

Visual function tests for glaucoma practice - What is relevant?

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Glaucoma represents one of the most important ocular diseases causing irreversible ganglion cell death. It is one of the most common causes of visual impairment and morbidity in the elderly population. There are various tests for measuring visual function in glaucoma. While visual field remains the undisputed method for screening, diagnosis, and monitoring disease progression, other tests have been studied for their utility in glaucoma practice. This review discusses some of the commonly used tests of visual function that can be routinely used in clinics for glaucoma management. Among the various modalities of testing visual function in glaucoma, this review highlights the tests that are most clinically relevant.

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Glaucoma, an age-related progressive optic neuropathy, represents the leading cause of irreversible blindness globally.^[1,2] This disease is well characterized clinically, with volumes of literature existing on the different forms and pathogenesis of the disease. An equally more extensive work of literature exists, detailing the diagnostics tools for screening and monitoring glaucoma progression.^[2-4] Visual function represents the functions of the eye that are compromised by glaucoma (such as visual acuity and visual field being of prime importance). In contrast, functional vision means the tasks in daily life served by visual acuity in vision-related activities (eg., reading ability and driving) that are quantified using various quality of life measures. Yet, visual field remains the gold standard for testing the visual function in glaucoma practice, with other faculties of visual function being conspicuously absent in routine glaucoma examination procedures.^[4] This review explores the various faculties of visual function and updates about the known and unknown anatomical basis of visual functions that are affected in glaucoma and evaluates the applicability of these into routine clinical glaucoma practice.

Functions of the Retinal Ganglion Cells and Its Implication in Visual Function: A Brief Update

Faculties of visual function served by ganglion cells

The retina houses 0.7–1.5 million retinal ganglion cells that connect to rods, cones, and photoreceptors.^[5,6] The distribution of the RGC in the central retina, their structure, and functions are different in the central and peripheral

part of the retina, which imparts the macula with specific functions served by the ganglion cells.^[5-9] Chemical messages sensed by receptors on RGC transform it to intracellular signals by the RGC dendrites and soma, which is conveyed as nerve spikes forward onto the visual specific neural circuitry.^[5-9] Processing of the information by complex processing systems in the vertebrate retina, with the maintenance of topographical localization and hierarchy of information in the visual circuitry, is what determines different visual functions such as visual acuity, color, movement, direction, and speed of movement and contrast (Fig. 1). The RGC axons are directed to specific visual centers according to the visual trigger or information they encode and transmit constituting topographic integrity along the visual circuitry. The RGCs are broadly classified as tonic or phasic cells.^[5,8,9] The tonic cells exhibit a sustained response and are called midget or parvocellular cells, which relay information to the parvocellular pathway.^[5,8,11-13] In contrast, the morphologically larger phasic cells relay information to the magnocellular layers of the lateral geniculate nucleus in the thalamus. Midget cells respond best to stimuli with high contrast whereas phasic cells respond to low contrast over larger areas.^[9,11] The visual system collects signals from various RGCs which relay information in parallel pathways. The RGC subtypes are distributed spatially in a nonrandom fashion with an overlap of dendritic/receptive fields occurring in a specified ordered mosaic or group of RGC subserving common or different visual functions.

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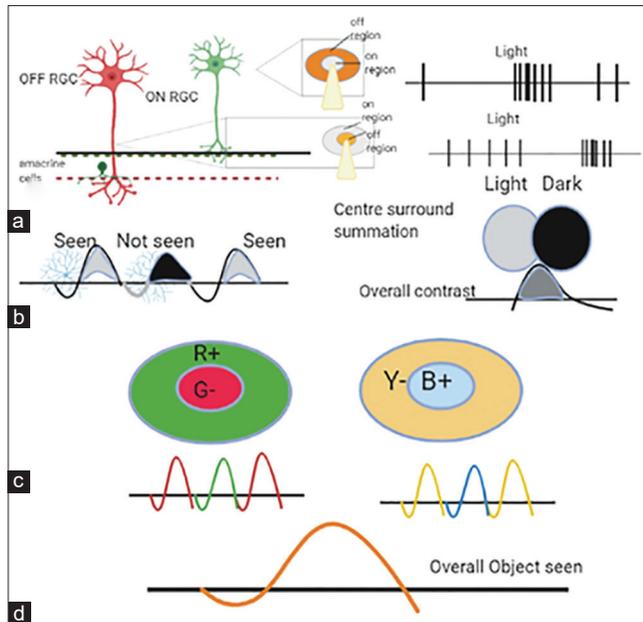


Figure 1: Different functions of ganglion cells serving different faculties of visual function. (a) left panel shows topographical stratification of ON and OF retinal ganglion cells (RGC) that stratify close to the ganglion cell bodies or amacrine cells, respectively. Middle panel shows center-surround response characteristics in response to the stimulus presented on to receptive fields of RGC. Right panel shows the response waveforms produced by ON-center or off-center stimuli presented on to RGC receptive fields. (b) Graphical representation of summation of responses from bright or dark stimuli by center-surround summation determining the overall contrast of any object. (c) Center-surround summation for different color-opponent RGC resulting in summation of the color of objects. (d) Overall object seen as a summation of visual stimulus responses along with the summation of color and contrast

Size selectivity of RGC and receptive fields - key for visual information processing

The "ON" type fibers respond with a transient burst of impulse followed by continuous elevated discharge rate throughout the time of light stimulation.^[10,11,13] The "OFF" center fibers respond to sustained impulse discharge after the light stimulus turns off (Fig. 1a). The "ON-OFF" fibers react with a burst of activity at the onset and offset of the stimulus. This type of stimulus-response forms the basis of hierarchy or subcategorization of information (also called visual function features, say color or contrast) by the RGCs, which also determines the area subserved in the visual cortex.^[6,11] The RGCs stratify and connect to bipolar cells in different layers of the inner plexiform layers with the ON-center fibers establishing connections close the RGC bodies, while the OFF-center fibers being close to the amacrine cells.^[13,15-17] This organizational hierarchy is further maintained by the receptive fields of the RGC that define the spatial properties of the RGC.^[11] The receptive field is merely the region in which the RGC would respond to a particular stimulus of a specific size. Increasing stimulus size after excitation of the RGC can result in the cessation of the stimulus excitation responses. The ON-center receptive field responds at the onset of a centrally placed bright light, while the OFF-center receptive field responds to an offset of the light stimulus. The ON-center

cell also responds at the offset of an annulus of light while the OFF-center cell responds to the onset of a light annulus. This center-surround physiologic function, combined with the selectivity of each RGC to stimulus size, determines the complementarity of the receptive field of ON- and OFF-center cells with overlapping receptive fields.^[10,12,14-17] This ensures excitation responses to changes from sustained to transient as stimulus moves from center to surround (for ON-center cells) and inhibition of the center with surround stimulation. These determine the final RGC response encoded by the stimulus, which forms the basis for the specific visual function recognized by the visual system.^[17-19]

Contrast sensitivity

Dendritic span is a critical factor that enables RGCs to collect signals over a large area of visual space.^[11,12,14,17] The size selectivity of RGC causes offset responses as stimulus size becomes more extensive. Contrast sensitivity functions are a result of spatial tuning on ON/OFF receptive field characterization induced by spatial sine waves that consist of alternating light and dark bands.^[6,11,20-26] Briefly, for contrast characterization, the difference in intensity of the light and dark stimulus is reduced until the ganglion cell responds to a stimulus, which forms the contrast threshold of that RGC (Fig. 1b). This threshold is different for patterns with varying widths of the bar, or "spatial frequencies" (number of light-dark bar-pairs per unit per distance), which determines the contrast sensitivity function curve, where the sensitivity (reciprocal of contrast threshold) is plotted against the spatial frequency.

Movement-speed, directional localization of movement

Hyperacuity is the ability to detect movements within the receptive field of the ganglion cell. Specific ganglion cells elicit excitatory responses to stimuli moving in a particular direction while being inhibited by stimuli moving in the opposite direction.^[27] These RGCs also have a preferred speed of motion of the stimulus while being indifferent to the size, nature, or contrast of the stimuli. They also exhibit ON-OFF center-surround characterization and display distinct dendritic morphology for ON and OFF cells. The machinery and pathways encoding these information signals are not fully understood. Yet, they form an integral function of the RGCs, which may affect the quality of vision in patients with glaucoma.

Chromatic vision

The RGC subserve an essential yet complex process in vertebrate retinas-color vision. They add or subtract information from cones and compare the information obtained from middle-long wavelength cones that determine the hue/saturation or amount of red/green in the stimulus.^[27-32] The on-off center-surround characterization also plays in deciphering the color and saturation of the color stimulus with excitation responses triggered by a stimulus in the center while getting inhibited at the periphery (Fig. 1c). The RGCs not only decipher the color of the stimulus with specific processing stratifications and characterization but also provide information about the extent of particular colors (hues/saturation) and the brightness of the stimulus.^[29,31] These are imparted by the color opponent responses and the responses of the RGCs to light. In cells receiving input from the various spectral class of cones, the relative strength of color cone

inputs can be altered by differently colored backgrounds; this is termed as “selective chromatic adaptation.” Color opponent ganglion cells have a center and surround with different color opponent properties (Fig. 1c). In a double opponent ganglion cell, each color mechanism in the receptive field at the center is opposed by the same color type but the opposite sense in the surround. This confers the ability to detect color changes at the edges or periphery of an illuminated target. In addition to information about color from cones, ganglion cells also relay a monochromatic or achromatic signal from rods.^[6,11,28,31]

Other less-known accessory RGC functions

It is less known that specific RGCs play a role in maintaining the circadian rhythm.^[33-35] These specific RGC project onto the suprachiasmatic nucleus in the hypothalamus and contain a chemical called melanopsin. They receive inputs from amacrine cells and cone bipolar cell axons. They have endogenous photoreceptive properties, implying that they can relay luminance signals directly without the need for information from rods and cones. These RGCs are also believed to relay signals of the pupillary light responses through additional projections to the project to the lateral geniculate nucleus and to the Edinger–Westphal nucleus (EW).^[34,35]

What is Affected in Glaucoma - Basis for Visual Function Tests?

Glaucoma affects the ganglion cells of the retina.^[2,3] While traditional knowledge exists that the magnocellular pathway is more susceptible to glaucoma damage, this has now been questioned, with histopathological evidence for identifying RGC types in sections not proving this theory unequivocally. Further shrinkage of cell soma with injury may cause shrinkage of large cells, thereby giving a false impression of small RGC on sections.^[8,11] Moreover, psychophysical tests of contrast and scotopic sensitivity suggest aberrations in both parvocellular and magnocellular pathways. While studies have demonstrated excitotoxic injury and loss of trophic factors causing axonal damage to RGC, it is now recognized that the dendrites of the RGC may show the earliest evidence of degeneration or cell death, which needs further exploration.^[2,3,8-13,31,32] Therefore, it may be wise to conclude that both small and larger ganglion cells are equally susceptible to damage that may cause disturbances in contrast, visual field, color vision, or scotopic sensitivity.

Currently, glaucoma monitoring entails regular perimetry and sometimes contrast function or quality-of-life measures.^[29-31] Other visual functions such as color vision have not found applicability in clinics so far. So far, only level II evidence exists on the use of other visual functions such as color vision in glaucoma.^[31] This is largely because of various issues with each instrument/technology, such as cost issues, lack of direct correlation with severity of glaucoma, lack of demonstration of the utility in monitoring progression, or simply the lack of wide access to the technology.^[31] No level I evidence states the superiority of any one visual function over the other, or studies do not compare the utility of all visual function tests in routine glaucoma clinics for screening and monitoring glaucoma progression. We now detail in brief routine tests that capture ganglion cell function in different ways and discuss the causes for their lack of applicability in routine glaucoma practice.

Tests for Assessing Ganglion Cell Function

Perimetry

As structural changes precede functional damage, various psychophysical tests of visual function have been developed for detecting early glaucomatous visual loss; however, standard automated perimetry (SAP) is the current gold standard.^[2,3,36-44] A perfect structure–function correlation is rare in glaucoma. Yet, newer tools aimed at minimizing this structure–function disparity are under investigation.^[37] While visual field or perimetry remains the mainstay of assessing visual function in glaucoma, the subjective responses, test–retest variability, and extended testing times have prompted the search for other alternatives to evaluate RGC function. Other forms of perimetry such as short-wavelength automated perimetry, SWAP, and microperimetry assess functions of different RGCs [Table 1].^[39,44,45-49] This is based on the premise that different RGCs may be more susceptible to early damage, which may be missed in normal visual field or standard automated perimetry. Table 2 details the essential aspects of the three main perimetry techniques used in clinical practice. Over the years, this technology has evolved, with various algorithms being developed for automated estimation of progression or stability of the disease and this has found wide applicability among routine clinics. As other forms of perimetry such as high pass resolution and microperimetry have not found their place in routine clinical practice, we restrict our following discussion on methods that are more common and readily available for use by clinicians.

Photopic negative response in glaucoma

Electroretinography (ERG) is a noninvasive or minimally invasive method of objective assessment of visual function.^[43,50,51] Pattern electroretinogram (pattern ERG) isolates retinal ganglion cell function and is highly specific for detecting early glaucoma.^[50-53] Yet, this cannot provide a measure of focal changes seen early in glaucoma. The pattern ERG amplitude correlates linearly with structural changes in the optic nerve head in glaucoma.^[50,54-57] Yet, level 2 evidence suggests that pattern ERG may not yet be a sensitive enough tool to detect very focal loss of ganglion cell function in the early stages of glaucoma. Full-field flash ERG is the cumulative response of distal retinal neurons rather than representing pure RGC responses. Nevertheless, there are few other features of full-field flash ERG such as scotopic threshold response (STR) and photopic negative response (PhNR) that are now recognized to measure RGC function.^[50,54,56,58,59] The PhNR is a useful clinical diagnostic procedure for the assessment of RGC function in optic nerve pathologies, including glaucoma.^[59-65] The photopic negative response (PhNR) is the negative-going wave following the b-wave of cone ERG response [Fig. 2a and b]. It measures both a-wave and b-wave simultaneously and evaluates the function of the middle and outer retinal layers.^[59]

Experimental studies have reported that the PhNR originates from RGCs and/or their axons with decreased amplitude seen in glaucoma.^[59,60] Focal PhNR has a higher sensitivity (90%) than full-field PhNR (77%) in recognizing early glaucomatous functional losses.^[60,62] The possible reason for decreased sensitivity of full-field PhNR in early glaucoma can be attributed to a higher population of RGC in the center and the other retinal cells in the periphery, which may therefore contribute more for full-field PhNR responses.

Table 1: Comparison of most used techniques for measuring visual function in glaucoma

	Visual field SAP	SWAP	Electroretinogram PERG, PhNR, mfERG	VEP	Microperimetry	Contrast	Color vision	Reading ability
Ease of use in routine clinics	✓	✓	-	✓/-	✓	✓	✓	-
Testing times	15 min per eye	10 min per eye	15 min per eye	15 min per eye	10-15 min per eye	5 min per eye	5 min per eye	10-20 min per eye
What they measure	RGC function/ threshold	Koniocellular pathway specific RGC	RGC + bipolar cells and other cells response possible	Signals generated in visual cortex to visual stimulus	Retinal sensitivity at various retinal regions	RGC function	Cones and RGC function	Ganglion cells?
Special equipment	Yes	Yes	Yes	Yes	yes	No	No	NO
Useful for monitoring progression	Yes	Uncertain	Uncertain	Uncertain	Uncertain	Uncertain	Not yet explored	Not yet explored
Disadvantage	Test-retest variability Time consuming/ fatigue	Fallacious in presence of cataract	Fallacious in presence of cataract Other cell responses, other diseases influence responses	Not sensitive for focal damage in glaucoma	Media opacities, other pathologies influence results	Media opacities, other pathologies influence results	Media opacities, other pathologies influence results	Media opacities, other pathologies influence results
Advantages	Useful for all stages, all ocular conditions with correlation, algorithms for progression	Useful for early glaucoma when SAP is normal	Useful for early glaucoma when SAP is normal	Useful for early glaucoma when SAP is normal	Useful for all ocular conditions	Can be an objective measure of the quality of visual function complimenting visual fields	Can be an objective measure of visual function complimenting visual fields	Can be an objective measure of the quality of vision complimenting visual fields

SAP - standard automated perimetry; SWAP - short wavelength automated perimetry; PERG - pattern electroretinogram; PhNR - photopic negative response; VEP - visual evoked potential; RGC - retinal ganglion cells

Table 2: Comparison of parameters involved in three different types of perimetry

Characteristics	Static automated perimetry (SAP)	Short Wavelength automated perimetry	Microperimetry
What they measure	Ganglion cell threshold sensitivities	Konicellular pathway ganglion cells	Retinal sensitivity across retinal regions
Background and stimulus color	White on white	Blue on yellow background	Red stimuli on white background or white on white
Stimulus luminance	High (3183 cd/m ²)	Low (100 cd/m ²)	Low (130 cd/m ²)
Fixation analysis	Poor, difficult in eccentric vision	Poor, difficult in eccentric vision	Superior, unaffected in eccentric vision
Procedure	Automated	Automated	Manual
Age corrected Threshold	Available	Available	Lack of age-corrected threshold Values
Level of luminance	Changes at each test location	Changes at each test location	Same at all test locations
Preferred retinal locus (PRL)	Cannot identify the location of fixation or PRL in advanced field loss	Cannot identify the location of fixation or PRL I advanced field loss	Can identify the location of fixation or PRL in advanced field loss

Machida *et al.* investigated focal ERG PhNR in 38 open-angle glaucoma patients (OAG), 12 glaucoma suspects (GS), and 32 healthy controls and found a strong correlation between local retinal sensitivity and amplitude of the focal PhNR, with high discriminatory power to differentiate glaucoma from normal eyes.^[63] Another study by Kamada *et al.*^[64] concluded that focal PhNR is effective in identifying functional losses in early

glaucoma where SAP is normal, and the amplitude significantly correlates with the localized damage of the optic nerve head and retinal neurons. Viswanathan *et al.*^[60] observed that PhNR is capable of detecting and monitoring glaucoma progression. Another notable study by Machida *et al.*^[65] found that PhNR amplitudes strongly correlated with the ganglion cell complex thickness on spectral-domain OCT in the center with poor

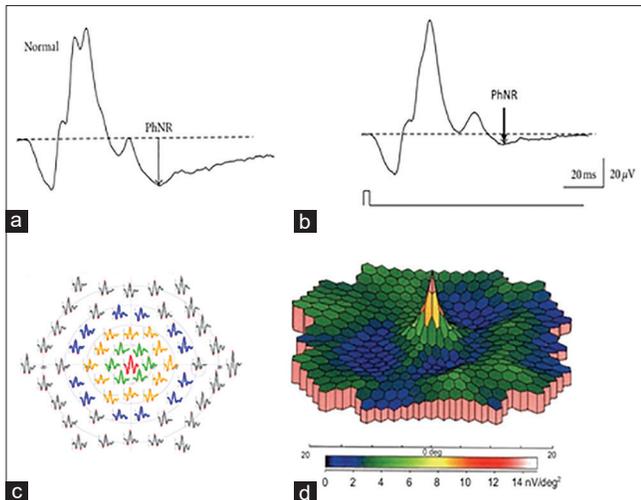


Figure 2: (a) Photopic negative response (PhNR) of a typical electroretinogram (ERG) of a normal patient. (b) Photopic negative response (PhNR) of a typical electroretinogram of a patient with glaucoma showing decreased PhNR amplitude. (c) multifocal ERG showing 103 hexagonal topographical testing regions with D showing a color-coded map of the relative sensitivity of response from each retinal region

correlation outside the macula. Further studies need to be conducted to evaluate its application in routine clinical practice and its correlation with visual field/structural parameters.

Pattern electroretinogram

Pattern electroretinogram (PERG) is a retinal bio-potential response to a pattern stimulus with temporal and spatial high contrast modulation.^[53-55,66,67] Transient PERG is formed by 2–4 reversal/second waveform with an initial positive P50 wave followed by a negative N95 wave, and steady-state PERG is generated by 16 reversals/s.^[50,53,54] This allows the cone bipolar and cone photoreceptor cells to cancel each other and only reveal the RGC function. Thus, PERG is a direct measure of RGC function and a promising clinical tool to detect early glaucomatous loss.

Ventura *et al.*^[67] evaluated RGC functions by using steady-state PERG in 200 glaucoma suspects, 42 early glaucoma, and 16 healthy subjects and found that PERG amplitudes correlated significantly with worsening of mean deviation (MD) values in SAP and larger vertical cup disc ratio. Bayer *et al.*^[68] examined SWAP, frequency doubling technique perimetry (FDT), and pattern ERG in patients with primary open-angle (POAG) and found that SWAP MD and PERG P1N2 amplitudes diagnose early glaucomatous functional damage in POAG patients even with a normal SAP. Reduced PERG amplitudes can precede future functional loss in SAP.^[54,55] However, Hood *et al.*^[69] demonstrated that transient PERG may overlook glaucomatous loss in 30% of patients with abnormal visual field in mfVEP. In summary, PERG is an important clinical tool in identifying RGC functions in early glaucoma patients with or without SAP defects. However, some technical and methodological aspects may hinder routine clinical use such as media opacities, advanced age, and technical difficulty. Future studies with advanced techniques will improve the ability of PERG to diagnose early-stage glaucoma.

Multifocal ERG

The multifocal ERG (mfERG) measures responses from multiple retinal locations from a single recording.^[50,70-77] It is primarily generated by the photoreceptor and bipolar cells of the retina. The stimulus in mfERG constitutes an array of either 61 or 103 white and black hexagons alternating in a semi-random sequence with the fixation target located at the center (Fig. 2c and 2d). The structure–function analysis can be enhanced in glaucoma when mfERG test is combined with OCT and SAP.^[74,75] Moon *et al.*^[72] studied the relationship between visual field defects and mfERG optic nerve head component (ONHC) in 39 glaucoma patients and 30 healthy controls. They found that the ONHC amplitude was decreased in glaucoma patients with excellent topographic relation with visual field defects. Golemez *et al.*^[70] demonstrated the good ability of the amplitude and implicit times of N2 mfERG responses in the center to discriminate glaucoma from normal before SAP. Rao *et al.*^[74] compared mfERG responses to retinal nerve fiber layer (RNFL) thickness in glaucoma patients and found that RNFL thickness significantly correlated with the P1N2 amplitude of mfERG. It is now recognized that N2P1 amplitude on mfERG may be an essential parameter for monitoring early and moderate glaucoma. In another subsequent study, the ganglion cell inner plexiform layer thickness on SD-OCT strongly correlated to mfERG responses in healthy and glaucoma patients.^[71,70,74,75] In conclusion, mfERG can be utilized to identify early glaucomatous changes in specific retinal or focal areas. Its routine use is limited by the need for longer testing times and the lack of a unified parameter defining glaucomatous damage in different stages of glaucoma.

Contrast sensitivity

Contrast sensitivity (CS) is the measure of the difference between the brightness of one object with its background, more acceptably the difference between two different amounts of dazzle from the target and the surroundings.^[78] Visual acuity measures visual function from lower luminance optotypes tested against a background of higher luminance, which does not represent a typical physiological scenario in the real world with different intensities of light of the target and background.^[79] However, contrast sensitivity function (CSF) measures the spatial frequency with different levels of contrast sensitivity (Fig. 3). Two formulas are universally used to quantify the contrast. Weber formula is used with constant background luminance. However, in the case of changing brightness of both target and the background, Michelson formula is more suited.^[79]

Weber contrast = (Luminance max – Luminance min)/Luminance background.

Michelson contrast = (Luminance max – Luminance min)/(Luminance max + Luminance min). The inverse of CS is known as the contrast sensitivity threshold (CST) and describes the minimum contrast required by an individual to discriminate an object from its background. Unlike visual acuity measurements, which maintain a steady 100% contrast level for all letters, contrast sensitivity tests often use targets of a given size with variable brightness until an image is no longer visible. Both photopic and scotopic contrast can be measured against a background of 80–100 cd/m² and 25–32cd/m², respectively. Measuring the CST for various stimulus sizes is used to plot the contrast sensitivity function curve (CSF)

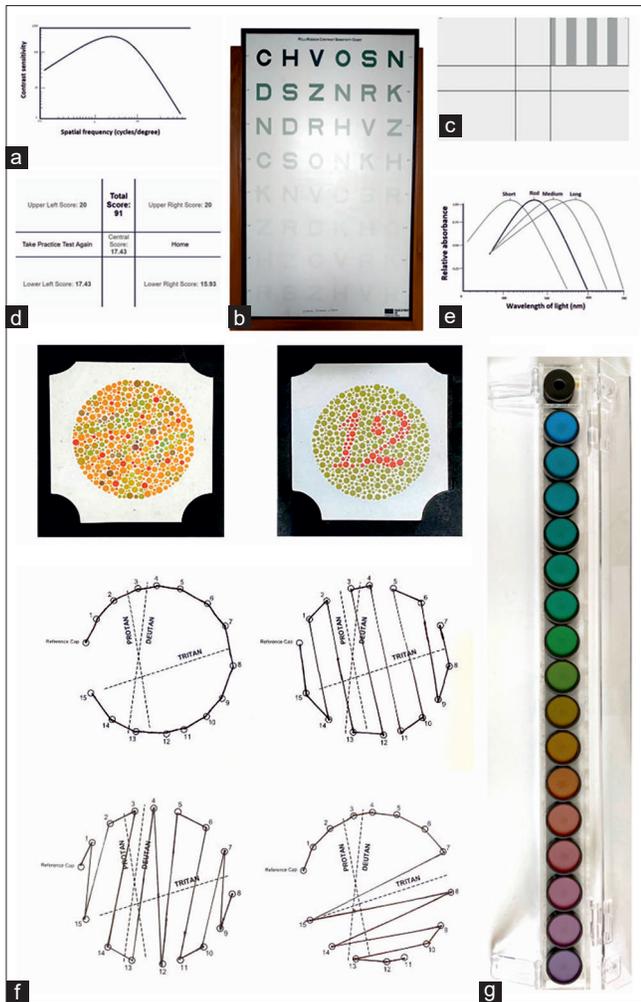


Figure 3: (a) The contrast sensitivity function curve showing the threshold of contrast as a function of spatial frequency. (b) Pelli–Robson contrast chart for measuring contrast sensitivity. (c) and (d) show Speth–Richman contrast sensitivity measure. (e) spectral sensitivity of rods and different types of cones serving color vision. (f) Ishihara color vision tests. (g) Farnsworth–Munsell D-15 panel test for measuring color vision (see text for detailed description)

for each patient to determine the exact distinction between the object and background. The better the discriminatory ability to identify an object amidst a background, the greater the quality of vision and processing of fine details. Several charts of different target stimuli, range of values, various step sizes, and psychophysical measures are available to assess the contrast sensitivity.^[80-83] All charts display the contrast sensitivity in the form of gratings or letters. The grating charts include the Arden grating plate, Cambridge, CSV-1000, and functional acuity contrast test (FACT); Vistech while letter-based charts include Regan, Pelli–Robson, Mars, and HACSS charts. Studies have shown that grating-based charts are time-consuming whereas letter-based charts are easy to understand and are more commonly used in clinics.^[80,83] The main drawback is test–retest variability and repeatability that have not encouraged their everyday use in routine clinics. The Pelli–Robson test (PR test), a wall-mounted chart, consists of 6 lines of letters in triplets on each line with a step size 0.15 log unit per triplet and each letter subtending an angle of 3°

from the subject's eye. The Mars letter contrast sensitivity test consists of eight rows of six letters (step size of 0.04 log units) with each letter subtending 2° from the subject placed at 0.5 m.

Previously, there was a thought to the loss of larger RGCs in glaucoma, but it is now known that shrinkage of all cell types of RGCs takes place wherein both cells of the magnocellular and parvocellular pathway are equally susceptible to damage.^[79,82,83-88] Studies have established a significant correlation between CS and Falls, motor accidents, reading speed, computer task ability, and driving performance.^[26,89-93] Unlike visual acuity, CST represents a more robust measure of visual function, which is valuable in diseases such as glaucoma. Contrast sensitivity tests can be used as a screening tool in those places where the expensive setup of visual field is not accessible. To further extend its use in routine clinics for glaucoma, a search for electronic CST tests has resulted in newer tools that are both easy and useful measures of visual function. Among all, the Spaeth/Richman contrast sensitivity (SPARCS) test has been a significant contribution in this field.

SPARCS is a novel, standardized Internet-based test that measures the central and peripheral contrast sensitivity.^[94-97] A monitor set with 1024 × 768 resolution represents the vertical square-wave gratings of 256 grey levels over an area that extends up to 30° horizontally, 23.5° vertically, 5° centrally, 3.5° horizontally and vertically. Sine-wave gratings (spatial frequency of 0.4 cpd appearing for 0.3 s) are presented in five quadrants of the field while the patient fixates on the central area (Fig. 3). The contrast sensitivity ranges from 100% to 0.45% with a decrease of 0.15 log units in each step. This test calculates CST using the Weber formula and displays the score in each quadrant and in the center-like visual field thresholds, which is tested at all quadrants. The SPARCS test has been shown to have good test–retest repeatability with excellent correlation to PR contrast and vision-related quality of life measures. This test can be administered at home or office without the need for an experienced technician for performing the test.^[22] This test also addresses the drawbacks of the Pelli–Robson chart, such as uneven illumination, chart fading, reflection, storage issue, and expensiveness, making SPARCS a good alternative for measuring visual function in glaucoma patients. More studies can reflect its utility in its use as a routine tool for glaucoma progression and monitoring complementing the visual fields, which are the gold standard.

Chromatic vision

It refers to the ability to distinguish hue, saturation, and brightness of different wavelengths of light. Color vision is predominantly contributed by three types of cones in which L and M cones are mostly packed in the center of the fovea.^[29-31,33,35,97-105] Multiple responses with different photopigments confer different light sensitivities: blue, green, and red, or short (S), medium (M), and long (L) wavelength cones represent these three cones providing the information of color that excite them. Various color vision tests are designed, including pseudoisochromatic test, arrangement test, anomaloscopes, and lanterns test (Fig. 3).^[97-105] Pseudoisochromatic plates easily detect red-green deficiency than blue-yellow deficiency. The premise of these tests is the inability to discriminate between specific colors. The widely used plate is the Ishihara test, which contains 38 plates. The

Richmond HRR test is also a pseudoisochromatic test, but in addition to Ishihara, it detects Tritan deficiencies and grades the color vision defect as mild, medium, and strong. Arrangement tests based on hue discrimination ability present a set of colored samples of different hues to the subject whose task is to arrange caps in a sequence. Hence, the color ability is measured by an observer's skill in organizing and matching color series and can therefore quantify color vision defect rather than just measuring the type of color vision deficiency. Farnsworth–Munsell 100-hue test and Farnsworth panel D-15 test are examples of such color vision tests. Another variant, the desaturated panel D-15 test, has samples paler than Farnsworth, which makes it more cumbersome. Yet, color vision charts either measure combined color vision deficiencies or do not quantify the depth of the defect, making its utility for glaucoma monitoring difficult.^[98,103]

Studies have also that color vision deficits with M cone contrast sensitivity is more susceptible in various ocular disease.^[98-103] In contrast, another study reported the presence of macular function damage in both blue-yellow and red-green opponent pathways in glaucoma. *Bayer et al.* found a 5% incidence tritans in glaucoma but huge with diffuse color vision defects.^[43] However, the other possible cause of diffuse defects, such as age, pupil miosis, cataract, and age-related macular edema, was not accounted for. It remains a debate whether cone-specific color sensitivity loss may be found in glaucoma as RGCs process color opponent signals that have already been transformed. Yet, no study has studied the relationship between color deficits versus structural loss or other measures of visual function in glaucoma across different stages.

Reading Ability - A Surrogate for RGF Function?

There is a common belief among clinicians that reading disabilities are related to uncorrected refractive errors, cataract, and maculopathy.^[105] It is unlikely to have reading difficulties from disorders such as peripheral vision loss such as glaucoma, especially when visual acuity is normal. However, this is not always true.^[106-116] The probable mechanisms for the reading disability and reading restrictions cited are aberrant eye movements from field defects, inability to read low contrast stimuli, poor visual acuity, and improper lighting.

Interestingly, glaucoma patients have poorer acuity, contrast sensitivity, with or without glare when measured at home versus in the clinic, suggesting that low contrast in the native environment impair reading.^[109,110,112] As a result, they often experience reading fatigue. It is also noted that glaucoma is associated with decreased reading speed, mainly when reading is evaluated through sustained silent reading (as opposed to short-duration out-loud reading) and when individuals are asked to read low-contrast materials.

In a study to delineate the reading difficulty of POAG patients with the use of Radner Reading Charts, the glaucoma patients, when compared to normal adults, read slowly and made more mistakes.^[107] Reading parameters also showed a moderate correlation with visual field mean deviation. The reading parameters were significantly impaired in the worst eye; this result confirms the impact of field loss on reading ability.

Burton *et al.*^[109] described an average reduction in reading speed caused by a difference in letter contrast between 100%, and 20% is significantly more apparent in patients with glaucoma when compared with visually healthy people.^[109] Richman *et al.*^[114] also showed that the aspects of visual function that best predict the ability of a patient with glaucoma to perform activities of daily living are binocular visual acuity and contrast sensitivity. High rates of spoken reading impairment have been reported in elderly glaucoma patients.^[111] The presence of glaucoma was associated with a slow pace of reading. A more significant reading impairment was noticed with advanced bilateral field loss.^[111,112]

It is understood that binocular reading is not useful if the fields are depressed differently in both eyes.^[112] In glaucoma patients, under binocular conditions, maximum reading speed, critical print size, and reading acuity are decreased significantly in comparison to normal.^[112] The critical print size decreased in proportion to the extent of the differences in the mean deviation values and the sensitivity values of the paracentral bottom left in the two eyes. Interestingly, there is a difference in which the superior or inferior field defect affects reading or other visual functions. Cheng *et al.*^[115] showed that MD of the superior hemifield was correlated only with near activities score ($P = 0.01$). In contrast, the MD of the inferior hemifield positively correlated with central vision, vision-specific role difficulties, and peripheral vision.^[113,114,116] This may explain why patients with glaucoma and worse binocular inferior VF have a slower walking speed, higher rates of falls, and more falls with injury among elderly individuals.^[114,116] While reading ability is recognized as being affected in glaucoma, its clinical utility remains unexplored owing to the subjectivity and other associated causes of reading impairment, which makes it a global measure rather than a measure of the RGC function.

Conclusion

In summary, visual function tests that can measure the RGC function include visual fields, which constitute the most used test in routine clinical practice. Yet, other visual function tests such as contrast sensitivity, color vision, and ERG are other tests that can measure the visual function as a complement to visual fields. Of these, contrast and color vision are not only easy but also measure specific attributes of RGC function, which can not only complement visual field but also help grade the severity of the damage. This makes them a useful tool for monitoring disease over time, along with visual fields, while serving as a robust measure of RGC function. It remains to be seen if these tests add value to the practice of visual field and possibly predict disease progression earlier than visual fields. Future studies would prove their utility in routine glaucoma practice and highlight how they can be effectively used in conjunction with conventional perimetry.

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Conflicts of interest

There are no conflicts of interest.

References

- Quigley HA, Broman AT. The number of people with glaucoma worldwide in 2010 and 2020. *Br J Ophthalmol* 2006;90:262-7.
- Fechtner RD, Weinreb RN. Mechanisms of optic nerve damage in primary open angle glaucoma. *Surv Ophthalmol* 1994;39:23-42.
- Weinreb RN, Aung T, Medeiros FA. The pathophysiology and treatment of glaucoma: A review. *JAMA* 2014;311:1901-11.
- Frisén L. Identification of functional visual field loss by automated static perimetry. *Acta Ophthalmol* 2014;92:805-9.
- Dowling JE. Organization of vertebrate retinas. *Invest Ophthalmol* 1970;9:655-80.
- Demb JB, Singer JH. Functional circuitry of the retina. *Annu Rev Vis Sci* 2015;1:263-89.
- Baylor DA, Fettiplace R. Transmission from photoreceptors to ganglion cells in turtle retina. *J Physiol* 1977;271:391-424.
- Carcieri SM, Jacobs AL, Nirenberg SH. Classification of retinal ganglion cells: A statistical approach. *J Neurophysiol* 2003;90:1704-13.
- Seung HS, Sümbül U. Neuronal cell types and connectivity: Lessons from the retina. *Neuron* 2014;83:1262-72.
- Wassle H. Parallel processing in the mammalian retina. *Nat Rev Neurosci* 2004;5:747-57.
- Wu SM. Synaptic organization of the vertebrate retina: General principles and species-specific variations: The Friedenwald lecture. *Invest Ophthalmol Vis Sci* 2010;51:1263-74.
- Famiglietti EV Jr Kaneko A Tachibana M. Neuronal architecture of on and off pathways to ganglion cells in carp retina. *Science* 1977;198:1267-9.
- Wu SM Gao F Pang JJ. Synaptic circuitry mediating light-evoked signals in dark-adapted mouse retina. *Vision Res* 2004;44:3277-88.
- Amthor FR, Oyster CW, Takahashi ES. Morphology of ON-OFF direction-selective ganglion cells in the rabbit retina. *Brain Res* 1984;298:187-90.
- Nelson R Famiglietti EV Jr, Kolb H. Intracellular staining reveals different levels of stratification for on- and off-center ganglion cells in cat retina. *J Neurophysiol* 1978;41:472-83.
- Barlow HB, Hill RM. Selective sensitivity to direction of movement in ganglion cells of the rabbit retina. *Science* 1963;139:412-4.
- hichilnisky EJ, Kalmar RS. Functional asymmetries in ON and OFF ganglion cells of primate retina. *J Neurosci* 2002;22:2737-47.
- Butts DA, Weng C, Jin JZ, Alonso JM, Paninski L. Temporal precision in the visual pathway through the interplay of excitation and stimulus-driven suppression. *J Neurosci* 2011;31:11313-27.
- Baccus SA, Meister M. Fast and slow contrast adaptation in retinal circuitry. *Neuron* 2002;36:909-19.
- Khani MH, Gollisch T. Diversity in spatial scope of contrast adaptation among mouse retinal ganglion cells. *J Neurophysiol* 2017;118:3024-43.
- Garvert MM, Gollisch T. Local and global contrast adaptation in retinal ganglion cells. *Neuron* 2013;77:915-28.
- Brown SP, Masland RH. Spatial scale and cellular substrate of contrast adaptation by retinal ganglion cells. *Nat Neurosci* 2001;4:44-51.
- Beaudoin DL, Borghuis BG, Demb JB. Cellular basis for contrast gain control over the receptive field center of mammalian retinal ganglion cells. *J Neurosci* 2007;27:2636-45.
- Jarsky T, Cembrowski M, Logan SM, Kath WL, Riecke H, Demb JB, *et al.* A synaptic mechanism for retinal adaptation to luminance and contrast. *J Neurosci* 2011;31:11003-15.
- Manookin MB, Demb JB. Presynaptic mechanism for slow contrast adaptation in mammalian retinal ganglion cells. *Neuron* 2006;50:453-64.
- Ross JE, Bron AJ, Clarke DD. Contrast sensitivity and visual disability in chronic simple glaucoma. *Br J Ophthalmol* 1984;68:821-7.
- Shapley R, Victor J. Hyperacuity in cat retinal ganglion cells. *Science* 1986;231:999-1002.
- Dacey DM, Lee BB. The 'blue-on' opponent pathways in primate retina originates from a distinct bistratified ganglion cell. *Nature* 1994;367:731-5.
- Anderson RS. The psychophysics of glaucoma: Improving the structure/function relationship. *Prog Retin Eye Res* 2006;25:79-97.
- Turalba AV, Grosskreutz C. A review of current technology used in evaluating visual function in glaucoma. *Semin Ophthalmol* 2010;25:309-16.
- Jampel HD, Singh K, Lin SC, Chen TC, Francis BA, Hodapp E, *et al.* Assessment of visual function in glaucoma: A report by the American Academy of Ophthalmology. *Ophthalmology* 2011;118:986-1002.
- Zhao J, Davé SB, Wang J, Subramanian PS. Clinical color vision testing and correlation with visual function. *Am J Ophthalmol* 2015;160:547-52.
- Berson DM. Strange vision: Ganglion cells as circadian photoreceptors. *Trends Neurosci* 2003;26:314-20.
- Moore RY, Speh JC, Card JP. The retinohypothalamic tract originates from a distinct subset of retinal ganglion cells. *J Comp Neurol* 1995;352:351-66.
- Foster RG. Shedding light on the biological clock. *Neuron* 1998;20:829-32.
- Stamper RL. The effect of glaucoma on central visual function. *Trans Am Ophthalmol Soc* 1984;82:792-826.
- Iester M, Altieri M, Vittone P, Calabria G, Zingirian M, Traverso CE. Detection of glaucomatous visual field defect by non-conventional perimetry. *Am J Ophthalmol* 2003;135:35-9.
- Sample PA, Bosworth CF, Blumenthal EZ, Girkin C, Weinreb RN. Visual function specific perimetry for indirect comparison of different ganglion cell populations in glaucoma. *Invest Ophthalmol Vis Sci* 2000;41:1783-90.
- Bagga H, Feuer WJ, Greenfield DS. Detection of psychophysical and structural injury in eyes with glaucomatous optic neuropathy and normal standard automated perimetry. *Arch Ophthalmol* 2006;124:169-76.
- Frisen L. High-pass resolution perimetry: A clinical review. *Doc Ophthalmol* 1993;83:1-25.
- Martin L, Wanger P. Five-year follow-up of treated patients with glaucoma using resolution perimetry. *J Glaucoma* 1998;7:22-6.
- Bengtsson B, Heijl A. Diagnostic sensitivity of fast blue-yellow and standard automated perimetry in early glaucoma: A comparison between different test programs. *Ophthalmology* 2006;113:1092-7.
- Bayer AU, Maag KP, Erb C. Detection of optic neuropathy in glaucomatous eyes with normal standard visual fields using a test battery of short-wavelength automated perimetry and pattern electroretinography. *Ophthalmology* 2002;109:1350-61.
- Orzalesi N, Miglior S, Lonati C, Rosetti L. Microperimetry of localized retinal nerve fiber layer defects. *Vision Res* 1998;38:763-71.
- Okada K, Watanabe W, Koike I, Tsumamoto Y, Mishima HK. Alternative method of evaluating visual field deterioration in very advanced glaucomatous eye by microperimetry. *Jpn J Ophthalmol* 2003;47:178-81.
- Johnson CA, Adams AJ, Casson EJ, Brandt JD. Blue- on yellow perimetry can predict the development of glaucomatous visual field loss. *Arch Ophthalmol* 1993;111:645-50.
- Polo V, Abecia E, Pablo LE, Pinilla I, Larrosa JM, Honrubia FM. Short-wavelength automated perimetry and retinal nerve fiber

- layer evaluation in suspected cases of glaucoma. *Arch Ophthalmol* 1998;116:1295-8.
48. Girkin CA, Emdadi A, Sample PA, Blumenthal EZ, Lee AC, Zangwill LM, *et al.* Short-wavelength automated perimetry and standard perimetry in the detection of progressive optic disc cupping. *Arch Ophthalmol* 2000;118:1231-6.
 49. Blumenthal EZ, Sample PA, Zangwill L, Lee AC, Kono Y, Weinreb RN. Comparison of long-term variability for standard and short-wavelength automated perimetry in stable glaucoma patients. *Am J Ophthalmol* 2000;129:309-13.
 50. Bach M, Poloschek CM. Electrophysiology and glaucoma: Current status and future challenges. *Cell Tissue Res* 2013;353:287-96.
 51. Wachtmeister L. Oscillatory potentials in the retina: What do they reveal. *Prog Retin Eye Res* 1998;17:485-521.
 52. Sieving PA, Murayama K, Naarendorp F. Push-pull model of the primate photopic electroretinogram: A role for hyperpolarizing neurons in shaping the b-wave. *Vis Neurosci* 1994;11:519-32.
 53. Bui BV, Fortune B. Ganglion cell contributions to the rat full-field electroretinogram. *J Physiol* 2004;555:153-173.
 54. Wilsey LJ, Fortune B. Electroretinography in glaucoma diagnosis. *Curr Opin Ophthalmol* 2016;27:118-24.
 55. Pfeiffer N, Tillmon B, Bach M. Predictive value of the pattern electroretinogram in high-risk ocular hypertension. *Invest Ophthalmol Vis Sci* 1993;34:1710-5.
 56. Frishman LJ, Shen FF, Du L, Robson JG, Harwerth RS, Smith EL 3rd, *et al.* The scotopic electroretinogram of macaque after retinal ganglion cell loss from experimental glaucoma. *Invest Ophthalmol Vis Sci* 1996;37:125-41.
 57. Wilsey L, Gowrisankaran S, Cull G, Hardin C, Burgoyne CF, Fortune B. Comparing three different modes of electroretinography in experimental glaucoma: Diagnostic performance and correlation to structure. *Doc Ophthalmol* 2017;134:111-28.
 58. Saszik SM, Robson JG, Frishman LJ. The scotopic threshold response of the dark-adapted electroretinogram of the mouse. *J Physiol* 2002;543:899-916.
 59. Machida S. Clinical applications of the photopic negative response to optic nerve and retinal diseases. *J Ophthalmol* 2012;2012:397178. doi: 10.1155/2012/397178.
 60. Viswanathan S, Frishman LJ, Robson JG, Walters JW. The photopic negative response of the flash electroretinogram in primary open angle glaucoma. *Invest Ophthalmol Vis Sci* 2001;42:514-22.
 61. Machida S, Gotoh Y, Toba Y, Ohtaki A, Kaneko M, Kurosaka D. Correlation between photopic negative response and retinal nerve fiber layer thickness and optic disc topography in glaucomatous eyes. *Invest Ophthalmol Vis Sci* 2008;49:2201-7.
 62. Colotto A, Falsini B, Salgarello T, Iarossi G, Galan ME, Scullica L. Photopic negative response of the human ERG: Losses associated with glaucomatous damage. *Invest Ophthalmol Vis Sci* 2000;41:2205-11.
 63. Machida S, Toba Y, Ohtaki A, Gotoh Y, Kaneko M, Kurosaka D. Photopic negative response of focal electroretinograms in glaucomatous eyes. *Invest Ophthalmol Vis Sci* 2008;49:5636-4.
 64. Kamada K, Machida S, Oikawa T, Miyamoto H, Nishimura T, Kurosaka D. Correlation between photopic negative response of focal electroretinograms and local loss of retinal neurons in glaucoma. *Curr Eye Res* 2010;35:155-64.
 65. Machida S, Kaneko M, Kurosaka D. Regional variations in correlation between photopic negative response of focal electroretinograms and ganglion cell complex in glaucoma. *Curr Eye Res* 2015;40:439-49.
 66. Robson AG, Nilsson J, Li S, Jalali S, Fulton AB, Tormene AP, *et al.* ISCEV guide to visual electrodiagnostic procedures. *Doc Ophthalmol* 2018;136:1-26.
 67. Ventura LM, Porciatti V, Ishida K, Feuer WJ, Parrish RK 2nd. Pattern electroretinogram abnormality and glaucoma. *Ophthalmology* 2005;112:10-9.
 68. Bayer AU, Erb C. Short wavelength automated perimetry, frequency doubling technology perimetry, and pattern electroretinography for prediction of progressive glaucomatous standard visual field defects. *Ophthalmology* 2002;109:1009-17.
 69. Hood DC, Xu L, Thienprasiddhi P, Greenstein VC, Odel JG, Grippio TM, *et al.* The pattern electroretinogram in glaucoma patients with confirmed visual field deficits. *Invest Ophthalmol Vis Sci* 2005;46:2411-8.
 70. Gölemez H, Yıldırım N, Özer A. Is multifocal electroretinography an early predictor of glaucoma? *Documenta Ophthalmologica* 2016;132:27-37.
 71. Brandão LM, Monhart M, Schötzau A, Ledolter AA, Palmowski-Wolfe AM. Applying a new automated perimetry pattern based on the stimulus distribution of the multifocal ERG to improve structure-function investigation in glaucoma. *J Ophthalmol* 2017;2017:1-11. doi: 10.1155/2017/8780934.
 72. Moon CH, Han J, Ohn Y-H, Park TK. Local relationship between global-flash multifocal electroretinogram optic nerve head components and visual field defects in patients with glaucoma. *J Ophthalmol* 2015;2015:397495. doi: 10.1155/2015/397495.
 73. Brandão LM, Monhart M, Schötzau A, Ledolter AA, Palmowski-Wolfe AM. Wavelet decomposition analysis in the two-flash multifocal ERG in early glaucoma: A comparison to ganglion cell analysis and visual field. *Doc Ophthalmol* 2017;135:29-42.
 74. Rao A, Singh AK, Mukherjee S, Chowdhury M. Comparing focal and global responses on multifocal electroretinogram with retinal nerve fibre layer thickness by spectral domain optical coherence tomography in glaucoma. *Br J Ophthalmol* 2015;99:500-7.
 75. Rao A, Chandrashekar RV, Padhy D, Mukherjee S, Das G, Sarangi S. Comparing ganglion cell-inner plexiform layer thickness with focal and global responses on multifocal electroretinogram in glaucoma. *Oman J Ophthalmol* 2017;10:205-12.
 76. Kaneko M, Machida S, Hoshi Y, Kurosaka D. Alterations of photopic negative response of multifocal electroretinogram in patients with glaucoma. *Curr Eye Res* 2015;40:77-86.
 77. Miguel-Jiménez JM, Blanco R, De-Santiago L, Fernández A, Rodríguez-Ascariz JM, Barea R, *et al.* Continuous-wavelet-transform analysis of the multifocal ERG waveform in glaucoma diagnosis. *Med Biol Eng Comput* 2015;53:771-80.
 78. Parisi V. Impaired visual function in glaucoma. *Clin Neurophysiol* 2001;112:351-8.
 79. Teoh SL, Allan D, Dutton GN, Foulds WS. Brightness discrimination and contrast sensitivity in chronic glaucoma--a clinical study. *Br J Ophthalmol* 1990;74:215-9.
 80. Wood JM, Lovie-Kitchin JE. Evaluation of the efficacy of contrast sensitivity measures for the detection of early primary open-angle glaucoma. *Optom Vis Sci* 1992;69:175-81.
 81. Pomerance GN, Evans DW. Test-retest reliability of the CSV-1000 contrast test and its relationship to glaucoma therapy. *Invest Ophthalmol Vis Sci* 1994;35:3357-61.
 82. Richman J, Lorenzana LL, Lankaranian D, Dugar J, Mayer J, Wizov SS, *et al.* Importance of visual acuity and contrast sensitivity in patients with glaucoma. *Arch Ophthalmol* 2010;128:1576-82.
 83. Richman J, Spaeth GL, Wiroszko B. Contrast sensitivity basics and a critique of currently available tests. *J Cataract Refract Surg* 2013;39:1100-6.
 84. Hawkins AS, Szlyk JP, Ardickas Z, Alexander KR, Wilensky JT. Comparison of contrast sensitivity, visual acuity, and Humphrey visual field testing in patients with glaucoma. *J Glaucoma* 2003;12:134-8.

85. Velten IM, Korth M, Horn FK, Budde WM. Temporal contrast sensitivity with peripheral and central stimulation in glaucoma diagnosis. *Br J Ophthalmol* 1999;83:199-205.
86. Wilensky JT, Hawkins A. Comparison of contrast sensitivity, visual acuity, and Humphrey visual field testing in patients with glaucoma. *Trans Am Ophthalmol Soc* 2001;99:213-7.
87. Zulauf M, Flammer J. Correlation of spatial contrast sensitivity and visual fields in glaucoma. *Graefes Arch Clin Exp Ophthalmol* 1993;231:146-50.
88. Sample PA, Juang PS, Weinreb RN. Isolating the effects of primary open-angle glaucoma on the contrast sensitivity function. *Am J Ophthalmol* 1991;112:308-16.
89. Jampel HD, Schwartz A, Pollack I, Abrams D, Weiss H, Miller R. Glaucoma patients' assessment of their visual function and quality of life. *J Glaucoma* 2002;11:154-63.
90. Parrish RK 2nd, Gedde SJ, Scott IU, Feuer WJ, Schiffman JC, Mangione CM, *et al.* Visual function and quality of life among patients with glaucoma. *Arch Ophthalmol* 1997;115:1447-55.
91. Haymes SA, LeBlanc RP, Nicoleta MT, Chiasson LA, Chauhan BC. Glaucoma and on-road driving performance. *Invest Ophthalmol Vis Sci* 2008;49:3035-41.
92. Friedman DS, Freeman E, Munoz B, Jampel HD, West SK. Glaucoma and mobility performance: The Salisbury Eye Evaluation Project. *Ophthalmology* 2007;114:2232-7.
93. Sun Y, Erdem E, Lyu A, Zangalli C, Wizov SS, Lo D, *et al.* The SPARCS: A novel assessment of contrast sensitivity and its reliability in patients with corrected refractive error. *Br J Ophthalmol* 2016;100:1421-6.
94. Richman J, Zangalli C, Lu L, Wizov SS, Spaeth E, Spaeth GL. The Spaeth/Richman contrast sensitivity test (SPARCS): Design, reproducibility and ability to identify patients with glaucoma. *Br J Ophthalmol* 2015;99:16-20.
95. Gupta L, Cvintal V, Delvadia R, Sun Y, Erdem E, Zangalli C, *et al.* SPARCS and Pelli-Robson contrast sensitivity testing in normal controls and patients with cataract. *Eye (Lond)* 2017;31:753-76.
96. Gupta L, Waisbourd M, Sanvicente CT, Hsieh M, Wizov SS, Spaeth EE, *et al.* Establishment of a normative database and evaluation of the test-retest repeatability of the Spaeth/Richman contrast sensitivity test. *Jpn J Ophthalmol* 2019;63:73-81.
97. Kici F, Loh R, Waisbourd M, Sun Y, Martinez P, Nayak N, *et al.* Relationships between measures of the ability to perform vision-related activities, vision-related quality of life, and clinical findings in patients with glaucoma. *JAMA Ophthalmol* 2015;133:1377-85.
98. Poinosawmy D, Nagasubramanian S, Gloster J. Colour vision in patients with chronic simple glaucoma and ocular hypertension. *Br J Ophthalmol* 1980;64:852-7.
99. FanloZarazaga A, Gutiérrez Vásquez J, PueyoRoyo V. Review of the main colour vision clinical assessment tests. *Arch Soc Esp Oftalmol* 2019;94:25-32
100. Pandey N, Chandrakar AK, Garg ML. Tests for color vision deficiency: Is it time to revise the standards? *Indian J Ophthalmol* 2015;63:752-3.
101. Hardy L, Rand G, Rittler C. Les épreuves de la vision des couleurs [Color vision tests]. *Ann Ocul (Paris)* 1950;183:515-8.
102. bramov I, Gordon J. Color vision panel tests: A metric for interpreting numeric analytic indices. *Optom Vis Sci* 2009;86:146-52.
103. Nork TM. Acquired color vision loss and a possible mechanism of ganglion cell death in glaucoma. *Trans Am Ophthalmol Soc* 2000;98:331-63.
104. Vingrys AJ, King-Smith PE. A quantitative scoring technique for panel tests of color vision. *Invest Ophthalmol Vis Sci* 1988;29:50-63.
105. Nilson UL. Visual rehabilitation of patients with advanced stages of glaucoma, optic atrophy, myopia or retinitis pigmentosa. *Doc Ophthalmol* 1988;70:363-83.
106. Rolle T, Dallorto L, Cafasso R, Mazzocca R, Curto D, Nuzzi R. Reading ability in primary open-angle glaucoma: Evaluation with radner reading charts. *Optom Vis Sci* 2019;96:55-61.
107. Swenor BK, Varadaraj V, Dave P, West SK, Rubin GS, Ramulu PY. Impact of the ability to divide attention on reading performance in glaucoma. *Invest Ophthalmol Vis Sci* 2017;58:2456-2462.
108. Burton R, Crabb DP, Smith ND, Glen FC, Garway-Heath DF. Glaucoma and reading: Exploring the effects of contrast lowering of text. *Optom Vis Sci* 2012;89:1282-7.
109. Nguyen AM, van Landingham SW, Massof RW, Rubin GS, Ramulu PY. Reading ability and reading engagement in older adults with glaucoma. *Invest Ophthalmol Vis Sci* 2014;55:5284-90.
110. Ramulu PY, West SK, Munoz B, Jampel HD, Friedman DS. Glaucoma and reading speed: The Salisbury Eye Evaluation project. *Arch Ophthalmol* 2009;127:82-7.
111. Ishii M, Seki M, Harigai R, Abe H, Fukuchi T. Comparison between binocular and monocular reading ability and its relation with central visual field sensitivity in glaucoma patients. *Nippon Ganka Gakkai Zasshi* 2013;117:925-30.
112. Patodia Y, Golesic E, Mao A, Hutnik CM. Clinical effectiveness of currently available low-vision devices in glaucoma patients with moderate-to-severe vision loss. *Clin Ophthalmol* 2017;11:683-7.
113. Richman J, Lorenzana LL, Lankaranian D, Dugar J, Mayer JR, Wizov SS, *et al.* Relationships in glaucoma patients between standard vision tests, quality of life, and ability to perform daily activities. *Ophthalmic Epidemiol* 2010;17:144-51.
114. Cheng HC, Guo CY, Chen MJ, Ko YC, Huang N, Liu CJ. Patient-reported vision-related quality of life differences between superior and inferior hemifield visual field defects in primary open-angle glaucoma. *JAMA Ophthalmol* 2015;133:269-75.
115. Haymes SA, Johnston AW, Heyes AD. Relationship between vision impairment and ability to perform activities of daily living. *Ophthalmic Physiol Opt* 2002;22:79-91.
116. Wei H, Sawchyn AK, Myers JS, Katz LJ, Moster MR, Wizov SS, *et al.* A clinical method to assess the effect of visual loss on the ability to perform activities of daily living. *Br J Ophthalmol* 2012;96:735-41.