion about the OCCP test's webcam facial monitoring. An optional textbox for further comments was provided.

Responses were recorded in a Likert scale: "strongly disagree," "disagree," 'neutral," "agree," or "strongly agree," corresponding from 1 to 5. Participants completed the survey anonymously. All data were stored securely on a password-protected database.

Study Outcomes

The primary outcome measured in this study was mean deviation (MD), which has been validated as a global endpoint to assess repeatability.[17,54] Secondary outcome measures were other perimetric parameters, including pattern standard deviation (PSD), visual index (VI), reliability indices, and test duration. OCCP MD, PSD,

TABLE 1. Participant Survey Questions for Home Monitoring Using Online Circular Contrast Perimetry

1	I was able to access the application at home via http://www.eyeonic.com
2	The app was easy to use
3	Logging in to the app was straightforward
4	It was easy to follow the link to the app via the email reminders
5	I understood how to set up my home environment for visual field testing
6	I was able to set up my home environment for visual field testing
7	I understood the instructions to perform the test
8	I was able to follow the test instructions when performing the test
9	A. I was able to commence the test
	B. If you were unable to commence the test please describe why:
10	A. I was able to complete the test
	B. Did you have any other issues, technical or otherwise, when performing the home testing? Please explain here
S1	How much do you value being able to do an online visual field test remotely (eg, at home)?
S2	Did you prefer the conventional (machine-based) or the online (computer-based) visual field test?
S3	I am not bothered by the webcam monitoring my face during the online test. (I understand the video is not saved and no facial recognition occurs)
	Do you have any additional comments?

and VI values were calculated using previously defined formulae and from an established normative dataset, which corrected for age-related changes in sensitivity.[19,55,56] VI is based on a weighted mean system similar to the visual field index (VFI). Reliability criteria (FP, FN, and FL) and participant attitudes toward OCCP home testing were recorded.

Statistical Analysis

Data were analyzed using R (Core Team 2023. A Language and Environment for Statistical Computing, Vienna, Austria) 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-Wilk statistic. Mixed linear regression models were used to determine the significant predictors of global indices.[57]

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. Intraclass correlation coefficients (ICCs) were calculated to assess the reliability of repeated tests. Collinearity was quantified using simple linear regression with Pearson's correlation and 95% CIs. Bland-Altman plots were generated to evaluate the 95% limits of agreement (LoA) for MD values obtained at baseline compared against subsequent retests.

Strength of associations among pointwise sensitivity at each timepoint was evaluated using Deming regression analyses with Deming's regression intercept and coefficient with 95% CIs.

Sample size was calculated based on the 95% CI of test: retest agreement of 0.51–0.98.[23] With an alpha of 0.05 and type 2 error rate 0.1, using the lower limit of the CI range gave a sample size of 36. Given the uncertainty of test: retest variability on different screens as well as potential test reliability issues, this was increased to 55.

Rasch analysis was used to assess the psychometric properties of the administered survey using the Andrich rating scale model with Winsteps software (Chicago, IL).[58–60] Differential item functioning was used to assess differences in responses based on gender, clinical group (controls vs. glaucoma), and age stratification: younger (age < 45 y) and older (age ≥ 45 y).

RESULTS

Fifty-five participants (110 eyes) were recruited into the study. No participants were excluded solely due to hardware access, and 5 excluded due to unreliable baseline SAP. Several participants had some difficulty with completing the online tests at home (Supplemental Table 2, Supplemental Digital Content 2, http://links.lww.com/IJG/B48), and 3 required remote aid from the research team with regards to home setup and test performance.

Table 2 presents the demographic and clinical data from the recruited participants.

Figures 2 and 3 present the global perimetric and reliability indices for OCCP, respectively. No statistically significant changes over time were observed within either control or glaucoma groups for MD, PSD, and VI ($P > 0.05$ for all global indices). Control participants performed perimetry faster than glaucoma patients and further demonstrated significantly higher MD and VI and lower PSD compared with glaucoma participants (Fig. 2, $P < 0.001$). There was no statistically significant difference in sensitivity values between the first and second eye in sequential testing ($P = 0.39$).

OCCP FP responses, given as mean ± SD, were statistically higher at home compared with baseline (2.17 ± 2.85 vs. 3.02 ± 4.70, $P = 0.002$, Fig. 3), as were FL responses (0.68 ± 0.88 vs. 0.93 ± 1.13, $P = 0.001$); however, FN rates were not (0.52 ± 1.03 vs. 0.59 ± 1.22, $P = 0.40$) as well as time ($3{:}58 \pm 1{:}25$ vs. $4{:}07 \pm 1{:}23$, $P = 0.18$). This analysis is true for both glaucoma and controls when analyzed separately, except FL responses for glaucoma participants were not significantly different (0.79 ± 0.79 vs. 1.01 ± 0.85, $P = 0.14$).

Table 3 presents the intratest change in OCCP global indices over time with corresponding ICCs and Pearson's correlation. Global indices, reliability indices, and test duration did not significantly differ for either glaucoma or normal cohorts when performed in clinic or at home, with no significant change over time during the home monitoring period. Test-retest intraclass correlation coefficients (ICCs) were defined as poor (< 0.5), moderate (0.5–0.75), good (0.75–0.9), or excellent (> 0.90).[61] ICCs for OCCP home use compared with in-clinic for MD ranged from 0.90 to 0.93, and for PSD ranged from 0.81 to 0.85 (all good or excellent). Pearson's values were defined as strong (> 0.75), moderate (0.45–0.75), weak (0.25–0.45), or very weak (< 0.25).[62] Pearson's correlation coefficients for OCCP

TABLE 2. Baseline Characteristics of Individuals Monitored at Home

	Control	Glaucoma	*P*
Number	20	35	0.058
Gender (n, % female)	11 (55)	17 (48)	0.742
Age (mean ± SD)	61.7 ± 11.4	64.6 ± 11.7	0.376
Disease severity (n, %)			
Mild	—	15 (42.9)	—
Moderate	—	12 (34.3)	—
Severe	—	8 (22.8)	—
Abnormal ONH (% eyes)	0	100	< 0.0001
LogMAR visual Acuity	−0.001 ± 0.213	0.121 ± 0.218	0.052
Corrected IOP (mm Hg)	14.9 ± 3.9	14.7 ± 3.7	0.719
CCT (μm)	550.7 ± 35.4	556.0 ± 33.3	0.493
Spherical equivalent (D)	−1.4 ± 2.8	−1.7 ± 2.6	0.505
Refractive correction (sphere, Cyl, D)	−0.9 ± 3.0, −0.8 ± 0.8	−1.6 ± 2.9, −0.5 ± 0.7	0.749
Near add (D)	1.2 ± 1.1	1.2 ± 1.0	0.841
OCT RNFL			
MT (μm)	85.6 ± 10.6	70.8 ± 12.2	< 0.0001
ST (μm)	103.3 ± 17.3	82.7 ± 20.1	< 0.0001
IT (μm)	104.7 ± 18.1	78.5 ± 21.7	< 0.0001
VCDR	0.55 ± 0.18	0.69 ± 0.17	0.0001
OCT GCC			
MT (μm)	78.0 ± 7.6	65.7 ± 14.9	< 0.0001
ST (μm)	79.6 ± 7.9	69.0 ± 19.3	0.0006
IT (μm)	75.4 ± 9.5	61.4 ± 18.4	< 0.0001
SAP			
MD	−0.43 ± 1.40	−7.78 ± 6.50	< 0.0001
PSD	1.71 ± 0.47	7.17 ± 3.79	< 0.0001
VFI	98.8. ± 1.20	79.5 ± 18.8	0.0098
OCCP (baseline)			
MD	0.58 ± 1.40	−5.41 ± 5.72	< 0.0001
PSD	1.61 ± 0.82	5.56 ± 3.22	< 0.0001
VI	99.1. ± 1.6	85.1 ± 15.0	< 0.0001
No. weekly at-home tests completed			
6	17	27	—
5	2	5	—
4	0	0	—
3	1	1	—
2	0	2	—
Total	20	35	0.962

home use compared with in-clinic for MD ranged from 0.87 to 0.93 and for PSD ranged from 0.82 to 0.96 (all strong).

Figure 4 presents the Bland-Altman plots for test-retest data for OCCP MD, with each week compared with the baseline average. Compared with the baseline tests all, weeks demonstrated a mean bias of zero and LoA as ± 5.28, ± 5.83, ± 5.57, ± 5.46, ± 5.78, and ± 5.55 for weeks 1–6, respectively.

Figure 5 displays linear regression correlation curves for baseline versus weekly home retest of OCCP MD. Correlation coefficient values were: 0.93 (95% CI: 0.90–0.95), 0.88 (95% CI: 0.82–0.92), 0.87 (95% CI: 0.81–0.92), 0.89 (95% CI: 0.83–0.92), 0.88 (95% CI: 0.83–0.92), and 0.87 (95% CI: 0.81–0.92) for weeks 1–6, respectively.

Figure 6 illustrates the pointwise agreement between OCCP baseline clinic testing averages and weekly at-home testing. Each of the 52 loci was analyzed individually using Deming regression to calculate slope values with ± 95% confidence intervals, which provides a direct assessment of the reproducibility and agreement of individual sensitivity values. The ideal Demings coefficient is 1, which indicates a 1:1 correspondence between baseline and home tests. A 3% of loci (highlighted with red text) did not fall within the 95% CI of the ideal Demings Coefficient, which is within the expected statistical variance.[63]

Rasch Analysis

Eleven individuals did not complete the survey; these participants were excluded from Rasch analysis of survey data, but their clinical and perimetry data were included. The survey results displayed a reasonable fit to the Rasch model, with no evidence of multidimensionality or disordered thresholds. However, precision was suboptimal (person separation index 1.44 and person reliability 0.67), and item misfitting was observed for item 9. "I was able to

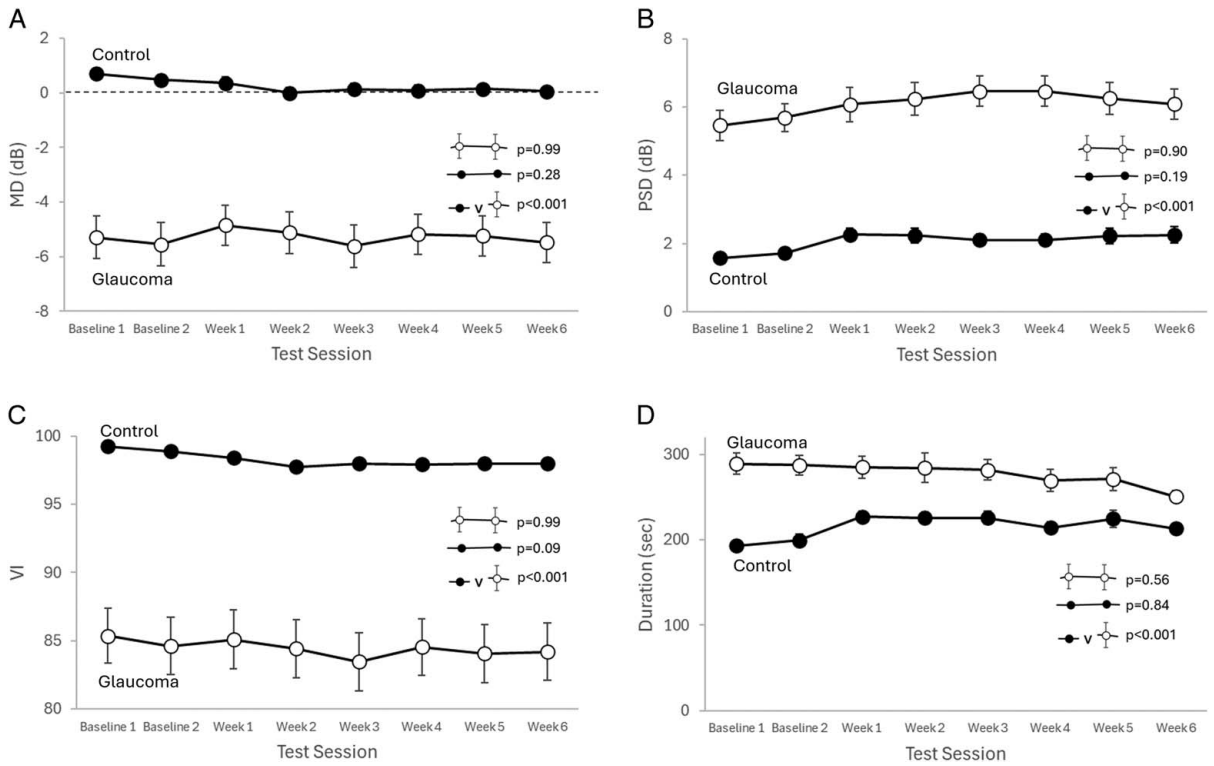

FIGURE 2. Global perimetric indices for online circular contrast perimetry (OCCP) presented over multiple time points for glaucoma versus control. A, Mean deviation (MD). B, Pattern standard deviation (PSD). C, Visual index (VI). D, Test duration. Black-colored circles represent controls, white-colored circles represent glaucomatous eyes. Error bars are given as standard error means (some are too narrow to be visualized for controls).

commence the test." Upon removal of question 9 and persons with extreme responses (ie, those who responded 5 on the Likert scale for all items, n = 7), person separation and person reliability indices did not improve, and so these were kept in the analysis. Targeting was suboptimal (3.21, ideal -1 to 1), with the high score indicating that the cohort was overall untroubled by the challenges assessed in the questionnaire. This suggests overall ease of use with OCCP. No differential item functioning was detected for clinical group, gender, or age.

Participants' attitudes and experience with OCCP home monitoring are outlined in Figure 7. Participants overall found it easy to set up, commence, and complete the application at home. Item 4, the ability to follow the link provided by emails, was the lowest scoring item. However, a high rate of participants (>85%) reported they were always able to complete their perimetry over the 6-week timeframe. Overall, 86% of participants greatly valued the ability to perform visual field testing at home (Fig. 8B) and 70% of participants preferred OCCP over conventional SAP, whereas only 2% preferred conventional SAP (Fig. 8C).

Participants were also able to provide qualitative feedback about challenges when performing the test

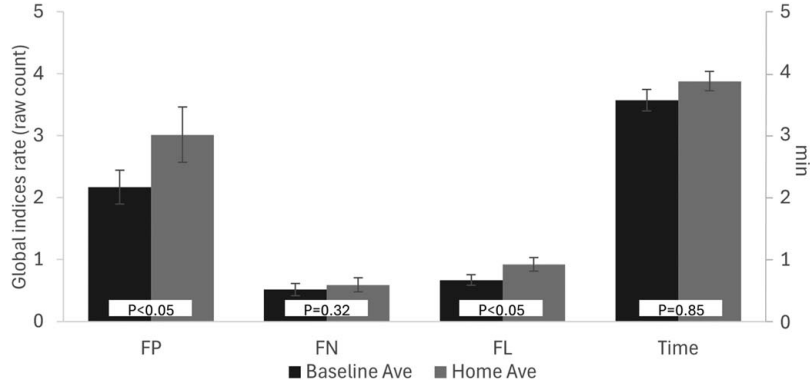

FIGURE 3. Baseline average versus 6-week home average of reliability indices and test durations from the combined cohort. FP: false positive, FN: false negative, FL: fixation loss. Bars provide mean values, and error bars represent standard error mean.

TABLE 3. OCCP Repeatability: At Home Testing

Test	Baseline 1	Baseline 2	Home 1	Home 2	Home 3	Home 4	Home 5	Home 6	*P*
Glaucoma eyes									
MD (dB)	−5.29 ± 5.71	−5.55 ± 5.87	−4.85 ± 5.49	−5.12 ± 5.65	−5.61 ± 5.72	−5.18 ± 5.36	−5.24 ± 5.49	−5.48 ± 5.43	0.998
PSD (dB)	5.46 ± 3.27	5.69 ± 3.05	6.08 ± 3.72	6.23 ± 3.59	6.46 ± 3.32	6.46 ± 3.32	6.25 ± 3.41	6.09 ± 3.27	0.896
VI (%)	85.37 ± 14.83	84.62 ± 15.69	85.09 ± 15.97	84.42 ± 15.98	83.47 ± 15.88	84.54 ± 15.42	84.06 ± 15.71	84.20 ± 15.52	0.999
FP	2.73 ± 2.64	2.48 ± 3.58	3.47 ± 3.44	3.36 ± 3.91	4.14 ± 4.50	3.18 ± 4.02	3.90 ± 5.14	2.68 ± 3.04	0.684
FN	0.85 ± 1.00	0.88 ± 1.74	0.95 ± 1.97	0.78 ± 1.18	0.98 ± 1.90	0.74 ± 1.01	1.04 ± 1.71	0.80 ± 1.17	0.971
FL	0.82 ± 0.86	8.18 ± 26.50	11.87 ± 31.14	4.44 ± 18.76	4.88 ± 19.44	8.92 ± 27.16	5.10 ± 19.81	5.85 ± 21.61	0.610
BS not detected rate (%)	5.5	5.5	10.1	3.6	3.6	7.3	3.6	3.6	0.230
Test time (min:sec)	4:49 ± 1:33	4:48 ± 1:27	4:45 ± 1:35	4:44 ± 2:09	4:42 ± 1:29	4:30 ± 1:33	4:31 ± 1:38	4:11 ± 0:53	0.556
Control eyes									
MD (dB)	0.70 ± 1.22	0.49 ± 1.71	0.36 ± 1.41	0.00 ± 1.65	0.13 ± 1.51	0.10 ± 1.37	0.15 ± 1.37	0.06 ± 1.64	0.280
PSD (dB)	1.58 ± 0.92	1.72 ± 0.88	2.26 ± 1.36	2.24 ± 1.64	2.11 ± 1.25	2.11 ± 1.25	2.22 ± 1.65	2.25 ± 1.74	0.194
VI (%)	99.24 ± 1.36	98.88 ± 1.99	98.42 ± 1.95	97.75 ± 2.95	97.98 ± 3.07	97.92 ± 2.81	98.00 ± 2.79	97.98 ± 3.00	0.086
FP	1.69 ± 2.23	1.86 ± 2.96	2.24 ± 2.41	2.36 ± 2.94	4.13 ± 9.21	1.75 ± 3.14	2.42 ± 5.58	2.54 ± 4.35	0.127
FN	0.24 ± 0.47	0.20 ± 0.45	0.18 ± 0.61	0.33 ± 0.61	0.42 ± 0.83	0.38 ± 0.74	0.32 ± 0.70	0.27 ± 0.71	0.311
FL	0.58 ± 0.91	0.57 ± 0.85	0.76 ± 1.30	0.76 ± 1.04	0.98 ± 1.33	0.92 ± 1.16	0.94 ± 1.12	0.74 ± 1.22	0.931
BS not detected rate (%)	7.27	14.55	18.18	18.18	18.18	10.91	18.18	18.18	0.535
Test time (min:sec)	3:13 ± 0:44	3:19 ± 0:52	3:47 ± 0:51	3:45 ± 0:52	3:46 ± 0:59	3:34 ± 0:48	3:45 ± 1:13	3:33 ± 0:46	0.840
Correlations*									
MD									
Intraclass correlation	—	0.93**	0.90	0.92	0.93	0.93	0.93	0.91	
Pearson correlation	—	0.98**	0.93	0.88	0.87	0.89	0.88	0.87	
PSD									
Intraclass correlation	—	0.95**	0.83	0.81	0.85	0.85	0.83	0.81	
Pearson correlation	—	0.95**	0.85	0.83	0.86	0.86	0.84	0.82	

*Intraclass and Pearson correlations were calculated for the whole cohort.

**Baseline 2 was compared with Baseline 1 visit. For the rest (home 1 to home 6 visits) correlations were compared with an average of baseline 1 and 2 data.

95% limits of agreement are indicated by value ± 1.96SD, LoA; BS, blind spot; dB, decibels; FL, fixation loss rate; FN, false negative rate; FP, false positive rate; ICC, intraclass correlation coefficient; MD, mean deviation; PSD, Pattern Standard Deviation; VI, visual index.

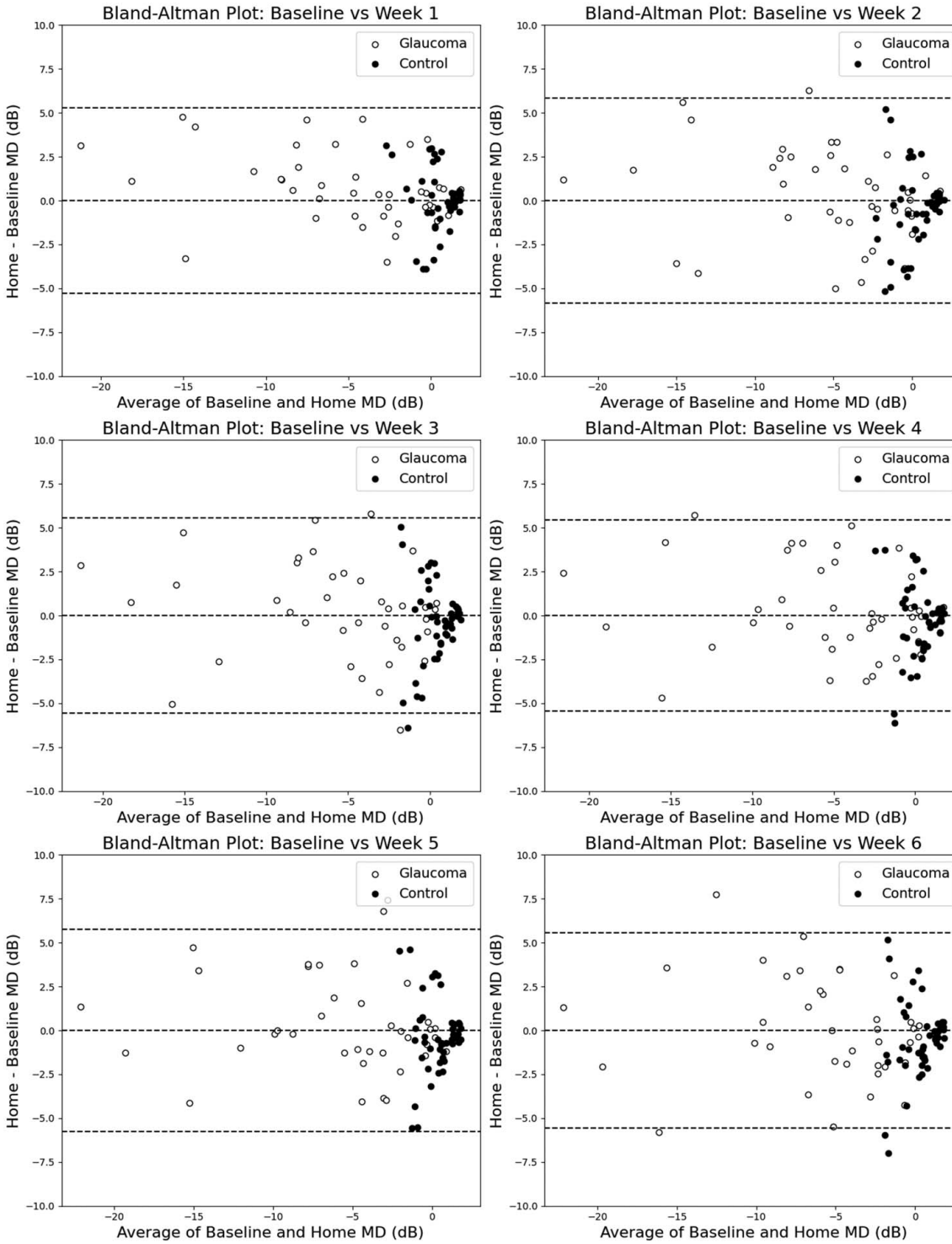

FIGURE 4. Bland-Altman plots displaying OCCP repeatability of mean deviation (MD) in home environment compared with baseline. Each graph displays a weekly test compared with the baseline average. For Bland-Altman plots, the continuous horizontal line represents the mean differences (bias) between tests, dashed and dotted horizontal lines represent the 95% limits of agreement (Bias ± 1.96SD). Black-colored circles represent controls, white-colored circles represent glaucomatous eyes.

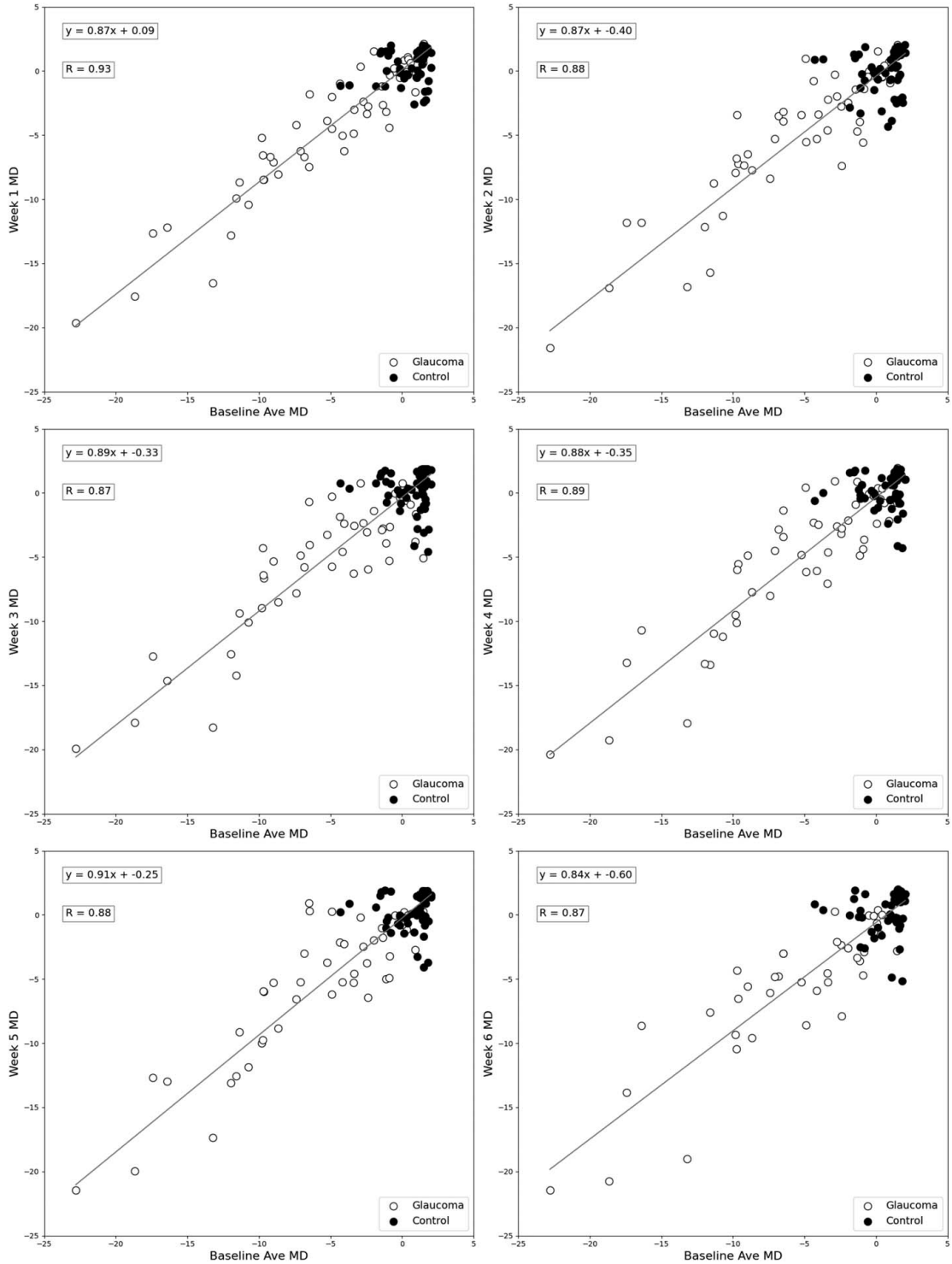

FIGURE 5. Linear regression of OCCP mean deviation (MD) in home environment versus baseline. Black-colored circles represent controls, white-colored circles represent glaucomatous eyes. Linear regression equations and R values are provided.

(Supplemental Table 2, Supplemental Digital Content 2, http://links.lww.com/IJG/B48). Some mentioned difficulties in commencing the test and included internet connectivity and email follow-up issues. Some participants described problems with concentrating on the fixation target or had some difficulties in setting up the correct home environment and distance from the screen, and felt the pretest instructions could be clearer.

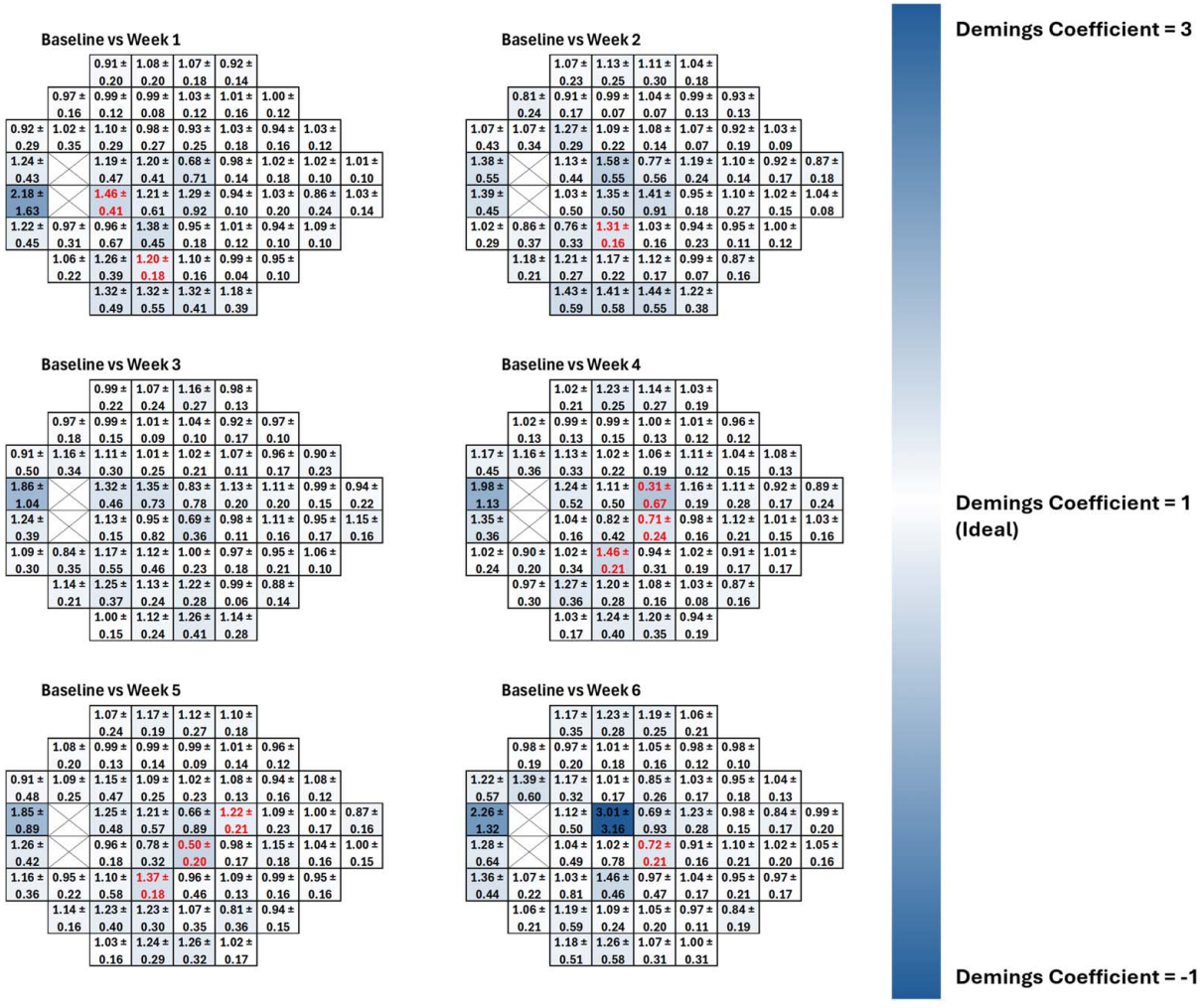

FIGURE 6. Loci maps displaying Demings regression slope values ± 95% CI for OCCP baseline average versus weekly at-home testing for each point. Blue-white background color grading scale is provided to allow visualization of slope variance around the ideal Demings Coefficient of 1, with points of outside of the 95% CI highlighted in red text. The slopes and confidence intervals provide a direct measure of test-retest reproducibility at each locus, accounting for measurement variability in both datasets. Figure 6 can be viewed in color online at www.glaucomajournal.com.

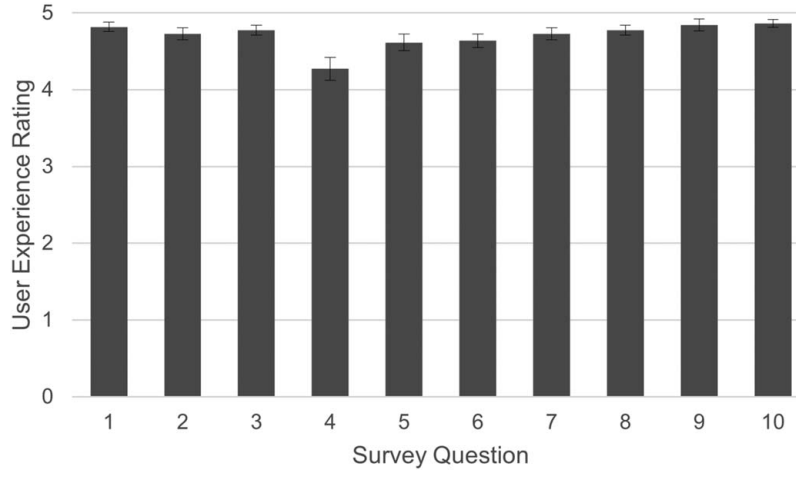

FIGURE 7. User experience ratings of Online Circular Contrast Perimetry (OCCP) when completing at home from survey questions 1–10. Boxes represent mean rating score, and whisker bars represent standard error.

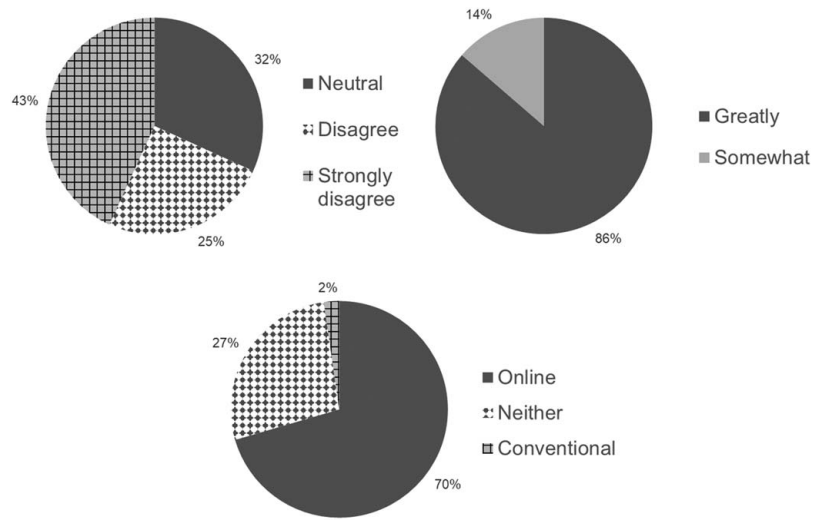

FIGURE 8. Survey Response questions: (A) "I am bothered by the webcam monitoring my face during the online test. Response options: Strongly agree, agree, neutral, disagree, strongly disagree." (B) "How much do you value being able to do an online visual field test remotely (eg, at home)? Response options: Greatly, somewhat, neutral, none at all." (C) "Did you prefer the conventional (machine-based) or the online (computer-based) visual field test? Response options: Online, conventional, neither."

DISCUSSION

This study builds on prior validation of OCCP against SAP, which demonstrated comparable diagnostic performance and repeatability in-clinic.[21,23] While direct comparisons with SAP in the clinic are critical and have been previously addressed, this study focuses on evaluating the feasibility, repeatability, and reliability of OCCP as an unsupervised at-home tool for monitoring visual fields in both glaucoma patients and normal controls. While areas for improvement have been identified in terms of patient messaging regarding email communications and pretest instructions, these findings demonstrate that OCCP, when performed in a home setting, is repeatable and reliable, similar to that previously established for OCCP in clinic-based environments.[23] By extension, this suggest that at-home, unsupervised OCCP retains diagnostic accuracy and clinically relevant perimetric capabilities comparable to clinic-based OCCP and the reference standard of SAP.[21,23]

Figures 2, 4, and 5 and Table 3 demonstrate that OCCP performs consistently across the global perimetric indices MD, PSD, and VI throughout the 6-week study timeframe with no significant differences when performed at home compared with baseline clinic tests, or change over the 6 weekly at-home tests. Figure 6 further reveals consistency across an event-based progression analysis in addition to trend-based, as loci maps align closely with the ideal Demings coefficient of 1. Only 3% of all loci over 6 weeks were significantly deviating from this; however, this falls within the expected deviation for a 95% CI range.

The ICCs for MD and PSD remained within the good to excellent range (0.81–0.93), and Pearson correlation coefficients between baseline clinic tests and subsequent at-home tests were strong, ranging from 0.87 to 0.93. The Bland-Altman Plots (Fig. 4) demonstrate a mean bias of approximately zero with 95% limits of agreement (LoA) ranged between ± 5.28 and ± 5.83 dB across the 6 weeks, which is consistent with the test-retest variability for OCCP in clinic.[23]

There was a significant difference in test duration between the 2 groups, with normal controls completing the OCCP test faster than glaucoma patients, consistent with conventional machine-based perimetry. The overall test duration remained lower than average SAP times, which is consistent with previous OCCP data.[21,22] The average test duration for home testing ($4:07 \pm 1:23$) was comparable to baseline clinic testing ($3:58 \pm 1:25$), with no significant difference ($P = 0.18$), demonstrating the adaptability of the OCCP timing algorithm in a home environment. The faster testing times potentially add to the utility of OCCP for home monitoring, by reducing the risk of patient disengagement and fatigue.

False positive rates were higher during home testing compared with baseline assessments performed in the clinic. Higher FP rates may be attributed to participants becoming less vigilant in unsupervised settings, or responding to other external stimuli, including ambient lighting, noises, and other environmental cues. In addition, there was a significant increase in the rates of FL during home testing. OCCP has in-built functions when FL occurs, including verbal cues, feedback sounds, and facial detection software that detects the user's head position. Our previous user experience study found that these were valued features and helped participants concentrate; however, other users found these distracting.[22] The quality of perimetric instruction is therefore important in influencing the reliability of the application.[64] Currently, gaze tracking functionality is under active development to enhance position monitoring for OCCP home use.

Despite the significant increase in FP and FL, this did not appear to affect the overall reliability of the tests, as evidenced by the stability of individual loci analysis and the global perimetric indices of MD, PSD, and VI. FN rates were not significantly higher in a home environment, which suggests that the contrast stimuli and design of OCCP are sufficient for reducing false negative responses across different settings. Given that false negative responses are more strongly correlated with visual field damage rather than poor patient vigilance, it is particularly important to maintain stable FN rates when monitoring glaucoma.[45] Recently the importance of traditional reliability criteria used has been questioned[65]; however, consistent with our previous studies, our view is that it is important to use orthodox metrics when evaluating new

devices.[21–23] It is important to note that a potential reduction in reliability during unsupervised testing can be counterbalanced by opportunities for more frequent testing.[17]

OCCP's ability to produce consistent results across multiple environments suggests that it can help overcome the barriers of frequent clinic visits, making it easier for patients to adhere to recommended monitoring schedules. Glaucoma progression can be challenging to detect and often takes several clinic visits over months. For instance, detecting 1 dB advancement annually with a single test can take up to 6 years. Glaucoma deterioration could be identified within 2 years if the patient has 3 tests annually.[66] According to current recommendations, patients should undergo perimetry 6 times in the first 2 years following diagnosis to establish a baseline, followed by 6-monthly or yearly reviews.[6,67] A front-loading approach has also been suggested to increase the yield of perimetry testing by having patients perform multiple tests and selecting the test with the highest reliability.[68] However, due to financial limitations, staffing, and equipment constraints, most health care systems—including those in relatively developed economies—are unable to provide this level of care for all glaucoma patients. Less than 75% of glaucoma patients in nations like the United States have their visual fields assessed every year.[69]

Frequent visual field tests conducted at home may identify glaucomatous progression earlier than conventional testing. Anderson and colleagues conducted home perimetry on 43 participants who had glaucoma, ocular hypertension, or were glaucoma suspects. While the sensitivity of detecting −2 dB MD loss every year is 80%, after 2.5 years of visual field testing performed every 6 months in the clinic, Anderson et al[70] found that a similar 80% sensitivity could be achieved with weekly home field test only after 0.9 years despite a 63% compliance rate. To date all home perimetry devices have involved special portable hardware given to the participant, presenting a significant barrier to access. In comparison, OCCP has been designed for and successfully used on the participants' devices, minimizing the cost and maximizing the accessibility of home perimetry. Furthermore, the majority of glaucoma participants in this study were classified as mild or moderate according to Hoddap-Parish-Anderson criteria, which match the cohort clinicians are most interested in detecting progression.[71] Given the high repeatability of home testing in this cohort along with the potential for more frequent testing, OCCP holds promise as a glaucoma surveillance tool.

A crucial aspect of at-home perimetry is user compliance and the feasibility of performing tests without professional supervision. In this study, most participants were able to complete all 6 tests with minimal difficulty and the overall high satisfaction levels across all survey items indicate that participants found OCCP to be accessible and easy to use. The survey reported rate of completion of all OCCP testing was high ($>85\%$); however, the true rate of completion was lower (80%), which may be due to the fact that not all participants completed the exit survey, and those that did were more likely to have completed all 6 home OCCP tests. The participant survey further indicated that 86% of users greatly valued the convenience of home testing, with 70% expressing a preference for OCCP and only 2% preferring conventional SAP. These findings suggest that OCCP not only offers a viable alternative to in-clinic testing but also improves the patient experience, which is consistent with previous studies.[22] The high appreciation of home testing reflects the growing demand for telehealth solutions, especially in the post-COVID-19 pandemic era and among patients who may have difficulty accessing frequent in-person care.[72]

Questionnaire precision and targeting were suboptimal in the Rasch analysis, suggesting that the survey questions were mismatched against the level of difficulty encountered when using OCCP, with participants finding OCCP easy to use and did not face the challenges raised in the questionnaire. No differential item functioning detected across clinical group, gender, or age indicates that these variables did not add extra difficulties in performing OCCP, which is consistent with our previous studies.[22] Future surveys will need to include more refined questions or scales that differentiate more subtle user difficulties, particularly in more complex home environments.

The qualitative feedback highlights several areas in which users experienced usability issues. An example of this is email reminders with the link to perform the visual field test embedded, as one user stated that, "The links came very infrequently. Weeks went by and there was no link." This experience was corroborated by 4 other feedback providers, which underscores the importance of ensuring reliable communication systems with patients, whether this be via email, other messaging systems, or phone call. Other participants gave feedback regarding the pretest instructions, including, "The instructions on obscuring one eye and using glasses should be 2 separate items and avoid using footnotes." As well as "Not sure if I was supposed to wear glasses." Clearer setup instructions will be included in future updates of the application. Evaluations comparing various Bayesian algorithms (eg, Zippy Estimation by Sequential Testing, ZEST vs. SITA-like algorithms) would be of interest to determine the optimal parameters for home perimetry. Such refinements will hopefully lead to greater test reliability and consistency over time, diagnostic sensitivity, and usability.

This study has limitations. The study population was restricted to individuals fluent in English, who had access to supportive technology and who harbored a reasonable level of technological literacy. This may limit the generalizability of the findings to more diverse populations, including those from non-English-speaking backgrounds or those with lower levels of technological proficiency. However, OCCP supports over 20 languages and the application displays the interface, including audio and written instructions in the user's local language based on region. OCCP has been evaluated outside Australia; for example, a longitudinal clinic cohort in Vietnam reported perimetric agreement with SAP and usability metrics comparable to Australian cohorts.[43] Further studies involving a more diverse participant pool are needed to explore the broader applicability of OCCP in resource-limited settings, exploring strategies that can encourage perimetry despite lower technological literacy. Currently, multisite collaborations in Asia and Africa are in progress. With increasing data collected, over time the age-sensitive normative database can be expanded for more accurate 2%, 1%, and 0.5% probability thresholds.

A conservative approach to BCVA (≤ 0.7) was chosen, as it was thought that participants with worse visual acuity may have difficulty seeing the fixation or test targets or using computer equipment reliably. Such patients were excluded due to reduced visual acuity from advanced or end-stage glaucoma affecting visual acuity, maculopathies, amblyopia, and non-glaucomatous optic neuropathies. It is planned

to develop a larger fixation target for low-acuity patients, and to test OCCP in those with worse vision and comorbid ocular conditions. This would include cases of end-stage glaucoma in which central vision is affected and therefore causing low BCVA.

The stimulus size of 3.5 degrees in OCCP is larger than the largest size stimulus (V, 1.7 degrees) used in SAP. Consequently, OCCP may be less effective for detecting small, localized scotomas compared with SAP. However, the trade-off in spatial resolution is mitigated by its ability to enhance reliability and usability in unsupervised home environments.

Unlike the controlled conditions in a clinic, home environments are subject to greater variation across a range of variables, including lighting, screen sizing, noise, and other potential distractors, all of which may affect the test's reliability. Although the physiological parameters of OCCP were chosen to help withstand these variations, and OCCP includes built-in calibration and pretest instructions to minimize these factors, the variability in home testing conditions could have introduced inconsistencies in the results. We were unable to assess and compare the range of hardware and software that was used at home, and it is unclear if these variables influenced ease of use or reliability. While this study demonstrated that OCCP performs similarly at home to a controlled, clinical setting, future computational analysis can be performed to better understand what visual field results are influenced by environmental factors impact test outcomes and whether additional improvements to the calibration process, user instructions, or algorithmic interpretations can further enhance the reliability of the application. Previously the impact of differences in displays, including monitor size and type has been evaluated with a high level of consistency detected despite differences in computers used.[41]

The relatively short follow-up period of 6 weeks is a limiting factor in assessing the long-term repeatability of OCCP for monitoring disease progression. Future research will focus on extending the follow-up period to assess the tool's utility in long-term disease monitoring as well as how OCCP may reduce the frequency of in-person clinic visits without compromising the quality of care. In areas with limited internet connectivity, OCCP may offer additional advantages, as it has the capability to store results locally when internet is lost, and then sync results when internet connection is re-established. The OCCP platform is API-enabled, which supports direct integration into existing electronic health records offering further ease of use in telehealth and remote settings.

Global perimetric indices are a summary statistic of all points on the visual field. While data synthesis is important for depicting global trends and analysis, focusing on global indices may lead to obscuration of otherwise variability in the visual field. To account for fluctuations in data, loci maps, intraclass correlation, and Bland-Altman analyses were used.

In conclusion, OCCP has similar repeatability at home compared with the clinic, with relative ease of use in an unsupervised home environment. Critically, results are convergent across different contexts, including clinic-based validation against SAP, short- and intermediate-interval repeatability cohorts, a central 10 degrees normative dataset, patient appraisal studies, the present multicity home-based cohort, varied hardware, and an international longitudinal cohort in Vietnam, both in clinic and at home.[19–23,41–43] Taken together, these findings support the generalizability of OCCP beyond a single site or protocol, and highlight its promise as an affordable, accessible, and scalable application that has an acceptable repeatability and agreement with conventional machine-based perimetry. With ongoing refinement and modifications, OCCP has the potential to enhance glaucoma monitoring, particularly in resource-limited settings where access to traditional perimetry may be constrained. By expanding the capacity for home-based surveillance, OCCP holds promise in improving the detection and management of glaucoma, ultimately contributing to better patient outcomes.

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