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ORIGINAL RESEARCH

Home-based visual field test for glaucoma screening comparison with Humphrey perimeter

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Purpose: To present a home-based visual field examination method using a PC monitor or virtual reality glasses and evaluate the reliability of the method by comparing the results with those of the Humphrey perimeter, in order to assess the possibility of glaucoma screening through the Internet.

Materials and methods: Software implementing a supra-threshold algorithm for the central 24° (52 points) of visual field at three threshold levels: 1) −4 db, 2) −8 db, and 3) −12 db, from the age-expected sensitivity was used for the purpose of testing. The software uses the web camera as a "virtual photometer" in order to detect room luminosity and allows self-testing using a computer monitor or virtual reality glasses using an Android smartphone with a 6-inch display. The software includes an expert system to analyze the visual field image and validate the reliability of the results. It also allows the physician to combine the results from two or more tests into a single test in order to achieve higher statistical accuracy of the final result. A total of ten patients, 20 eyes tested×52 points per eye=1,040 visual field test points, were compared point to point to those obtained using the Humphrey perimeter for the same patients, as they appeared randomly and consecutively at the glaucoma department within hours.

Results: Good receiver operating characteristic/area under the curve coefficient was found, ranging from 0.762 to 0.837 ($P<0.001$). Sensitivity ranged from 0.637 to 0.942, and specificity ranged from 0.735 to 0.497.

Conclusion: The home-based visual field test exhibits a reasonable receiver operating characteristic curve when compared to the Humphrey perimeter, without the need of specialized equipment. The test may be useful for glaucoma screening.

Keywords: glaucoma, screening, internet, computer monitor, android smart-phone, online visual field, virtual reality, teleophthalmology, telemedicine

Introduction

Glaucoma represents a diverse group of disorders that have common characteristic changes in the optic nerve neuroretinal rim tissue and is a major cause of blindness. It is estimated that half of glaucoma cases are undiagnosed.[1] The prevalence of glaucoma in the general US population 40 years of age and older is 2.1%, and ~2.4 million people in the US have undetected and untreated glaucoma.[2]

Visual field testing remains one of the most important exams for determining the stage of glaucoma, the efficacy of medical or surgical treatment, and the prognosis, as well as for assessing the patient's quality of life and his/her ability to perform the activities of daily living. Increasing the frequency of visual field testing leads to earlier detection of glaucoma progression.[3]

The most widely used method to assess visual field deficits in glaucoma is automated perimetry. Despite the several advantages of automated perimetry, there are a

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few disadvantages. Often, it is tiring and difficult for patients to concentrate throughout the test and a large majority of the patients who have visual field test examination belong to the age group over 50. Automated perimeters are objective and accurate devices, but they are also bulky and heavy and are neither portable nor available for home use.

Online visual field testing is interesting for its potential to be used as a low-cost method for glaucoma screening. The potential benefits of an effective online telemedicine system are plentiful, especially in countries with high prevalence of glaucoma or in developing countries, and may save costs to patients and costs to the health care system as a whole.

In the past, various computerized visual field systems were tested, such as: 1) Peristat, 2) Visual Fields Easy (VFE), 3) Testvision.org, and so on.[4–7]

Peristat is an online visual field. It is based on Adobe/Flash technology and runs in a web browser. Flash technology is becoming obsolete. Adobe is planning to remove support for it by the end of 2020 and encourages content creators to migrate to new open formats such as HTML5. Flash technology had security issues. Chrome, Microsoft Edge, and Safari browsers have all been blocking Flash over the past year. In 2010, Steve Jobs banished Adobe Flash from the iPhone. It was too insecure, Jobs wrote, and too resource intensive.

VFE runs on a small smartphone screen (iPhone) which must be held steady by the patient using his/her hands throughout the whole test.

Testvision.org is a test based on ophthalmokinetic perimetry. It is based on Flash technology and has similar limitations to Peristat.

Visual field testing is affected by ambient luminosity. The test has to be performed under specific luminosity conditions in order to achieve standardization in testing conditions, but personal computers/smartphones do not have photometers. None of the previous systems has the ability to check room luminosity.

Visual field testing is also a subjective examination. The patient must be able to understand the testing instructions and must fully cooperate and complete the entire test in order to provide useful information. As a result, visual fields tests have high within-test and between-test variability and it is not rare to have false-positive or false-negative responses.[8–10] For such reasons, the widespread use of these systems has been limited.

To overcome these issues, a telemedicine visual field test with novel features is presented in this paper. The system 1) uses the web camera as a "virtual photometer" to detect ambient luminosity in order to make sure that the test is performed under standard conditions (dark room); 2) analyzes the visual field image and validates the test results in order to prevent a patient from sending a test to his/her physician if the test was not performed correctly; and 3) allows the physician to combine the results from two or more tests into a single test to achieve higher statistical accuracy of the final result.[11] The test is based on Microsoft's .NET technology as well as on Google's Android platform.

The purpose of this study was to check the diagnostic ability of the test and calculate its receiver operating characteristic (ROC)/area under the curve (AUC) characteristics as well as the optimal cut-off points when compared with the Humphrey perimeter.

Materials and methods

To test the reliability of the method, proprietary software implementing a supra-threshold visual field test algorithm at three threshold levels, 1) −4 db (high level), 2) −8 db (medium level), and 3) −12 db (low level), from the age-expected sensitivity, at the central 24°/(52 points) of visual field was used.[12]

The points are projected using proper trigonometry calculations to compensate for classical perimeter bowl for liquid crystal display (LCD) monitor, so that the stimuli appear on the retina as if they were projected from a classical bowl perimeter. The white/gray stimuli were projected on black background (Figure 1).

The software alternatively allows the use of virtual reality glasses with a 6-inch Android smartphone for visual field testing (Figure 2). If the smartphone uses the same display technology (LCD) as the computer monitor, the results are expected to be comparable.

Display adjustment

Visual field testing requires specific display luminosity settings. Gamma describes the relationship between the pixel levels and the luminance of the monitor (the light energy it emits). LCD displays show S-shaped curve between the input digital values and the output luminance unlike the conventional cathode ray tube monitor represented by a power function. The relationship between the voltage in an LCD pixel and the light intensity is an S-shaped curve that is nearly linear for the large region between the foot and shoulder of the s-curve.[13] For this reason, LCD displays are approximately linear devices. Contrast sensitivity decreases by age.[14] Brightness, contrast, and gamma were adjusted before testing using a step-wedge gray scale. The step-wedge gray scale has 40 distinct shades/steps of gray from

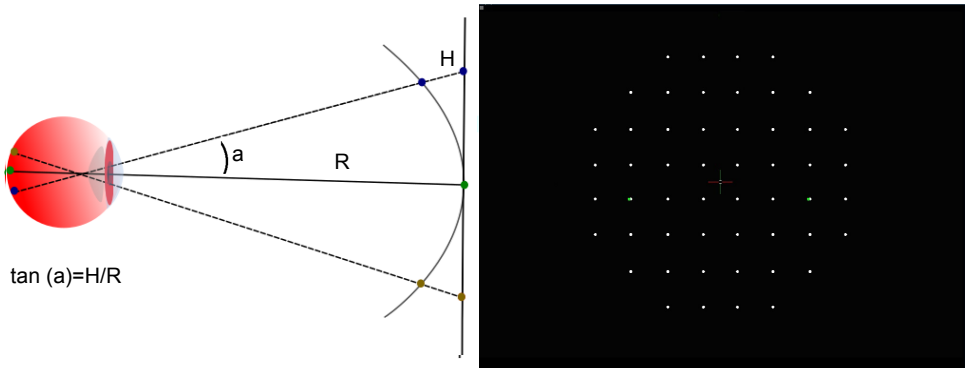

Figure 1 Trigonometry relation between display and bowl perimeter, 52 points 24° to be tested.

black to white, with equal differences in brightness between each step. The display was adjusted so that all the shades of gray were distinct and clearly visible. This was about 50% of the maximum available brightness (Figure 3).[15,16]

When the brightness is properly adjusted, 36–38 dB should be the approximate upper limit for contrast sensitivity in young observers.[12] Contrast sensitivity data between different perimeters are similar, albeit not exactly the same.[17–20]

Software features

1. Supra-threshold strategy, 52 points, central 24° of visual field (nasally and temporally from the fixation point), at three threshold levels, 1) −4 db (high level), 2) −8 db (medium level), and 3) −12 db (low level), from the age-expected sensitivity. White/gray on black background or black/gray on white background stimuli are available.
2. The software uses the Heijl–Krakau blind spot method to monitor fixation and head position by projecting the stimuli at maximum luminosity at possible blind spot locations until finding the correct response and adjusts stimuli positions and size automatically.[21]
3. Supra-threshold stimuli are used to check for false-negative results. The software also checks for false-positive responses by recording positive responses when no response was expected.
4. Variable stimuli presentation rate, adjusted to patient's response time.
5. Stimuli presentation time 250 ms.
6. Statistics. False positive, false negative, fixation losses.
7. Web camera used as virtual "photometer" to detect room luminosity, so that the test is performed under standard conditions (dark room) and records the (red, green, blue) luminosity data in the printout, to provide this information to the doctor.
8. An expert system to analyze the visual field image and detect tests that were not performed correctly.
9. The software allows the doctor to combine the results from two or more tests into a single test to achieve higher statistical accuracy.

Figure 2 Monitor or virtual reality glasses can be used for visual field testing.

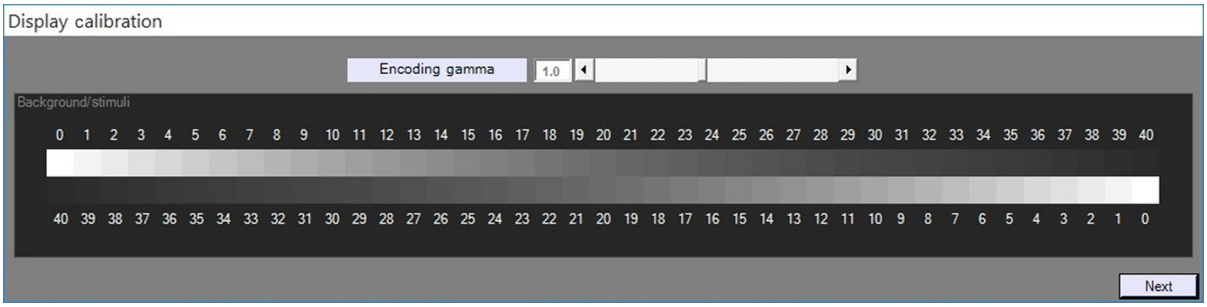

Figure 3 Display – gamma calibration using a gray scale step-wedge.

Examination procedure

During testing, the user sits comfortably in front of a screen and stares at the central fixation point, while using a mouse to click whenever he/she sees a visual stimulus on the screen. The software has only manual response option. Each eye is tested separately. The users wear their near correction glasses if it is necessary. The eye that is not being tested is covered with the palm of the hand (Figure 4).

All the patients tolerated the test well and they said they found the test simple and easy to perform. The user can test his/her visual field at home and send the results to his/her doctor for evaluation. If the results are not within normal limits, the doctor may advise the patient accordingly, whether or not further examinations are required.

Testing procedure

To find the right distance from the screen, the following procedure is used. The user closes/covers one eye and stares perpendicularly at the central cross target with the other eye. The user is aware of the blind spot dot, but he/she should not look at it. The user should instead keep his/her eye on the central target. Then, the user slowly moves toward the display, while still staring at the cross target with his/her open eye. At a distance, somewhere around 1–1.2× the height of the display from the computer screen, the blind spot dot will disappear and the area where the blind spot was will be all black. This is the right distance from the computer display. If the user moves closer to the screen or farther away, the blind spot dot will reappear. At just the right distance, the blind spot dot disappears. Peristat online perimetry test uses a similar procedure. Alternatively, the user places his/her eye at a distance ~1–1.2× the height of the display from the computer screen and stares perpendicularly at the central cross target. The software then locates the blind spot automatically by projecting the stimuli at possible blind spot locations and recording the responses until the user does not see the stimulus/blind spot. Then the locations and sizes of test points are adjusted automatically. If the user is out of limits (too far away or too near from the screen), the blind spot stimuli are visible. In that case, the process fails and a

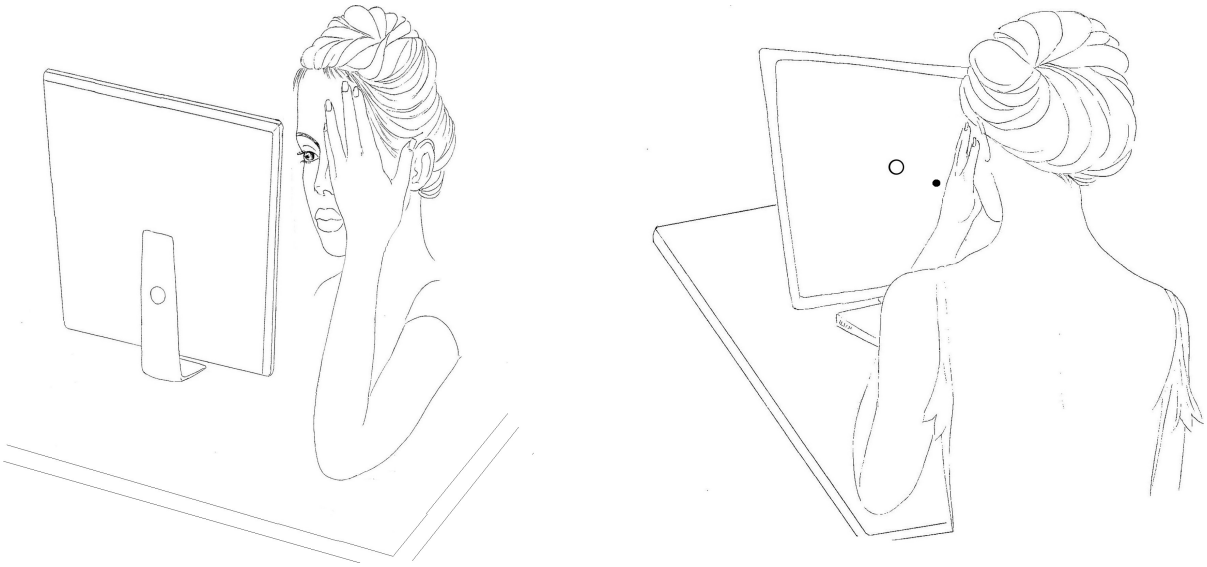

Figure 4 Patient testing in front of a monitor.

message appears. These methods cannot be applied if there is a scotoma affecting the blind spot or in hemianopic field defects. In that case, all that the patient can do is to place his/her eye at a distance ~1× the height of the display from the computer screen, stare perpendicularly at the center of the display, and start the test.

The user can select three sensitivity levels either under the guidance of his/her doctor or his/her self-preference. High sensitivity might detect shallow defects, but has more false-positive findings. Low sensitivity detects deep scotoma only, but has a lower false-positive findings rate. Medium sensitivity gives intermediate results. The system includes eye tracking capability using AForge.NET computer vision and artificial intelligence General Public License library and is able to track the pupil in order to set the central target's location accordingly on the display (Figure 5).

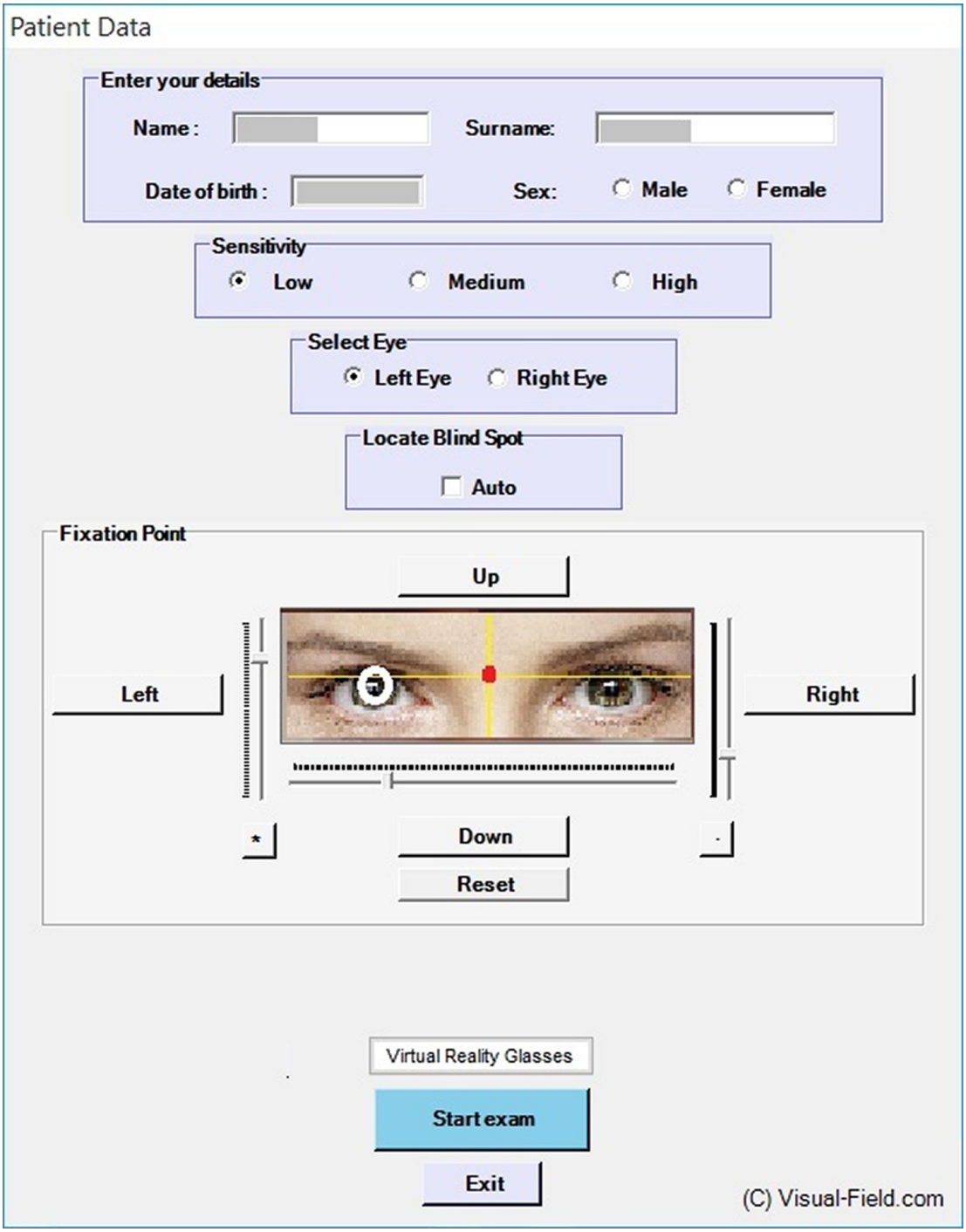

Figure 5 Examination form of the software, eye tracking.

Test sensitivity is selected at the start of the test. The room should be dark during testing. The web camera is used as a "photometer" to check and record room luminosity before testing starts. The average RGB color values are calculated. RGB color values range from 0 (dark) to 255.

The tests were performed using a 22″ LCD display, albeit a smaller or bigger monitor could be used because the software can detect the blind spot automatically and calculate the distance between the display and the patient in order to adjust the locations of the projected points as well as their sizes automatically.

During testing, the software projects stimuli at the selected threshold level, at each point tested. If the patient clicks/sees the stimulus, the response is recorded as positive: 1; if the patient does not respond, it is recorded as a zero response: 0. Testing stops when a response, either 1 or 0, is recorded for each point. The purpose of the test is only to record whether the patient sees or does not see the threshold stimuli. The test is fast (2–3 minutes per eye) because only the selected threshold is tested at each point. The system checks for fixation losses by projecting stimuli at the blind spot. It also checks for false-positive responses and false-negative responses by projecting supra-threshold stimuli at points where the threshold stimulus is found to be visible.

The stimulus presentation rate is variable. The maximum response – waiting time is adjusted to the patient's response time, within limits.

In the results/printout, false-negative test errors are marked in red, while false-positive test errors are marked in green, so that the doctor knows, for example, if a "scotoma" is due to a false-negative test error or a non-scotoma is due to a false-positive test error. Points where false-negative and false-positive errors were recorded are marked in yellow color. The exam output is binary (seen/clicked=1, not seen/not clicked/missed=0). At the end of the test, the image is analyzed and the results are validated in order to prevent a user from sending a test to his/her doctor, if the test was not performed correctly. A test is considered as "valid" if 1) the blind spot is detected/located at the expected position and 2) the false-positive, false-negative, and fixation losses are all <25%. If the test is valid, the user can send the test results by email (as an embedded image) to his/her doctor for review (Figure 6).

If the results are not within normal limits, the doctor will advise the patient accordingly whether or not standard automated perimetry and/or further/other examinations are required.

Study participants

Permission was obtained from the Scientific and Ethical Committee of the General Hospital of Athens "G. Gennimatas" to perform the study. Written informed consent was obtained from all participating patients, and the study adhered to the tenets of the Declaration of Helsinki.

A total of ten patients, 20 eyes tested×52 points per eye=1,040 visual field test points, were compared point to point to those obtained using the Humphrey perimeter for the same patients as they appeared consecutively at the glaucoma department within hours for comparison[22,23] (Figure 7). All the patients completed the test and were included in the study. The mean age was 67.9 years (SD=12, ranging from 47 to 81).

The results from the visual field screening tests were binary (seen/not seen). ROC curves are widely used in the biomedical sciences and give us the ability to assess the performance of a binary classifier over its entire operating range using a graphical approach. The results were statistically

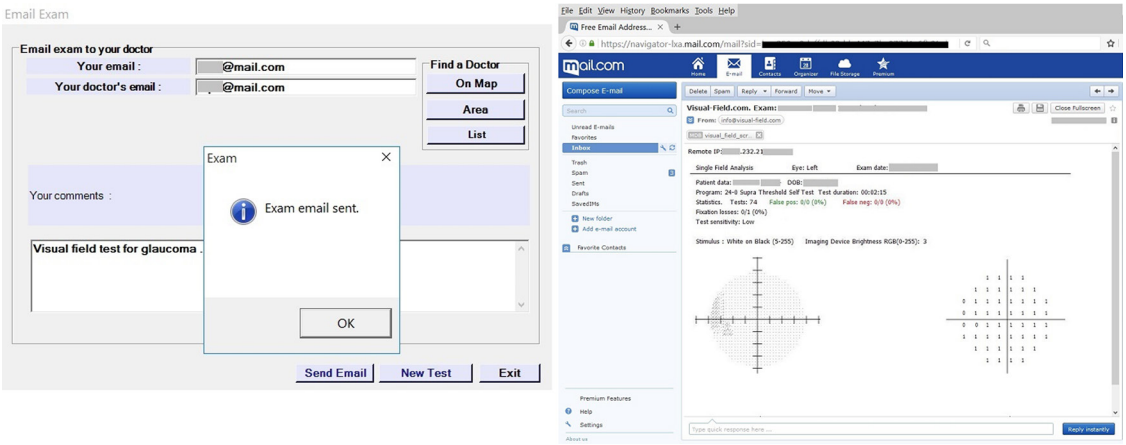

Figure 6 Exam sent by email.

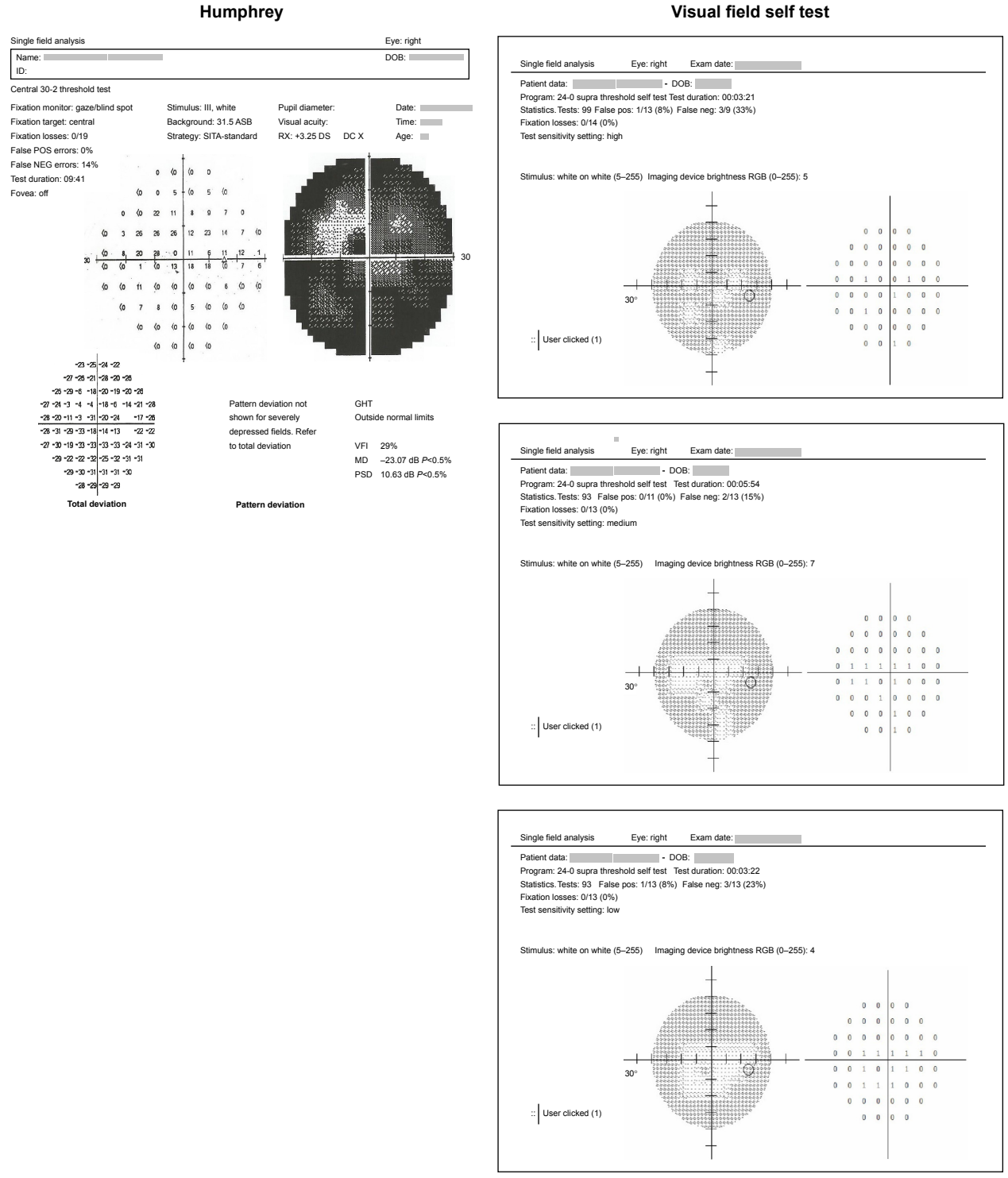

Figure 7 Eye 1 of 20. Humphrey field analyser test compared with three screening tests at high, medium, and low sensitivity levels (brightest stimulus, –12 dB).
Note: As the stimulus gets brighter, the number of positive responses increases.

analyzed and the ROC curves for each threshold level as well as the generalized Youden Index and the optimal cut points were computed using easyROC, an interactive, open-source web tool for ROC curve analysis using R Language Environment.[24] The easyROC uses the "OptimalCutpoints" software package to determine the cut-off values for diagnostic tests[25] (Figure 8; Table 1). The reliability indices were also calculated (Table 2). The results were similar, albeit not identical because the algorithms and the technology used were different.

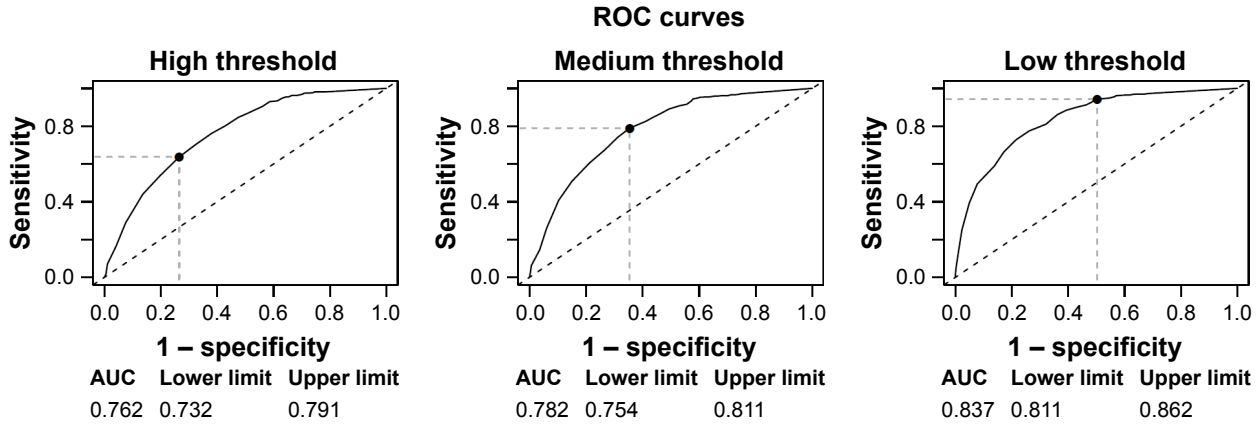

Figure 8 ROC curves for each threshold.
Abbreviations: AUC, area under the curve; ROC, receiver operating characteristic.

Statistical analyses

The patients were tested successively using a Humphrey perimeter and the telemedicine method. Telemedicine visual field screening tests were 24° (52 points), while Humphrey field analyser (HFA) tests were 30° (76) points because the patients were tested with HFA as part of their scheduled/routine examination and not because of this study. Only the inner common (52) points matching the 24° central degrees between the HFA and the screening test were compared.

Results

The results show that the AUC was 0.762 ($P<0.001$) for high threshold, 0.782 ($P<0.001$) for medium threshold, and 0.837 ($P<0.001$) for low threshold.

Table 1 Threshold data at high, medium, and low sensitivity

High threshold			
Cut-off method: generalized Youden Index optimal cut-off point: 28			
	Value	**Lower limit**	**Upper limit**
Sensitivity	0.637	0.592	0.680
Specificity	0.735	0.696	0.771
Positive predictive value	0.675	0.632	0.715
Negative predictive value	0.701	0.660	0.740
Positive likelihood ratio	2.401	2.059	2.800
Negative likelihood ratio	0.494	0.435	0.562
Medium threshold			
Cut-off method: generalized Youden Index optimal cut-off point: 25			
Sensitivity	0.790	0.755	0.822
Specificity	0.646	0.599	0.690
Positive predictive value	0.748	0.709	0.785
Negative predictive value	0.697	0.654	0.738
Positive likelihood ratio	2.229	1.953	2.543
Negative likelihood ratio	0.326	0.275	0.386
Low threshold			
Cut-off method: generalized Youden Index optimal cut-off point: 16			
Sensitivity	0.942	0.939	0.936
Specificity	0.497	0.503	0.509
Positive predictive value	0.788	0.790	0.791
Negative predictive value	0.812	0.806	0.801
Positive likelihood ratio	1.874	1.889	1.906
Negative likelihood ratio	0.116	0.121	0.125

Table 2 Reliability indices

	HFA			High			Medium			Low		
	FL	FP	FN	FL	FP	FN	FL	FP	FN	FL	FP	FN
Mean	16	1.5	7.4	16	17	20	22	13	10	23	17	12
SD	26	2.1	12	26	13	23	32	12	19	29	14	16

Abbreviations: FL, fixation losses; FN, false negative; FP, false positive; HFA, Humphrey field analyser.

In summary, we see that as the threshold tested gets lower, the sensitivity increases while the specificity decreases and vice versa. The optimal cut-off point for Humphrey data was 28 dB for the high threshold, 25 dB for the medium threshold, and 16 dB for the low threshold.

Black/gray stimuli on white background were also tested with similar results, but they are not included in this paper.

In practice, when a single test is used repeatedly in routine screening, the same screening threshold is typically used at each screening visit. One possible alternative is to adjust the threshold at successive visits according to individual-specific characteristics.[26] The test results can be combined in series or in parallel.[27] Parallel testing is recommended for ruling in diagnoses, while series testing is recommended for ruling out diagnoses.[28] The software allows the user to select and combine the results from two or more tests into a single test. The sum of positive responses at each point merged is shown.

Discussion

Telemedicine visual field screening testing has many similarities to classical bowl perimetry, but there are some differences due to the hardware used.

We presented a visual field test with novel features and evaluated the reliability of the method by comparing the results with those of Humphrey perimeter.

The purpose of the test is to help glaucoma patients become aware of their problem, albeit other disorders that affect the visual field might be detected as well.

The advantages of our system are that it uses the web camera as a "photometer" and validates the reliability of the results when the test is completed. This system also allows the patient to send the results to his/her doctor by email and allows the doctor to combine the results from two or more tests into a single test to achieve higher statistical accuracy.

The test is simple, easy, and fast and does not require specialized equipment. It only takes 2–3 minutes per eye and can be repeated as many times as needed. The patients were asked at the end of the test and they reported that it was easy and simple.

The test implements a supra-threshold visual field test algorithm at three sensitivity levels. It is intended to indicate whether there are findings in the visual field that might require further examinations. Standard automated perimetry test should be used to quantify the defects. The test is not intended to monitor the progression of diagnosed cases, but to be used as a screening test.

The optimal cut-off points as well as the ROC/AUC characteristics of this test were calculated when comparing the results with those obtained from the Humphrey perimeter for the same group of patients. ROC analysis is a widely used method for evaluating the accuracy of medical diagnostic systems. The most desirable property of ROC analysis is that the accuracy indices derived from this technique are not distorted by fluctuations caused by the use of arbitrarily chosen decision criteria or cut-offs. In other words, the indices of accuracy are not influenced by the decision criterion. Using this as a measure of a diagnostic performance, one can compare individual tests or judge whether the various combination of tests can improve diagnostic accuracy.[29] Good ROC/AUC coefficient was found, ranging from 0.762 to 0.837 ($P<0.001$). Sensitivity ranged from 0.63 to 0.94, and specificity ranged from 0.73 to 0.49.

Other systems have found similar results. Peristat online perimetry had comparable ROC curves and Spearman's rank correlation coefficient ranging from 0.55 to 0.77 (all $P<0.001$) when compared with the Humphrey perimeter.[30] VFE, which is an iPad application for visual field testing, had ROC/AUC ranging from 0.687 to 0.784.[31,32]

The prevalence of glaucoma increases with age. It is most common in adults in their 70s and 80s. The main limitation of this test is that many older people never learned to use computers. Barriers may include physical and mental limitations. As with any other computer system, older people may still need a little help and support by younger people, family, or professionals who care for older adults.

Conclusion

The ROC characteristics of this low-cost test show it is reliable at least when compared with the Humphrey perimeter and does not require specialized equipment. The test may be useful for home-based glaucoma screening.

Data sharing statement

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request. Non-profit institutions can freely avail the software by contacting the corresponding author or by sending an email to info@visual-field.com.

Ethics approval and consent to participate

Permission was obtained from the Scientific and Ethical Committee of the General Hospital of Athens "G. Gennimatas" to perform the study. Written informed consent was obtained from all participating patients, and the study adhered to the tenets of the Declaration of Helsinki.

Disclosure

The authors report no conflicts of interest in this work.

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用于青光眼筛查的家庭视野检查与Humphrey周边视野的比较

摘要

目的：提出一种基于 PC 显示器或虚拟现实眼镜的家庭视野检查方法，并通过与 Humphrey 周边视野检查结果的比较来评价该方法的可靠性，以评估通过互联网进行青光眼筛查的可能性。

材料和方法：为了实现从龄预期灵敏度来测试的目的，使用了在 3 个阈值水平上实现视野中央 24° (52 分)的超阈值算法的软件：1) - 4 db，2) - 8 db，3) - 12 db。该软件使用网络摄像头作为“虚拟光度计”来检测房间亮度，并允许使用电脑显示器或使用 6 英寸显示器的 Android 智能手机和虚拟现实眼镜进行自我测试。该软件包括一个专家系统来分析视野图像并验证结果的可靠性。它还允许医师将两次或多个测试的结果合并为一次测试，以便达到对最终结果更高的统计准确性。共十名患者，检测 20 只眼×每只眼 52 个点=1040 个视野检测点，与使用 Humphrey 周边视野检测的相同患者进行点对点比较，因为他们在数小时内随机连续出现在青光眼科。

结果：发现良好的受试者工作特征/曲线下面积系数，范围为 0.762 至 0.837 (P <0.001)。灵敏度范围为 0.637 至 0.942，特异性范围为 0.735 至 0.497。

结论：在不需要专门设备的情况下，与 Humphrey 周边视野检测相比，基于家庭的视野检测显示出合理的接收器工作特性曲线。该测试可能对青光眼筛查有用。

关键词：青光眼，筛查，互联网，电脑显示器，Android 智能手机，在线视野，虚拟现实，远程眼科，远程医疗

介绍

青光眼代表了视神经神经视网膜缘组织有共同特征性改变的多种疾病群，是致盲的主要原因。据估计，半数青光眼病例未确诊[1]。青光眼的患病率美国一般人群 40 岁及以上，患病率为 2.1%，美国约有 240 万人未发现和未治疗青光眼[2]。

视野检查仍然是确定青光眼的分期、药物或手术治疗的疗效以及评估患者生活质量和日常生活活动能力的最重要检查之一。增加视野检查的频率，可以更早地发现青光眼的进展[3]。

评估青光眼视野缺损最常用的方法是自动视野计。尽管自动测量法有几个优点，但也存在一些缺点。往往患者在整个测试过程中很累很难集中精力，有视野测试检查的患者绝大多数属于 50 岁以上年龄组。自动周界是客观和准确的设备，但它们也体积庞大和笨重，既不便携，也不适合家庭使用。

在线视野检测因其作为青光眼筛查低成本方法的潜力而备受关注。一个有效的在线远程医疗系统的潜在益处是丰富的，特别是在青光眼发病率很高的国家或发展中国家，可能会节省病人的费用和整个保健系统的费用。

过去，人们对各种计算机视觉系统进行了测试，如：1) Peristat，2) Visual Fields Easy (VFE)，3) Testvision.org 等[4-7]。

Peristat 是一个在线视野。它基于 Adobe / Flash 技术，运行在 Web 浏览器中。随着 Flash 技术正变得过时，Adobe 计划在 2020 年底之前取消对它的支持，并鼓励内容创建者迁移到新的开放格式，例如 HTML5。Flash 技术存在安全性问题。Chrome、Microsoft Edge 和 Safari 浏览器在过去的一年里都在阻塞 Flash。2010 年，史蒂夫·乔布斯将 Adobe Flash 从 iPhone 中逐出。乔布斯写道，它过于不安全，资源过于密集。

VFE 运行在一个小的智能手机屏幕(iPhone)上，在整个测试过程中，必须由患者用手持稳。

Testvision.org 是基于眼动视野测量测试。它基于 Flash 技术，具有类似于 Peristat 的局限性。

视野测试受环境光度的影响。为了实现测试条件的标准化，测试必须在特定的光度条件下进行，但个人电脑/智能手机没有光度计。以前的系统都没有检查

房间亮度的能力。

视野测试也是一种主观检查。病人必须能够理解测试说明，并且必须全力配合并完成整个测试，以便提供有用的信息。因此，视野测试具有较高的测试内和测试间变异性，出现假阳性或假阴性反应并不罕见[8-10]。由于这些原因，这些系统的广泛应用受到了限制。

为了克服这些问题，本文提出了一种具有新颖特征的远程医学视野测试。系统 1)使用网络摄像机作为“虚拟光度计”来检测环境光度，以确保测试在标准条件下(暗室)进行；2)分析视野图像并验证测试结果，以防止患者在测试未正确执行的情况下向医生发送测试; 3)允许医生将两次或两次以上测试的结果合并为一次测试，以获得更高的最终结果统计准确性[11]。该测试基于 Microsoft 的 .NET 技术以及 Google 的 Android 平台。

本研究的目的是检查测试的诊断能力，开发和评估适用于电脑显示器和 Android 平台的移动应用程序的可用性，该应用程序包含可提高患者对青光眼的了解并促进其治疗的功能。并计算其受试者工作特征(ROC) /曲线下面积(AUC) 特征以及与 Humphrey 周边视野比较的最佳截断点。

材料和方法

为验证该方法的可靠性，采用自主研发的软件，从年龄预期灵敏度出发，在视野中心 24 ° / (52 点)处，在 3 个阈值水平 1) - 4 db (高水平)、2) - 8 db (中等水平)和 3) - 12 db (低水平)下，实施超阈值视野测试算法 [12]。

这些点用适当的三角学计算投影，以补偿液晶显示器 (LCD) 显示器的经典碗周长，使刺激像从经典碗周长投影一样出现在视网膜上。白色/灰色刺激被投射到黑色背景上(图 1)。

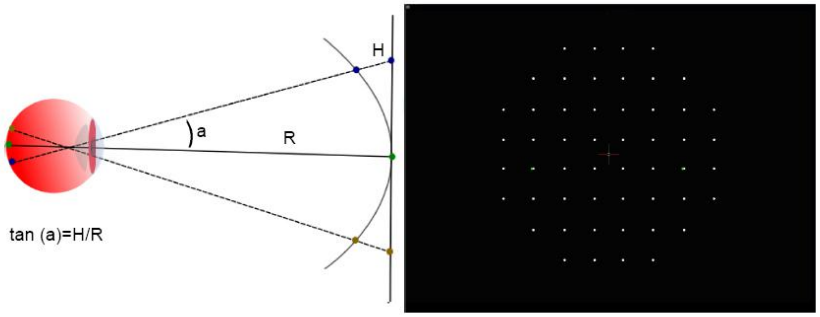

Figure 1 Trigonometry relation between display and bowl perimeter, 52 points 24° to be tested.

图 1 显示器与碗周长的三角关系，52 点 24°待测

该软件还允许将虚拟现实眼镜与 6 英寸 Android 智能手机一起用于视野测试（图 2)。如果智能手机采用与计算机监视器相同的显示技术(LCD)，其结果有望具有可比性。

Figure 2 Monitor or virtual reality glasses can be used for visual field testing.

图 2 监视器或虚拟现实眼镜可用于视野测试。

这是一个横向的、定量的研究，分为两个阶段。第一阶段是 Android 平台应用程序的创建和开发。最后阶段包括测试应用程序，验证其操作、可用性和可接受性。所有参与者均签署知情同意书。

“GlaucoCheck”的整个布局和界面被设计和制造成直观和易于可视化，因为许多青光眼患者已经经历了一些视力丧失，使远程医疗功能得以实现。因此，在访问应用程序时，患者将面临一个初始屏幕，有六个选项触发："关于青光眼"、"我的滴眼液"、"治疗"、"我的考试"、"我的压力"和"问题"。

"关于青光眼"的主题是记录一些快速的视频，根据青光眼患者和一般人群的主要疑虑和抱怨进行主题。

在“我的滴眼液”部分，有选择权选择患者目前使用的药物，并设定使用时间，包括在确切选择的时间通知。此外，通过选择“治疗”选项，可以存储有关患者手术治疗的信息。

"My Exams"使已执行的检查得以注册，如 Goniscope、Pachymetric、Visual Field、Retinography，以及神经和纤维的 OCT (图 2)。

在“我的压力”一节中，患者可以存储被测眼压(IOP)的值，从而能够及时监测眼压的变化，并自动生成随访图。

在“问题”菜单中，青光眼患者有可用的常见问题(FAQ)，有各自的答案。除此之外, 还有一种远程医疗选择, 可以向开发人员发送带有新问题的电子邮件, 方便患者和专业人员之间的交流。

移动应用客户反馈纳入标准为青光眼患者, 在 Cearense de Oftalmologia 研究所注册，或对熟悉 iOS ar Android 平台的患者负责的亲属。不患有青光眼或与青光眼无关的参与者、不识字的志愿者，以及不熟悉智能手机和 iOS 或 Android 平台的参与者

本研究的志愿者被选择使用合理的选择样本，以非随机的方式正当与否。选择是有意或出于方便, 考虑到研究组的特点或研究者对他们正在调查的内容的了解程度。

最初，发生了关于研究的非正式交谈，澄清疑虑，邀请志愿者正式邀请参加并签署同意书。

21 例(58.3 %)患者认为对本病的认识不足。然而，31 名(86.1 %)患者表示对自己的考试和治疗有足够的了解。关于 SUS 问卷，按年龄分组，55 岁以下或 55 岁以上患者的可用性没有差异(表 2)。

应用获得了公平的可用性评估，平均 SUS 评分为 75.6 (95 % CI 74.1 ~ 77.2)

(表 3)。‘GlaucoCheck’被指出在 22 名(61.1 %)志愿者中引起了频繁使用它的兴趣，而有 8 名(22.2 %)的志愿者相当感兴趣，显示了 83.3 %的志愿者对应用的接受水平。35 名(97.2 %)参与者认为该应用容易使用。

显示调整

视野测试需要特定的显示光度设置。Gamma 描述了像素级与监视器亮度(其发射的光能)之间的关系。LCD 显示器显示的是输入数字值与输出亮度之间的 S 型曲线，这与以幂函数表示的传统阴极射线管监视器不同。LCD 像素中的电压与光强之间的关系是 S 形曲线，对于 S 形曲线的脚和肩之间的大区域来说，它几乎是线性的。对比敏感度随着年龄的增长而降低 14。在使用阶梯楔形灰度进行测试之前，亮度、对比度和伽马在使用阶梯楔形灰阶进行测试前进行了调整。阶梯-边缘灰度由黑到白有 40 个不同的灰度阴影/阶梯，每个阶梯之间亮度差异相等。显示屏进行了调整，使所有的灰色阴影都清晰可见。这大约是最大可用亮度的 50%（图 3）[15,16]。

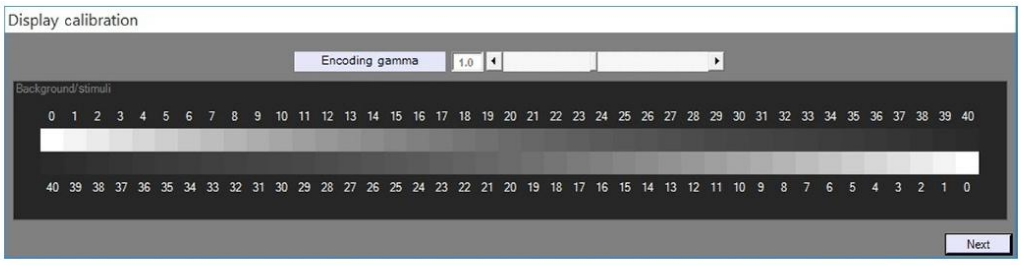

Figure 3 Display – gamma calibration using a gray scale step-wedge.

图 3 使用灰度阶梯楔形进行伽马校准

当亮度适当调整时, 36 ~ 38 dB 应该是年轻观察者对比敏感度的近似上限 [12]。不同周长的对比敏感度数据相似，但不完全相同 [17 ~ 20]。

软件特点

1. 超阈值策略，52 点，视野中央 24°（鼻侧和颞侧距注视点），三个阈值水平，1) -4 db（高水平），2）-8 db（中等水平），和 3) -12 db（低电平），从年龄预期的灵敏度出发。可以使用黑色背景上的白色/灰色或白色背景上的黑色/灰色刺激。

2. 该软件使用 Heijl-Krakau 盲点方法通过在可能的盲点位置以最大亮度投射刺激直到找到正确的响应并自动调整刺激位置和大小来监控注视和头部位置[21]。
3. 超阈值刺激用于检查假阴性结果。该软件还通过在预期没有响应时记录正响应来检查误报响应。
4. 可变刺激呈现率，根据患者的反应时间进行调整。
5. 刺激呈现时间 250 毫秒。
6. 统计数据。假阳性、假阴性、注视损失。
7. 网络摄像头用作虚拟“光度计”来检测房间光度，以便在标准条件（暗室）下进行测试，并在打印输出中记录（红、绿、蓝）光度数据，以将这些信息提供给医生。
8. 用于分析视野图像并检测未正确执行的测试的专家系统。
9. 该软件允许医生将两个或多个测试的结果合并为一个测试，以实现更高的统计准确性。

测试流程

在测试过程中，用户舒适地坐在屏幕前，盯着中心注视点，当看到屏幕上的视觉刺激时，使用鼠标点击。该软件只有手动响应选项。每只眼都单独进行测试。如果有必要，用户佩戴近距矫正眼镜。未被测试的眼睛被手掌复盖(图 4)。

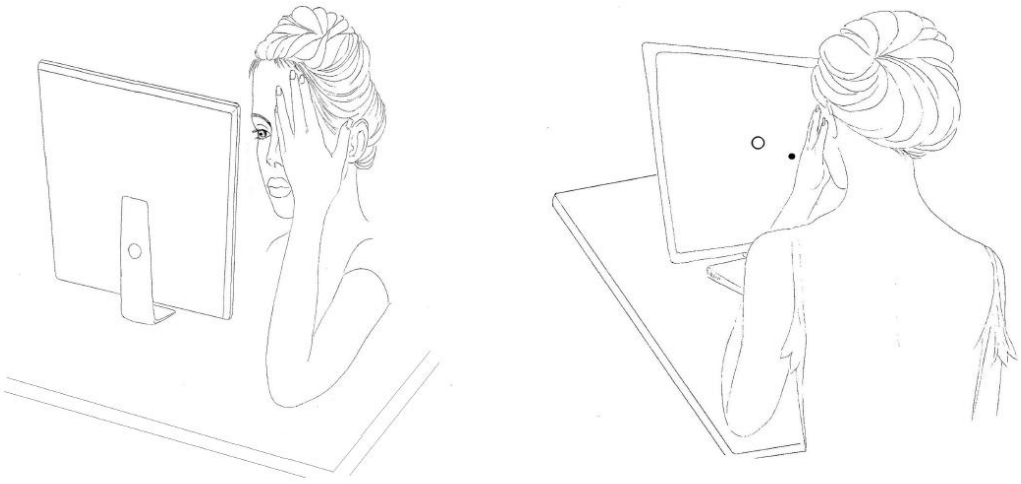

Figure 4 Patient testing in front of a monitor.

图 4 在显示器前进行患者测试

所有患者都很好地进行了测试，他们说他们发现测试简单易行。用户可以在家中测试自己的的视野，并将结果发送给自己的医生进行评估。如果检查结果不在正常范围内，医生可能会相应地告知患者是否需要进一步检查。

所有志愿人员都表示，他们不需要任何技术援助的支持来使用申请。关于此应用程序功能的完整性，100 %的参与者认为这些功能整合良好，应用程序非常一致，不存在使用障碍。

测试程序

要找到与屏幕的正确距离，请使用以下程序。用户闭上/盖住一只眼睛，并用另一只眼睛垂直凝视中央交叉目标。用户知道盲点，但他/她不应该看它。相反，用户应该将他/她的注意力集中在中心目标上。然后，用户慢慢地向显示器移动，同时仍然睁着眼睛盯着十字目标。在距离计算机屏幕大约 1-1.2 倍显示器高度的地方，盲点点将消失，盲点所在的区域将全黑。这是与计算机显示器的正确距离。如果用户靠近屏幕或远离屏幕，盲点会重新出现。在恰到好处的距离，盲点消失。Peristat 在线视野测试使用类似的程序。或者，用户将他/她的眼睛放在距计算机屏幕显示器高度约 1-1.2 倍的距离处，并垂直凝视中央十字目标。然后，软件通过在可能的盲点位置投射刺激并记录响应来自动定位盲点，直到用户看不到刺激/盲点。然后自动调整测试点的位置和大小。如果用户超出限制（离屏幕太远或太近），盲点刺激是可见的。在这种情况下，该过程将失败并显示一条消息。如果存在影响盲点或偏盲视野缺损的暗点，则不能应用这些方法。在这种情况下，用户可以在他/她的医生的指导下或他/她的个人偏好下选择三个灵敏度级别。高灵敏度可能会检测到浅层缺陷，但会有更多的假阳性结果。低灵敏度仅检测深暗点，但假阳性发现率较低。中等灵敏度给出中间结果。该系统包括使用 AForge.NET 计算机视觉和人工智能通用公共许可证库的眼睛跟踪功能，并且能够跟踪瞳孔以便在显示器上相应地设置中心目标的位置（图 5）。

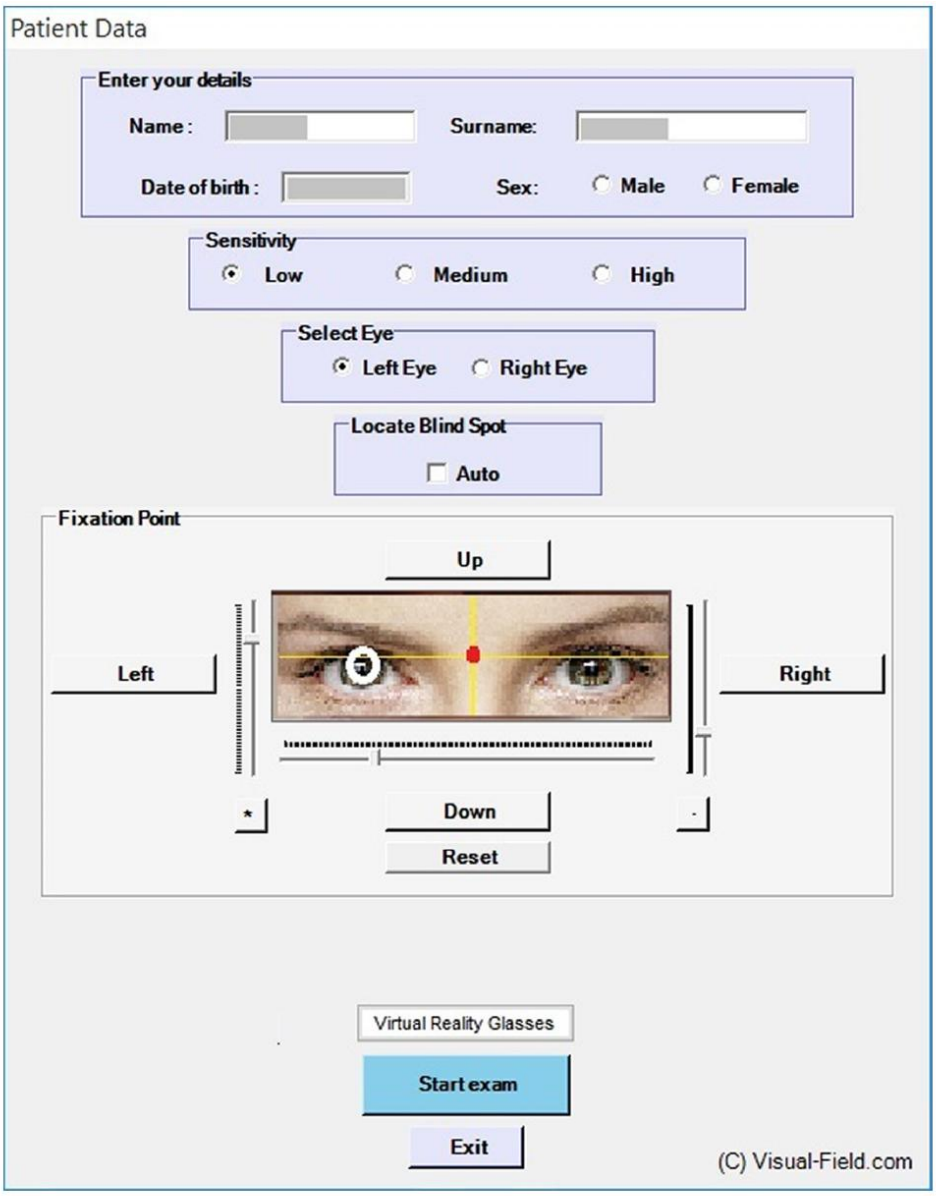

Figure 5 Examination form of the software, eye tracking.

图 5 软件检查表、眼动追踪

在测试开始时选择测试灵敏度。测试期间房间应该是黑暗的。网络摄像头用作“光度计”，在测试开始前检查和记录房间亮度。计算平均 RGB 颜色值。RGB 颜色值范围从 0（暗）到 255。

测试是使用 22 英寸 LCD 显示器进行的，尽管可以使用更小或更大的显示器，因为软件可以自动检测盲点并计算显示器与患者之间的距离，以便调整投影点的位置作为以及它们的大小自动。

在测试期间，软件会在每个测试点以选定的阈值级别投射刺激。如果患者点击/看到刺激，则反应记录为阳性：1；如果患者没有响应，则记录为零响应：0。

当每个点的响应为 1 或 0 时，测试停止。测试的目的只是记录患者是否看到或没有看到阈值刺激。测试速度很快（每只眼睛 2-3 分钟），因为在每个点只测试选定的阈值。该系统通过在盲点处投射刺激来检查固定损失。它还通过在发现阈值刺激可见的点处投射超阈值刺激来检查假阳性反应和假阴性反应。

刺激呈现率是可变的。最大响应 – 等待时间在限制范围内根据患者的响应时间进行调整。

在结果/打印输出中，假阴性测试错误标记为红色，而假阳性测试错误标记为绿色，以便医生知道，例如，“盲点”是否是由于假阴性测试错误造成的或非盲点是由于假阳性测试错误。记录了假阴性和假阳性错误的点用黄色标记。检查输出是二进制的（看到/点击=1，未看到/未点击/错过=0）。在测试结束时，分析图像并验证结果，以防止用户在测试未正确执行时将测试发送给他/她的医生。如果 1)盲点被检测/定位在预期位置，2)假阳性、假阴性和注视损失均< 25 %，则认为测试有效。如果测试有效，用户可以通过电子邮件(作为嵌入图像)将测试结果发送给医生进行复查(图 6)。

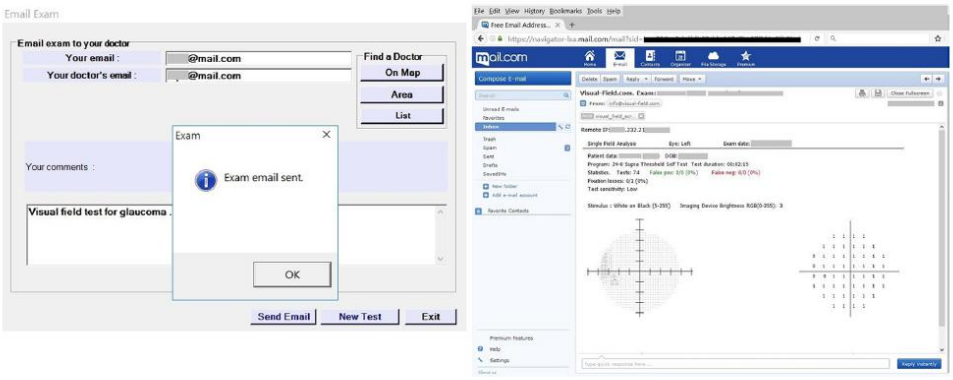

Figure 6 Exam sent by email.

图 6 通过电子邮件发送测试结果

如果结果不在正常范围内，医生会相应地建议患者是否需要标准自动视野检查和/或进一步/其他检查。

研究参与者

雅典" G . Gennimatas "总医院科学和伦理委员会获准进行这项研究。所有参与患者均获得书面知情同意，研究坚持《赫尔辛基宣言》的宗旨。

共有 10 名患者，20 只眼睛测试×每只眼睛 52 个点=1,040 个视野测试点，与使用 Humphrey 周边视野获得的相同患者在数小时内连续出现在青光眼科进行比较[22,23](图 7)。所有患者都完成了测试并被纳入研究。平均年龄为 67.9 岁 (SD=12，范围从 47 到 81)。

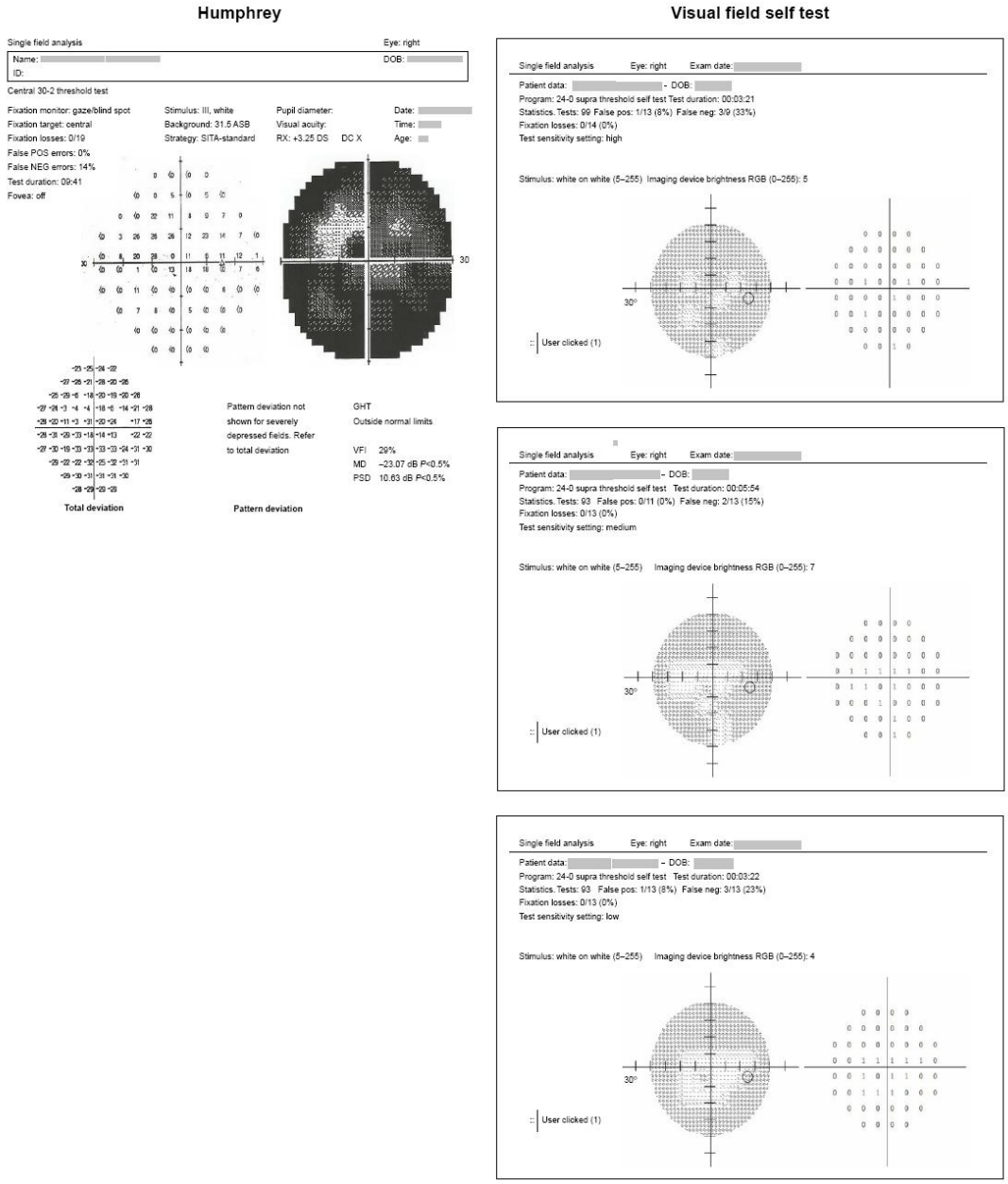

Figure 7 Eye 1 of 20. Humphrey field analyser test compared with three screening tests at high, medium, and low sensitivity levels (brightest stimulus, –12 dB).
Note: As the stimulus gets brighter, the number of positive responses increases.

图 7　20 中的第 1 眼。Humphrey 分析仪测试与高、中和低灵敏度级别（最亮刺激，-12 dB）下的三个筛选测试进行了比较。

注意：随着刺激变得更亮，积极响应的数量会增加

视野筛选测试的结果是二元的（可见/不可见）。ROC 曲线广泛用于生物医

学科学，使我们能够使用图形方法评估二元分类器在其整个操作范围内的性能。结果进行了统计分析，每个阈值水平的 ROC 曲线以及广义 Youden 指数和最佳切割点是使用 easyROC 计算的，easyROC 是一种使用 R 语言环境进行 ROC 曲线分析的交互式开源网络工具[24]。easyROC 使用“OptimalCutpoints”软件包来确定诊断测试的临界值[25]（图 8；表 1）。还计算了可靠性指标（表 2）。结果是相似的，但不完全相同，因为所使用的算法和技术不同。

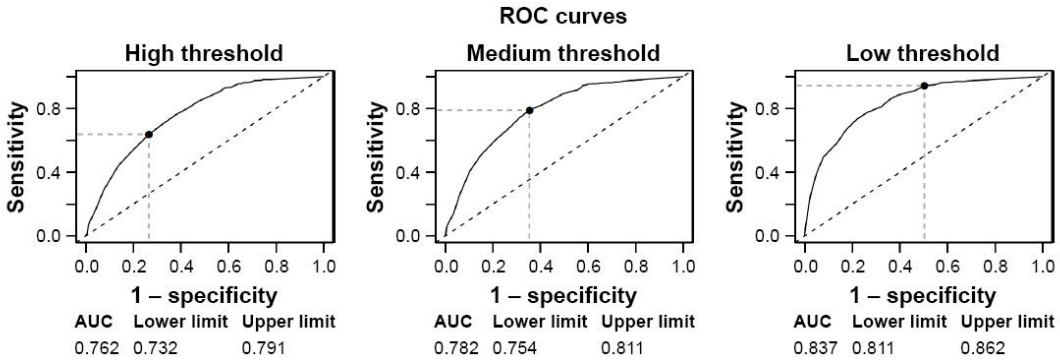

Figure 8 ROC curves for each threshold.
Abbreviations: AUC, area under the curve; ROC, receiver operating characteristic.

图 8 每个阈值的 ROC 曲线。**缩写：** AUC，曲线下面积；ROC，接收器操作特性。

Table 1 Threshold data at high, medium, and low sensitivity

High threshold			
Cut-off method: generalized Youden Index optimal cut-off point: 28			
	Value	**Lower limit**	**Upper limit**
Sensitivity	0.637	0.592	0.680
Specificity	0.735	0.696	0.771
Positive predictive value	0.675	0.632	0.715
Negative predictive value	0.701	0.660	0.740
Positive likelihood ratio	2.401	2.059	2.800
Negative likelihood ratio	0.494	0.435	0.562
Medium threshold			
Cut-off method: generalized Youden Index optimal cut-off point: 25			
Sensitivity	0.790	0.755	0.822
Specificity	0.646	0.599	0.690
Positive predictive value	0.748	0.709	0.785
Negative predictive value	0.697	0.654	0.738
Positive likelihood ratio	2.229	1.953	2.543
Negative likelihood ratio	0.326	0.275	0.386
Low threshold			
Cut-off method: generalized Youden Index optimal cut-off point: 16			
Sensitivity	0.942	0.939	0.936
Specificity	0.497	0.503	0.509
Positive predictive value	0.788	0.790	0.791
Negative predictive value	0.812	0.806	0.801
Positive likelihood ratio	1.874	1.889	1.906
Negative likelihood ratio	0.116	0.121	0.125

表 1 高、中、低灵敏度阈值数据

Table 2 Reliability indices

	HFA			High			Medium			Low		
	FL	FP	FN	FL	FP	FN	FL	FP	FN	FL	FP	FN
Mean	16	1.5	7.4	16	17	20	22	13	10	23	17	12
SD	26	2.1	12	26	13	23	32	12	19	29	14	16

Abbreviations: FL, fixation losses; FN, false negative; FP, false positive; HFA, Humphrey field analyser.

表 2 可靠性指标 **缩写：** FL，固视损失；FN，假阴性；FP，误报；HFA，Humphrey 分析仪。

统计分析

使用 Humphrey 周长和远程医疗方法对患者进行了连续测试。远程医疗视野筛查测试为 24°（52 分），而汉弗莱视野分析仪（HFA）测试为 30°（76）分，因为患者接受 HFA 测试是他们计划/常规检查的一部分，而不是因为这项研究。仅比较了 HFA 和筛选测试之间与 24° 中心度匹配的内部公共 (52) 点。

关于确诊时间，大部分志愿者患病时间在 6 至 10 年之间，6 人(16.6 %)患病时间长达 5 年。55 岁以上的患者在 6 - 10 年前被诊断的频率高于 55 岁以下的患者(p = 0.026)。

当问及滴眼液的名称时，大多数患者都知道药物的名称。对于 55 岁以上的参与者，34 人(94.4 %)知道自己的滴眼液名称，而 55 岁以下的患者中，21 人(58.3 %)知道滴眼液名称，15 人(41.6 %)不知道。16 名(44.4 %)志愿者肯定自己始终正确使用药物，20 名(55.5 %)不正确使用滴眼液。

结果

结果表明，所述 AUC 为 0.762（*P* 为高阈值<0.001），0.782（*P* <0.001）为介质的阈值，和 0.837（*P* 为低阈值<0.001）。

总之，我们看到随着测试的阈值变低，灵敏度增加而特异性降低，反之亦然。Humphrey 数据的最佳截止点是高阈值 28 dB、中阈值 25 dB 和低阈值 16 dB。

白色背景上的黑色/灰色刺激也进行了类似的测试，但不包括在本文中。

在实践中，当在常规筛查中重复使用单个测试时，通常在每次筛查访问中使用相同的筛查阈值。一种可能的替代方法是根据个人特定特征在连续访问时调整阈值[26]。测试结果可以串联或并联组合[27]。建议在诊断中进行平行测试，而在排除诊断时建议进行系列测试[28]。该软件允许用户选择两个或多个测试的结果并将

其合并为一个测试。显示了合并的每个点的积极响应的总和。

讨论

远程医疗视野筛查测试与经典的碗状视野检查有许多相似之处，但由于所使用的硬件而存在一些差异。

我们提出了一种具有新颖特征的视野测试，并通过将结果与 Humphrey 周边视野检测的结果进行比较来评估该方法的可靠性。

该测试的目的是帮助青光眼患者意识到他们的问题，尽管也可能检测到其他影响视野的疾病。

我们系统的优势在于它使用网络摄像头作为“光度计”，并在测试完成后验证结果的可靠性。该系统还允许患者通过电子邮件将结果发送给他/她的医生，并允许医生将两个或多个测试的结果合并为一个测试，以实现更高的统计准确性。

该测试简单、容易、快速，不需要专门的设备。每只眼睛只需要 2-3 分钟，并且可以根据需要重复多次。在测试结束时询问患者，他们报告说这很容易和简单。

移动应用是帮助促进人群健康的实用、低成本的工具，特别是对于风险人群，作为本研究的目标人群。从这个角度来看，一些研究已经在全球范围内证明了其他健康应用的可接受性和可用性[15，16，17，18]，但其中一些可用的应用没有评估用户随后的可用性及其对健康的积极影响，这与" GlaucoCheck "的设计和研究得到了印证。此外，这类应用的主要好处之一是它的大规模可及性，它通过使用便携式技术的可接受性转化为对获取健康信息的积极影响。

该测试在三个灵敏度级别实施超阈值视野测试算法。它旨在表明视野中是否有可能需要进一步检查的发现。应使用标准自动视野测试来量化缺陷。该测试并非旨在监测确诊病例的进展，而是用作筛查测试。

当将结果与从同一组患者 Humphrey 周边视野检测获得的结果进行比较时，计算了该测试的最佳截止点以及 ROC/AUC 特征。ROC 分析是一种广泛使用的评估医疗诊断系统准确性的方法。ROC 分析最理想的特性是从该技术得出的准确度指标不会因使用任意选择的决策标准或截止值而引起的波动而失真。换言之，准确度指标不受决策标准的影响。将此作为诊断性能的衡量标准，人们可以比较

单个测试或判断各种测试组合是否可以提高诊断准确性[29]。发现了良好的ROC/AUC 系数，范围从 0.762 到 0.837（P <0.001）。灵敏度范围为 0.63 至 0.94，特异性范围为 0.73 至 0.49。

其他系统也发现了类似的结果。与 Humphrey 周边视野检测相比，Peristat 在线视野测量具有可比的 ROC 曲线和范围从 0.55 到 0.77（所有 P <0.001）的 Spearman 等级相关系数。30 VFE 是一款用于视野测试的 iPad 应用程序，其 ROC/AUC 范围从 0.687 到 0.784[31,32]。

青光眼的患病率随着年龄的增长而增加。它在 70 多岁和 80 多岁的成年人中最为常见。该测试的主要限制是许多老年人从未学会使用计算机。障碍可能包括身体和精神上的限制。与任何其他计算机系统一样，老年人可能仍然需要年轻人、家人或照顾老年人的专业人员的帮助和支持。

结论

这种低成本测试的 ROC 特性表明，至少与 Humphrey 周边视野检测相比，它是可靠的，并且不需要专门的设备。该测试可能对家庭青光眼筛查有用。

数据共享声明

在当前研究期间生成和/或在当前研究期间分析的数据集可根据合理要求从相应作者处获得。非营利机构可以通过联系相应作者或发送电子邮件至 info@visual-field.com 来免费使用该软件。

伦理批准和同意参与

已获得雅典总医院科学与伦理委员会的许可“G. Gennimatas”进行研究。从所有参与的患者那里获得了书面知情同意书，并且该研究遵守了赫尔辛基宣言的原则。

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