Review

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Assessing the Accuracy and Clinical Potential of Virtual Reality-Based Visual Field Perimetry

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Assessing the Accuracy and Clinical Potential of Virtual Reality-Based Visual Field Perimetry

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Abstract

Visual field testing is critical in diagnosing and managing glaucoma, which affects over 80 million people worldwide, as well as other ocular diseases and stroke. Visual field test perimeters detect blind spots (scotomas) and map the boundaries of a patient's visual field. Standard perimetry machines are accurate, but prohibitively expensive and inaccessible in low-resource settings, while traditionally accessible forms of perimetry are less reliable. Virtual reality (VR)- based perimetry systems offer a potential low-cost, accessible alternative. This study reviews the development, clinical potential, and accuracy of VR perimetry. Findings showed that VR-based perimetry systems were comparable to, and in some cases even more effective than, standard perimetry tests, but these results were not universal, suggesting that greater standardization of testing protocols is necessary.

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Introduction

Visual impairment affects an estimated 2.2 billion people globally, and according to the World Health Organization, at least 1 billion of these cases were preventable or have yet to be addressed [1]. Visual field loss represents a significant fraction of these cases [2]. Glaucoma is the leading cause of visual field loss, followed closely by stroke and other optic nerve diseases [3]. Glaucoma typically occurs when the eye's drainage system becomes clogged or produces too much fluid, resulting in a buildup of excess fluid within the anterior chamber of the eye that can damage the optic nerve, as shown in Figure 1, causing vision loss [4].

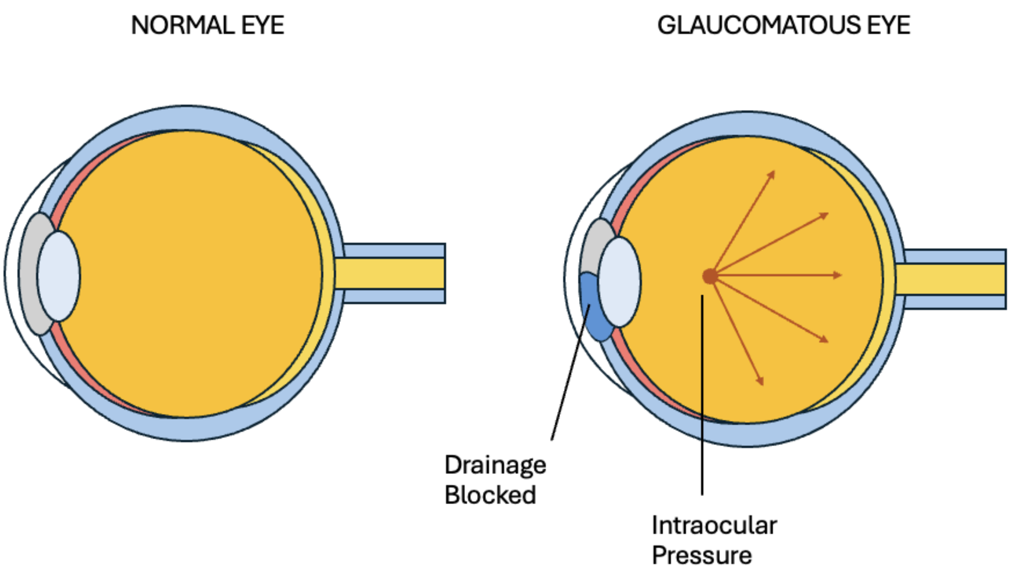

Figure 1. Healthy Eye Compared With Glaucomatous Eye Anatomy.

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The visual field is the total area in which objects can be seen in the peripheral vision as the eye focuses on a central point. Changes in a patient's visual field over time are often the most critical metric for evaluating a patient's vision progression. Visual field perimetry is therefore necessary for the diagnosis of glaucoma as well as for monitoring the progression of the disease [5]. Perimetry is used to recognize blind spots, called scotomas, and measure the boundary of a patient's visual field. Perimetry machines assess the visual field by measuring the retina's sensitivity to visual stimuli. Perimetry tests can be broadly categorized into two methodologies: static perimetry and kinetic perimetry. Static perimetry, the current gold standard for visual field testing, measures the retina's sensitivity to light at fixed points by displaying static stimuli at increasing brightness levels. Kinetic perimetry operates on a similar principle as static visual field tests; however, it involves detecting moving targets as opposed to stationary ones.

There exist different types of static and kinetic perimetry, which incorporate different concepts per their use case. Standard automated perimetry (SAP) is the most commonly used form of static perimetry. It uses a computer-controlled device to present stimuli on a white background at various locations in the visual field. Other experimental/specialized static VFTs include short-wavelength automated perimetry, frequency-doubling perimetry, reaction-time perimetry, and microperimetry. In low-resource settings, tangent screen perimetry, an older, manual form of kinetic perimetry, is used to assess the visual field despite being relatively imprecise compared to automated visual field tests.

Visual field perimetry is critical for the early detection of glaucoma, a disease that often progresses with few noticeable symptoms. Glaucoma is the leading cause of visual field loss, and missed or late diagnosis of glaucoma can lead to irreversible damage. Visual field testing has evolved over the past century from manual mapping with tangent screens to advanced computer-automated platforms capable of highly precise threshold measurements, yet it has also become increasingly expensive and inaccessible. Thus, in low-resource and rural settings, visual field assessment capabilities are relatively limited and outdated, leading to worldwide disparities in care. However, in recent years, advances in electronics and immersive technologies such as virtual reality have opened the door to the development of novel approaches to perimetry that may help address the limitations of traditional automated perimeters and bridge this gap.

Background

The ZEISS Humphrey Field Analyzer (HFA) is the gold standard perimeter for visual field testing, primarily in glaucoma assessment. The HFA is an automated perimeter that measures a patient's ability to detect light stimuli at various points in their field of vision [6]. HFA visual field test formats are named by two numbers, separated by a hyphen. The first number represents how far out in degrees the test measures in each direction. The second number denotes the test type or version. For example, the 30-2 visual field test extends out in 30 degrees in each direction, encompassing 60 degrees across every axis. Humphrey machines can perform multiple test formats, such as 24-2, 30-2, and 10-2. The 30-2 visual field test takes far more time than the 24-2 or 10-2 visual fields, resulting in more patient fatigue and less reliability. Droopy eyelids are frequently a symptom of fatigue, which obscures vision in the superior part of the visual field. 24-2 is considered to be the best of the three tests, covering a similar area to the 30-2 visual field while maintaining its reliability [7]. During a test, the patient places their head on a chinrest and concentrates their gaze on a central fixation point located in a large, white bowl [6]. The test is usually conducted in a dark environment so that the patient may see the lights.

Modern visual field perimetry tests can be classified as static or kinetic. Static perimeters evaluate the visual field by displaying stationary stimuli at increasing levels of brightness until they are visible to the eye. The patient indicates when they are able to see the stimuli, thus determining the threshold of vision and mapping out the patient's visual field [8]. There are many types of static perimetry. Standard automated perimetry (SAP), also known as white-on-white perimetry, is the most trusted form of perimetry and uses a white background with white stimuli. While the placement and size of stimuli are used to record spatial vision loss, light intensities record sensitivity loss. The machine

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varies the stimulus intensity until the patient can no longer see the point. Afterward, the machine then increases the sensitivity once again until the patient can see the stimuli, pinpointing the dimmest stimulus that the patient can see 50% of the time. Short-wavelength automated perimetry (SWAP), also referred to as blue-on-yellow perimetry, has been shown to detect visual field loss reduction faster than standard perimetry methodology [9]. Unlike SAP, SWAP uses blue stimuli on a yellow background. The blue color deficit in the eyes has been associated with glaucoma. Short-wavelength colors like blue are thought to be recognized primarily by a specific population of retinal ganglion cells, which are thought to be lost in earlier stages of glaucoma. In frequency doubling perimetry, an automated device displays a striped pattern that flickers rapidly, creating an optical illusion where the stripes seem closer together than they actually are. Certain regions in the retina that are lost early in glaucoma are associated with recognizing illusions like frequency doubling, and the test can therefore evaluate loss of function in specific regions [10].

Kinetic perimeters evaluate the visual field by displaying moving stimuli as opposed to stationary ones. Stimuli that are constant in brightness and size move across the visual field, enabling clinicians to map the boundaries of the visual field based on where the stimuli are seen. Goldmann perimetry is a form of kinetic perimetry that requires a high level of skill and precision from the clinician, as each point in the visual field is manually mapped out. The test involves presenting six different stimulus sizes with varying brightness levels on a hollow white spherical bowl, starting outside the patient's visual field and slowly moving inward [11]. The patient signals when they see the stimulus by providing a simple response such as pressing a button or tapping the table. The clinician then marks the point where the stimulus becomes visible. Scotomas are mapped in a reverse process: the stimuli begin in the center of the visual field and slowly move outwards until they are no longer visible. Varying stimulus sizes and brightness levels are represented by specific colors on the resulting diagram. The final result is similar to a topographic map, where scotomas appear as dark regions, showing areas of reduced vision and designating the patient's visual field [6]. Tangent screen perimetry, also known as Bjerrum screen perimetry, is another form of kinetic perimetry typically used to assess the central 30 degrees of a patient's visual field. The test is manually administered by a clinician and utilizes a large black screen with a pattern of radians and circles sewn, a white button in the center of the screen, a black wand, black pins, different targets, an occluder (used to cover one eye), and a score sheet. The white button serves as a central fixation point, and the patient sits a meter away from it, with their eyes leveled with the button. The clinician attaches targets of varying sizes and colors to the black wand and covers one of the patient's eyes. Each target is moved along different radii of the screen, and the patient indicates when they can see it. Tangent screen perimetry is more commonly administered in low-resource settings, although it is considerably less accurate compared to other forms of perimetry.

Development of VR Perimetry

Gold standard, reliable perimeters, namely the HFA, have several critical limitations: their high cost, limited portability, and dependence on developed clinical infrastructure. These limitations contribute to a worldwide disparity in ophthalmologic care. As a result, considerable research has been performed by research groups and companies on advanced perimetry systems utilizing novel virtual reality (VR) technology. These emerging VR-based perimeters seek to offer accessible, portable, and user-friendly alternatives for visual field testing in both clinical and remote settings.

Testing time is a key metric in evaluating the effectiveness of perimeters. Longer testing times can contribute significantly to patient fatigue, leading to increased error. Several studies reported that VR-based perimetry systems demonstrated lower testing times compared to the HFA's static perimetry test [12]. For example, the GlauCUTU VR perimeter showed an average efficiency of 254.41 seconds for 24-2 tests, compared to 609 seconds using the HFA [13]. However, these results were not universal. Other studies, conversely, reported that VR-based perimetry systems demonstrated higher testing times compared to HFA tests [14]. For example, an experimental perimeter running the LUXIE VR perimetry software on the HTC Vive Pro Eye headset had tests of 10.0 ± 1.4 min, which was significantly longer than that of the HFA (7.3 ± 0.1 min). This suggests that efficiency depends on factors like test and headset design, and user interface.

In terms of accuracy, studies have shown promising results for VR-based perimetry. VisuALL showed strong detection capabilities for glaucomatous visual field loss, while VirtualEye, which includes advanced eye-tracking hardware and software, showed high correlations with the HFA [14,15]. However, the setting of test administration seems to play a crucial role in the accuracy of tests. Turner et al. found that remotely administered tests proved to have a lesser correlation with the HFA compared to clinically administered visual field tests using the same VR-based perimeter [16].

Fixation monitoring remains one of the most critical challenges in VR-based perimeters. Unlike traditional perimeters like the HFA that track fixation using expensive equipment and cameras, VR-based perimeters have only recently begun to incorporate fixation monitoring. Fixation loss introduces false negatives and positives, making it a common source of error in VR-based perimeters. For example, the C3 Field Analyzer was demonstrated to be less accurate than the HFA and largely struggled with fixation loss [17]. Conversely, VirtualEye showed higher accuracy and reliability with the inclusion of eye tracking [15]. Additionally, Hotta et al. showed that using eye tracking and gaze estimation led to higher accuracy and a reduction of fixation loss in VR-based perimetry [18].

Discussion

In order for VR-based perimetry to become clinically viable, several technological challenges must be addressed. Firstly, VR-based perimeters must achieve measurement accuracy that is comparable to that of gold-standard devices such as the Humphrey Field Analyzer. VR-based perimeters must also overcome limitations in testing times, especially compared to the Humphrey Field Analyzer, and improve patient comfort during prolonged testing sessions, as the weight of the headset could create postural discomfort or introduce greater testing fatigue that is not present in traditional visual field tests. Additionally, VR-based perimeters must overcome limitations in fixation monitoring due to a lack of precise eye tracking, as fixation loss introduces an increased frequency of false negatives [19]. Some studies reported lower correlations between VR headset-based perimetry and standard testing due to differences in test administration, emphasizing that standardized testing protocols for VR-based perimetry must be developed to ensure consistency in results and across platforms [16,20].

In the future, virtual reality may prove to be the optimal medium for perimetry. Next-generation perimetry systems will combine sleeker virtual reality technology with advanced artificial intelligence and sensing capabilities, increasing accuracy and reliability profoundly. As VR hardware evolves, VR-based perimetry systems will also become lighter and more affordable. Improvements in eye-tracking and pupil monitoring will allow VR headsets to compensate for the lack of large machinery in reducing fixation loss. An exciting possibility is the prospect of patient self-monitoring of the visual field, which becomes feasible as VR headsets become more affordable. Moreover, VR-based tests could be designed to be more engaging, perhaps even gamelike, to reduce test fatigue, and tests could assess visual field function in everyday scenarios, such as in driving simulations. Thus, while precision, reliability, and clinical integration remain key challenges, VR perimetry holds great promise as a next-generation visual field screening tool.

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