

PERSPECTIVE

Acquired colour vision defects in glaucoma—their detection and clinical significance

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Colour vision defects associated with ocular disease have been reported since the 17th century. Köllner¹ in 1912 wrote an acute description of the progressive nature of colour vision loss secondary to ocular disease, dividing defects into “blue-yellow” and “progressive red-green blindness”.² This classification has become known as Köllner’s rule, although it is often imprecisely stated as “patients with retinal disease develop blue-yellow discrimination loss, whereas optic nerve disease causes red-green discrimination loss”. Exceptions to Köllner’s rule^{3–4} include some optic nerve diseases, notably glaucoma, which are primarily associated with blue-yellow defects, and also some retinal disorders such as central cone degeneration which may result in red-green defects. Indeed, in some cases, there might be a non-specific chromatic loss.

Colour vision defects in glaucoma have been described since 1883⁵ and although many early investigations indicated that red-green defects accompanied glaucomatous optic neuropathy,¹ later studies suggested that tritan defects predominate.^{6–9} This change of view largely reflected improved experimental design over time—in early studies no distinction was made between the various types of glaucoma, nor was any allowance usually made for the age distribution of subjects in the sample. A summary of the early research can be found in Drance *et al.*⁷

Although modern studies control for confounding factors such as increasing lens density and decreasing pupil size with age, some controversy still surrounds the nature of colour vision defects in primary open angle glaucoma (POAG). Comparing previous research evaluating chromatic discrimination in POAG is complicated by wide variations in methodology and experimental conditions.

In recent years, computer generated colour tests have provided the means for isolating the processing of chromatic signals from the accompanying achromatic cues.^{10–15} In these tests, typically, the subject is asked to report the presence of a coloured target such as a spot, bar, or grating on a background of a different colour. To avoid detection based on luminance cues, either the equiluminance is determined empirically or any luminance cue is masked using spatial masking techniques. One advantage of using computer generated colour tests comes from their ability to test neuronal processing at specific retinal locations, giving them the potential to be used to detect and monitor ocular disease in a way similar to standard white on white perimetry. Although white on white threshold perimetry remains the gold standard for detecting and monitoring loss of visual function in POAG, one third or more of the optic nerve axons may be lost before a field defect can be detected.¹⁶ Therefore, much recent research into colour vision in POAG has focused on the usefulness of colour discrimination tests in the early detection and monitoring of progression of the disease.

The aims of this paper are:

- to provide a review of the modern literature on acquired colour vision in POAG
- to differentiate the characteristics of congenital and acquired defects, in order to understand the type of colour vision defect associated with glaucomatous damage
- to compare classic clinical and modern methodologies (including modern computerised techniques) for assessing visual function mediated through chromatic mechanisms
- to assess the effects of acquired colour vision defects on quality of life in patients with POAG.

Comparing congenital and acquired colour vision defects

Congenital colour vision deficiencies result from inherited cone photopigment abnormalities. The most common form of deficiency is due to abnormal responses to red-green stimuli, originating from an abnormal/functionally absent long wavelength sensitive photopigment (protan-type anomalies) or intermediate wavelength sensitive (deutan-type) photopigment. A less frequent form of chromatic anomaly is the tritan-type, caused by an absent or abnormal short wavelength photopigment. Inherited red-green colour vision deficiencies have a two gene X linked recessive inheritance.¹⁷

The prevalence of red-green deficiency is reported to be approximately 8% in males, made up of approximately 6% deutan-type and 2% protan-type defects, and 0.4% in females.¹⁸ Tritanopia, in which the short wavelength sensitive photopigment is absent, shows autosomal dominant inheritance and Wright¹⁹ estimated its prevalence to lie between 1 in 13 000 and 1 in 65 000. Tritanomaly, in which short wavelength sensitive photopigment is abnormal, has a prevalence of approximately 1 in 1000.²⁰

Unlike congenital defects, acquired colour vision anomalies are evenly distributed between males and females. A summary of characteristic differences between congenital and acquired defects is given in Table 1.²¹

Of the many attempts to classify acquired colour vision deficiencies, Verriest’s classification published in 1963³ is the most widely used, and a simplified version is given in Table 2 describing the three main types of anomaly. More precise classifications²² based on Table 2 and other classifications of acquired colour vision deficiencies²³ are available.

This classification suggests the key element defining the type of acquired chromatic discrimination defect²⁴—the relation between the retinal distribution of chromatic mechanisms and the localisation of the disease process. For example, a patient suffering from a disease resulting in early destruction of foveal function will normally present initially with a central scotoma, poor visual acuity, and a

Table 1 Comparison between the characteristics of congenital and acquired colour vision defects

Congenital defects	Acquired defects
Present at birth	Onset after birth
Type and severity of defect is stable throughout life	Type and severity of defect may fluctuate
Type of defect can be classified precisely	Type of defect may not be easy to classify. Combined or non-specific deficiencies frequently occur
Both eyes are equally affected	Monocular differences in the type and severity of the defect often occur
Visual acuity is unaffected (except in monochromatism) and visual fields are normal	Visual acuity is often reduced and visual field defects often occur
Predominantly protan or deutan	Predominantly "tritan-like"
Higher prevalence in males	Approximately equal prevalence in males and females

Table 2 Verriest's classification of acquired colour vision anomalies

Name	Alternative names	Colour discrimination defect	Visual acuity
Type I	Acquired R-G, protan-like	Mild to severe confusion of R-G hues, little or no loss of B-Y CD	Moderate to severe reduction
Type II	Acquired R-G, deutan-like	Mild to severe confusion of R-G hues with a concomitant mild loss of B-Y CD	Moderate to severe reduction
Type III	Acquired B-Y, tritan-like	Mild to moderate confusion of B-Y hues with a lesser impairment of R-G CD	May be normal or moderately reduced

R-G = red-green, B-Y = blue-yellow, CD = colour discrimination.

type I (red-green) defect. However, in patients with diseases of the macula where visual acuity is well preserved, most will have type III (blue-yellow or tritan-like) defects, at least in the early stages of the disease process.

Optic nerve disease often produces a type II (red-green) deficiency, but if visual acuity is preserved then the predominant colour deficiency is type III (blue-yellow). In early glaucomatous optic neuropathy, paracentral scotomas and a reduction of sensitivity in the arcuate regions are common visual field defects, while visual acuity is spared; hence the most frequent chromatic anomaly associated with POAG is a type III defect.

Acquired colour vision anomalies tend to mimic the chromatic deficiency patterns of congenital defects—for example, type III (blue-yellow) defects are reminiscent of congenital tritan anomalies. As a result, there has been a tendency to regard acquired defects as being the result of selective damage to a specific anatomical structure or specific physiological colour vision mechanism (for example, blue cones, or their ganglion cells, in type III). Also, the fact that in many cases colour vision is affected but visual acuity is preserved reinforces the idea of chromatic mechanisms being more susceptible to damage than those of light sensitivity.²⁴

Deterioration of chromatic discrimination with age

Because the prevalence of POAG increases with advancing age, it is important to distinguish between age related deterioration in chromatic discrimination ability and deterioration caused by the disease itself. In normal eyes, for example, miosis and yellowing of the aging lens result in a loss of hue discrimination of a type similar to that found in tritan-like defects.^{3 25} It is generally believed that interindividual differences in colour vision are significantly affected by individual variations in the density of the macular pigment. Werner *et al*²⁶ used a psychophysical monochromatic flicker technique to measure the optical density of human macular pigment at the central one degree of the retina in 50 subjects aged between 10 and 90 years. Although substantial interindividual differences were present, these variations were not systematically related to age. Normative data for different age groups have been established for the widely used Farnsworth-Munsell (F-M) 100 hue test.²⁷

Assessment of acquired colour vision defects

Colour vision testing is always performed monocularly when acquired colour deficiency is suspected or when monitoring for possible progression of ocular disease.

CLASSIC TESTS

Arrangement tests

In general, these use a variety of Munsell hues of the same saturation and luminance. The hues are chosen to be distributed around a complete circle surrounding the equal energy white point in the CIE (Commission Internationale de l'Éclairage) diagram. Arrangement tests are particularly useful for evaluating patients with eye disease because their demands on acuity are low,²³ and no specific colour confusions are predicted.

Farnsworth-Munsell 100 hue test (F-M 100 hue)

This consists of 85 coloured caps, numbered on the back, and arranged in four trays.²⁸ The patient arranges each tray of randomly ordered caps in a natural colour order between two fixed colours in each tray, and the result is plotted on a polar chart. Completely correct ordering produces a perfect circle of points, and the numbers on the backs of the caps will be consecutive. However, transpositional errors cause points to be further away from the centre of the chart, with some or all non-consecutive numbers. Subjects with significant congenital colour vision defects produce characteristic patterns, which have clusters of errors confined to restricted areas, localised at nearly diametrically opposite regions of the circle. The "error score" for each cap is the sum of the absolute numerical differences of the two adjacent caps, minus 2, and each error score is either plotted on the line representing that colour²⁸ or plotted serially.²⁹ The severity of the discrimination defect is quantified by the "total error score" (TES), obtained by summing the error scores for each cap. Although the F-M 100 hue test is particularly useful for monitoring progression in acquired deficiency, it is unable to distinguish subtle differences, such as between severe trichromatic anomalies and pure dichromacy.

Farnsworth-Munsell D-15

The D-15 is designed to identify moderate to severe colour vision defects.³⁰ The 15 caps are arranged in a natural colour order from one fixed colour, in a similar way to the F-M 100 hue test. The plotted error pattern, which in subjects with moderate to severe colour deficiency consists of criss crossing lines which demonstrate isochromatic confusion axes, will indicate the type of defect. Although a quicker test than the F-M 100 hue, the D-15 was not designed to be a screening test and is not considered to be very sensitive for screening for use in POAG. There are several versions of this test in circulation and the "desaturated" version, using the same colours, but with low saturation is often used.

The City University test

There have been three editions of this test,³¹ a derivative of the D-15 test, with the most recent in 1998. Most published clinical data are for the second edition, which has 10 charts. Each chart has a central colour and four surrounding colours, three of which are typical isochromatic confusions for protan, deutan, and tritan congenital deficiency, while the fourth is an adjacent colour in the D-15 sequence and is the usual preference of those with normal colour vision. Although classification of congenital protan and deutan deficiency is imprecise, the City University test is useful for acquired defects.³²

Pseudo-isochromatic plates

These are the most widely used clinical tests to assess colour vision because they are portable and easy to use. In general, these tests are most useful for detection of congenital anomalies.

Ishihara plates are the most efficient pseudo-isochromatic test. The major disadvantages of the Ishihara plates are that they do not contain designs for the detection of tritan defects, and that patients require 6/18 visual acuity¹⁸ to resolve the test. Consequently, the Ishihara test is not appropriate for the assessment of the majority of acquired anomalies, which are associated with tritan-type defects.

The *H-R-R* test was designed for the detection of congenital, including tritan, deficiencies and has a series of plates having different colour difference steps allowing grading of protan, deutan, and tritan defects. The minimum visual acuity required for interpretation of the test is 6/60. Moderate and severe acquired type III deficiencies are detected by the H-R-R plates. A third edition became available in 1991 (Richmond International Inc). Other pseudo-isochromatic tests with tritan plates include the *Lanthyony Tritan Album*, and the *F2* plate, introduced by Farnsworth to detect congenital tritanopia.

The ability of quick, simple to apply clinical tests to detect type III (tritan-like) deficiencies in POAG and patients with ocular hypertension has been assessed,³² and the battery of tests consisted of the H-R-R, Lanthyony, and *F2* plates, plus the D-15 and desaturated D-15, and the City University test. In general, individual tests showed poor sensitivity for the detection of glaucoma. Indeed, the Farnsworth *F2* test did not detect any type III defects. Best validity was shown by the City University and the H-R-R tests, and the results from a combination of these tests may be a useful addition to other data collected in glaucoma screening programmes.

Anomaloscopes

These colour matching instruments are more efficient than arrangement and pseudo-isochromatic tests for the discrimination between normal trichromats and the various types of colour deficiency. The patient matches one half of a field, using a variable mixture of two colours of fixed luminance, with the test colour of variable luminance. Of particular importance in acquired colour deficiency is the "matching range"—the range of colour ratios over which the mixture of the two fixed luminance colours appears to match the test colour. In types I and II acquired deficiency, when red and green are mixed to match yellow, the matching range widens as the disease progresses. Patients with type III (tritan-like) deficiencies, due to retinal disease, frequently exhibit pseudoprotanomaly, where the colour match is slightly displaced towards red.

In the *Nagel anomaloscope*, the spectral colours red and green are mixed to match monochromatic yellow. In addition to matching yellow with a red and green mixture, the *Pickford-Nicolson* anomaloscope, which uses broad band glass filters, also matches blue-green with blue plus green.

The *Pickford-Nicolson* anomaloscope has been used extensively by Lakowski and his co-workers in the study of acquired colour deficiency in glaucoma patients.^{7, 33} However, the blue and green filters are not optimal, leading to high variance in the normal match because of variations in macular pigment.³⁴ This problem can be overcome by choosing blue and green wavelengths for which macular pigment absorbance is equal. A further slight modification of the wavelengths used allows them to lie on a tritanopic confusion line,³⁵ while retaining approximate equality of macular pigment absorbance. Patients suffering from glaucoma usually accept wide ranges of matching compared with normal subjects, but in general do not show complete tritanopia.³⁶

Both red-green and blue-green matches are available on the Spectrum "colour vision meter", from Interzeag. Although anomaloscopes have been widely used in research into colour deficiency in POAG they have little place in screening procedures because the test procedure for the blue-green match is complicated.

Some of the most common clinical colour vision tests described above are simplified versions of psychophysical methods and are usually based on pigment colours. The more sophisticated psychophysical methods used in research involve computerised and calibrated equipment, and allow a more detailed evaluation of the deficient chromatic mechanisms. A review of the earlier psychophysical techniques has been described in King-Smith 1991.³⁷

COLOUR MONITOR METHODS

The introduction, in the late 1980s, of high resolution colour monitors under computer control, paved the way for a new generation of techniques to assess colour vision. Often, the observer's task is to detect a stimulus whose chromaticity is modulated in different directions of chromatic space on a background of different chromaticity. Computer emulations of clinical colour vision tests (for example, HRR, Ishihara, City) have also been introduced.^{21, 38, 39}

The most extensively used research methods to assess acquired colour vision defects are based on one of the following techniques:

- (1) Measurement of colour contrast sensitivity by means of flicker heterochromatic photometry.⁴⁰⁻⁴⁴ The chromatic threshold for detection of a striped pattern at constant luminance is determined, allowing the measurement of pure chromatic discrimination.
- (2) Measurement of computer controlled colour mixture thresholds, in order to estimate equiluminous, chromatic thresholds and compare them with achromatic thresholds measured under the same conditions.⁴⁵
- (3) Measurements of the luminance threshold for detection of a coloured target presented on a coloured background. The technique is similar in principle to the two colour increment threshold developed by Stiles⁴⁶ to probe the basic colour vision mechanisms. Coloured backgrounds are used to adapt two types of cone, so that the resulting spectral sensitivity curve is dominated by the third type. Blue on yellow perimetry uses this principle to study the loss of sensitivity of chromatic mechanisms (SW cones) as a function of position in the visual field.
- (4) Determination of pure chromatic discrimination thresholds in the absence of possible additional luminance cues formed at the stimulus boundaries. Luminance masking techniques are used to eliminate the luminance cues. The stimuli are often formed by small elements, each one with its own profile and randomly set luminance.^{14, 47, 48} The mean luminance of the stimulus is always the same as that of the background, therefore the observer is forced to use

chromatic signals to solve the perceptual task presented. Chromatic sensitivity can be measured in any direction of chromatic space, allowing the determination of discrimination ellipses.

Acquired colour vision defects in glaucoma

Prevalence estimates for the different types of colour vision defect in POAG have been obtained using a variety of non-computerised tests. Based on these reports^{33 49-51} typical prevalences are 20–40% for normal colour discrimination, 30–50% blue-yellow defects, 5% for red-green defects, and 20–30% for a general loss of chromatic discrimination.

Several possible explanations have been suggested for this predominance of blue-yellow (tritan-like) defects in POAG, including:

- short wavelength cones or their neuronal connections are less able to resist the effects of raised IOP⁵²
- there is selective damage to blue-yellow sensitive ganglion cells or their axons. Blue-yellow ganglion cells have larger receptive fields, are larger than red-green cells, and have a unique morphology and connectivity to second order neurons,⁵³ which may make blue-yellow ganglion cells more susceptible to IOP related damage⁵²
- the relative scarcity of ganglion cells which code blue-yellow signals,⁵⁴ and the relatively little overlap between adjacent receptive fields of these ganglion cells. As a consequence, although only a few ganglion cells may cease to function, there is preferential impairment of the blue-yellow discrimination threshold compared with red-green, even if the proportion of damaged fibres is the same for both types.⁵⁵

Differentiation between age related and glaucomatous changes in colour vision was established when a group of patients with POAG was compared with a control group, matched for age and lens density.⁵⁶ There were significantly more F-M 100 hue error scores in the glaucoma group, demonstrating that their colour vision loss is partly caused by the disease process, and cannot be explained solely on the basis of changes in age and lens density.

Specific losses of the red-green chromatic mechanism are usually associated with advanced POAG.⁵⁷ When chronically raised IOPs were induced in monkeys, the greatest losses in the red-green opponent channel were found in those animals with the most advanced glaucoma.⁵⁸

In many patients with POAG, colour vision defects precede the development of standard white on white visual field loss. However, some patients with POAG never develop chromatic defects^{7 59} or only develop them in advanced disease. Several studies⁶⁰⁻⁶⁴ have found greater colour vision losses in high tension POAG compared with normal tension glaucoma, suggesting that there may be two separate mechanisms for damage to visual function in glaucoma. One mechanism operates as a result of elevated IOP and is responsible for central and paracentral visual function loss, including chromatic discrimination loss, and the second mechanism is independent of the level of IOP.

There have been many attempts to correlate the severity of visual field defects in POAG with colour vision changes measured using clinical tests. Lakowski and Drance⁶⁵ reported that 34% of those with early visual field defects, 54% with moderate visual field defects, and 74% with severe defects produced scores beyond the 95th percentile for normals on the F-M 100 hue test. In a 5 year study, the percentage of patients with ocular hypertension with F-M 100 hue error scores of >100 and/or a score of more than 80 on the Pickford-Nicolson anomaloscope who subsequently developed field defects were 77% and 55% respectively.^{7 59} Surprisingly though, around one third of those who developed visual field defects failed to show a

colour vision defect initially, and were false negatives. Although age, visual acuity, and pupil size were not controlled in this study, it offers some pointers to the predictive ability of these clinical colour vision tests. In cases of POAG with suspicious visual fields,⁸ elevations of the differential threshold at the centre of the field were associated with high F-M 100 hue error scores. This demonstrates the existence of chromatic disturbance at the foveal level, even when field defects are not extensive. Breton and Krupin,⁶⁶ on the other hand, taking care to minimise the effects of age by applying a correction for age related changes in F-M 100 hue scores, in a sample of suspicious and glaucomatous patients, found a significant correlation between colour anomalies and visual field defects only in the 60–69 years age group. In addition, there was no evidence that the overall loss of field was closely related to the severity of the colour vision deficit.

A comparison of the foveal luminance and chromatic sensitivities in a group of glaucoma patients and glaucoma suspects was carried out using a flicker detection technique by Adams *et al.*⁶⁷ They demonstrated a loss of foveal sensitivity in both mechanisms in glaucoma patients and in some glaucoma suspects indicating that the foveal sensitivities are also affected relatively early in the disease process. Greenstein *et al.*⁵⁷ also studied the foveal effects of POAG on the colour opponent and luminance systems by measuring the chromatic modulation threshold necessary to discriminate a 3 degree disc from a white background. The equiluminance was determined by flicker photometry. Both those with the disease and suspects demonstrated similar sensitivity losses for both the red-green and blue-yellow opponent systems, accompanied by decreased sensitivity to achromatic contrast—that is, sensitivity losses were not restricted to the S cone system.

All these studies used tests which evaluate colour discrimination at the fovea only. Although foveal processing of colour is often affected in POAG, modern computerised techniques allow the determination of colour discrimination both at foveal and eccentric retinal locations, which can be analysed in conjunction with visual field data from the same locations. The following studies describe the use of such techniques.

Falcao-Reis *et al.*⁴⁰ measured colour contrast sensitivity using an extramacular stimulus, at 6 month intervals for a period of 2 years in POAG patients and those with ocular hypertension. Colour contrast sensitivity thresholds were more than 2 SDs greater than the control group in 69% of POAG subjects and 32% of ocular hypertensive subjects.

All 84 patients with POAG examined by Yu *et al.*⁴¹ using a colour contrast heterochromic flicker technique, showed thresholds of more than 2 SDs above the normal mean. Their extramacular stimulus was a 25 degree diameter annulus of thickness 1 degree, concentric with a central white fixation spot. The subjects' task was to identify the quadrant in which a 45 degree gap was introduced into the annulus, while the colour of the annulus was modulated. Furthermore, their 77 high risk hypertensive patients fell into two differentiated groups—one with thresholds similar to normals and one with elevated thresholds, which in 50% of cases were more than 3 SDs above the normal mean. Using a similar method, Felius *et al.*⁴³ measured cone contrast thresholds along long (L), medium (M), short (S), L-M, and L+M cone contrast directions at 12 degrees eccentricity in groups of POAG patients, at-risk patients, and normals. Colour contrast defects in POAG and in at-risk subjects occurred in all five modulation directions, although abnormalities in the short wavelength (blue) direction were more pronounced. Fristrom⁴⁴ used the colour contrast threshold technique to compare groups of glaucomatous, normal, and ocular hypertensive subjects.

The colours tested were varied along the protan, deutan, and tritan colour confusion axes. At all axes there were significant differences in mean colour contrast threshold between the glaucomatous and normal groups. However, because values for colour contrast thresholds overlapped for all groups, it was difficult to determine a cut off point which achieved an adequate separation between normals and those with POAG.

Using a novel computerised technique⁶⁸ we have compared chromatic discrimination (CD) thresholds in a group of 19 POAG patients, 10 ocular hypertensives, and 28 normal age matched controls.⁶⁹ Chromatic discrimination thresholds were measured both for foveal and peripheral viewing conditions, along 12 equispaced orientations in x, y CIE colour space. The foveal data showed a significant decline in discrimination performance for chromatic displacements towards the red region of colour space as well as the tritan axes in POAG patients compared with normal controls. These results were in agreement with other reports described above using F-M 100 hue tests. It is noteworthy that the CD thresholds were elevated significantly, along all orientations tested, for the 6 degree peripheral viewing condition in all POAG patients. Results for the small ocular hypertensive group in both foveal and peripheral viewing conditions were not significantly different from those in the normal controls. Although these studies show that the progress of the disease can be monitored by measuring peripheral chromatic discrimination, whether it can be used as a predictor of those patients who will convert from ocular hypertension to glaucoma remains to be established in follow up investigations with a larger group of patients.

The neurobiology of the functional deficits outlined above are not yet fully understood. From the literature reviewed so far, it appears that the chromatic sensitivity loss and the reduction in luminance sensitivity as measured by conventional perimetry may appear either in isolation or together in POAG. This had led Airaksinen *et al*⁷⁰ to suggest that multiple mechanisms may be responsible for the measured functional deficits. Both diffuse and localised nerve fibre damage occurs in POAG. Flammer⁷¹ has suggested that a diffuse loss may be as a result of a direct mechanical damage related to an increased IOP, whereas a localised nerve fibre loss may be primarily caused by a vascular disorder. Both diffuse and localised losses may result in functional deficits. It has been suggested that the foveal colour vision loss observed in POAG patients is as a result of a diffuse nerve fibre loss.^{70 71} On the other hand, localised glaucomatous field defects may be detected earlier using the short wavelength automated perimetry technique⁷² described below.

Short wavelength automated perimetry (SWAP), or blue on yellow perimetry

Short wavelength sensitive cones and ganglion cells are relatively sparsely distributed throughout the retina.⁵⁴ Therefore, short wavelength visual losses resulting from early POAG may be detected earlier than those from other pathways in which there is less redundancy.⁷³ SWAP is a technique that employs a high luminance yellow background which adapts the medium wavelength and long wavelength cones, and simultaneously saturates rod activity. The stimulus is a size V blue stimulus, and standard Humphrey visual field analyser full threshold techniques are often used. In eyes with early to moderate glaucomatous loss, scotomas detected using SWAP are more extensive^{74 75} and deeper than conventional perimetry,⁷⁵ and blue on yellow defects may precede the development of white on white defects by several years.^{73 76}

However, short wavelength transmission losses resulting from absorption and forward light scatter by the ocular media may be indistinguishable from early glaucomatous loss. There are several methods for correcting SWAP results for individual differences in lenticular absorption and scattering of short wavelength light,^{76 77} but the methods are either time consuming, or expensive, or both. Also, data from SWAP exhibit increased test variability compared with conventional perimetry which may result in less sensitive detection of visual field progression.⁷⁵

The examination of the visual fields using SWAP is a technique that in itself takes longer than conventional perimetry using the equivalent Humphrey program. An increase of 15% (full threshold) to 17% (FASTPAC) in SWAP examination duration was found in one study compared with white on white perimetry.⁷⁸ There was also an increase in short term fluctuation with SWAP. Increased interindividual variability is another clinical limitation of current methods of SWAP⁷⁸ and this persists even when allowance is made for ocular media absorption. Faster threshold strategies, such as SITA for SWAP,⁷⁹ offer improvements in the speed of the procedure, but await validation.

There is a reduction in SW cone sensitivity with increasing age,⁸⁰ although the methods used in this study did not permit any differentiation between the effects on sensitivity resulting from yellowing of the crystalline lens, and the effects resulting from an increase in neural losses in the SW cone pathway. A similar rate of decline was found in an age matched group with POAG, who suffer both the normal age related decline in SW cone sensitivity, plus a concurrent disease related sensitivity reduction. When allowance is made for media absorption in healthy older subjects, a small, statistically significant loss of sensitivity with aging remains.⁸¹

Quality of life measures in POAG

Although the assessment of symptomatology and quality of life measures among patients with glaucoma have received little attention until recently, there is growing recognition of the importance of these measures across a wide range of ophthalmic conditions.⁸² Parrish *et al*⁸³ investigated the relation between visual field impairment, visual functioning, and global quality of life in POAG, finding a modest correlation between a visual acuity impairment score and colour vision ($r = -0.47$), and between visual field loss, assessed by Estermann binocular visual field impairment score, and colour vision ($r = -0.42$). Colour vision is one subscale in the National Eye Institute visual functioning questionnaire (NEI-VFQ), and this was completed by 147 POAG subjects in a recent survey.⁸² There was no significant correlation between the extent of their visual field loss, as assessed by the AGIS scale, and the colour vision subscale. However, other NEI-VFQ subscales which were significantly correlated with the extent of visual field loss may be affected by defective colour vision—for example, the general vision scale, the dependency scale, and the driving scale. To date, there is insufficient evidence to be certain of the significance of acquired colour deficiency in POAG symptomatology and quality of life measures. Symptom scales specific to POAG are now in use,⁸⁴ and their successors may tease out further quantitative data on the impact of acquired colour deficiency on patients' lives. Clinical reports confirm that patients with acquired tritan-type defects observe that colours in general appear desaturated or "washed out". Perception of specific colours can be especially impaired, with yellow appearing white and blues appearing black.

Summary

By the time the earliest visual field defects in POAG can be detected using typical increment threshold perimetry, extensive and irreversible neuronal damage has occurred. Investigation of colour mechanisms may allow detection of POAG at an earlier stage than conventional perimetry, resulting in improved prognosis. Standard clinical colour vision tests involving anomaloscopes, pseudo-isochromatic plates, and arrangement tests, although distinguishing patients with well developed glaucoma from normals, do not appear to have high enough sensitivity and specificity to act as screening techniques at earlier stages of the disease. Compared with these clinical tests, the new computerised techniques are potentially more valuable in detecting POAG because they can assess colour vision at specified retinal locations. However, data published to date suggest that investigation of chromatic signals on its own may not be sufficient to detect or predict the progress of the disease. This is partially due to the fact that the precise neurobiology of the disease is not yet fully understood and POAG may differentially affect various neuronal layers of the retina. It is, therefore, possible that a battery of tests which include investigation of chromatic signals together with transient motion signals, flicker/luminance sensitivity, and SWAP may yield more accurate indices for predicting/monitoring the various stages of the disease.

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- Köllner H. Die Störungen des Farbensinnes. *Ihre Klinische Bedeutung und ihre Diagnose*. Berlin: Karger, 1912.
- Marre M. The investigation of acquired colour deficiencies. In: *Colour 1973*. London: Adam Hilger, 1973:99–135.
- Verriest G. Further studies on acquired deficiency of color discrimination. *J Opt Soc Am A—Optics Image Science and Vision* 1963;53:185–95.
- Grutzner P. Acquired color vision defects. In: Jameson D, Hurvich LM, eds. *Handbook of sensory physiology*. Vol 7, No 4. *Visual psychophysics*. Berlin: Springer Verlag, 1972:643–59.
- Bull O. Bemerkungen über Farbensinn unter verschiedenen physiologischen und pathologischen verhalten nissen. *Albrecht Von Graefes Arch Ophthalmol* 1883;29:71–116.
- Francois J, Verriest G. Les dyschromatopsies acquises dans les glaucome primaire. *Ann Ocul* 1959;192:191–9.
- Drance SM, Lakowski R, Schulzer M, et al. Acquired color vision changes in glaucoma. Use of 100-hue test and Pickford anomaloscope as predictors of glaucomatous field change. *Arch Ophthalmol* 1981;99:829–31.
- Flammer J, Drance SM. Correlation between color vision scores and quantitative perimetry in suspected glaucoma. *Arch Ophthalmol* 1984;102:38–9.
- Hamill TR, Post RB, Johnson CA, et al. Correlation of color vision deficits and observable changes in the optic disc in a population of ocular hypertensives. *Arch Ophthalmol* 1984;102:1637–9.
- King-Smith PE, Chioran GM, Sellers KL, et al. Normal and deficient colour discrimination analysed by colour television. In: Mollon JD, Sharpe LT, eds. *Colour vision: physiology and psychophysics*. London: Academic Press, 1983:167–72.
- Fallowfield L, Krauskopf J. Selective loss of chromatic sensitivity in demyelinating disease. *Invest Ophthalmol Vis Sci* 1984;25:771–3.
- Hart WM Jr, Hartz RK, Hagen RW, et al. Color contrast perimetry. *Invest Ophthalmol Vis Sci* 1984;25:400–13.
- Arden G, Gunduz K, Perry S. Color vision testing with a computer graphics system: preliminary results. *Doc Ophthalmol* 1988;69:167–74.
- Regan BC, Reffin JP, Mollon JD. Luminance noise and the rapid determination of discrimination ellipses in colour deficiency. *Vis Res* 1994;34:1279–99.
- Barbur JL, Harlow AJ, Plant GT. Insights into the different exploits of colour in the visual cortex. *Proc R Soc Lond B Biol Sci* 1994;258:327–34.
- Quigley HA, Addicks EM, Green WR. Optic nerve damage in human glaucoma. III. Quantitative correlation of nerve fiber loss and visual field defect in glaucoma, ischemic neuropathy, papilledema, and toxic neuropathy. *Arch Ophthalmol* 1982;100:135–46.
- Piantanida T. Genetics of inherited colour vision deficiencies. In: Foster DH, ed. *Inherited and acquired colour vision deficiencies*. London: MacMillan, 1991:88–114.
- Birch J. Clinical tests design and examination procedure. In: Foster DH, ed. *Diagnosis of defective colour vision*. Oxford: Butterworth-Heinemann, 1993:53–70.

- Wright WD. The characteristics of tritanopia. *J Opt Soc Am* 1952;42:509–21.
- Van Norren D, Went LN. New test for the detection of tritan defects evaluated in two surveys. *Vis Res* 1981;21:1303–6.
- Birch J. Colour vision tests: general classification. In: Foster DH, ed. *Inherited and acquired colour vision deficiencies*. London: MacMillan, 1991:215–34.
- Hermes D, Roth A, Borot N. The two equation method II. Results in retinal and optic nerve disorders. In: Drum B, Verriest G, eds. *Colour vision deficiencies IX*. Amsterdam: Kluwer Academic Publishers, 1989.
- Krastel H, Moreland JD. Colour vision deficiencies in ophthalmic diseases. In: Foster DH, ed. *Inherited and acquired colour vision deficiencies*. London: MacMillan, 1991:115–72.
- Hart WM Jr. Acquired dyschromatopsias. *Surv Ophthalmol* 1987;32:10–31.
- Birch JM, Chisholm IA, Kinnear P, et al. Acquired colour vision defects. In: Pokorny J, Smith VC, Verriest G, Pinckers AJL, eds. *Congenital and acquired colour vision defects*. New York: Grune and Stratton, 1979:243–5.
- Werner JS, Donnelly SK, Kliegl R. Aging and human macular pigment density. *Vis Res* 1987;27:257–68.
- Verriest G, Van Laethem J, Uvijls A. A new assessment of the normal ranges of the Farnsworth-Munsell 100-hue test scores. *Am J Ophthalmol* 1982;93:635–42.
- Farnsworth D. The Farnsworth-Munsell 100 hue and dichotomous tests for color vision. *J Opt Soc Am* 1943;33:568–78.
- Kinnear PR. Proposals for scoring and assessing the 100-hue test. *Vis Res* 1970;10:423–33.
- Farnsworth D. *The Farnsworth dichotomous test for color blindness—panel D-15*. New York: Psychological Corporation, 1947.
- Fletcher RJ. A modified D-15 test. *Mod Probl Ophthalmol* 1972;11:22–4.
- Heron G, Erskine NA, Farquharson E, et al. Color-vision screening in glaucoma—the tritan album and other simple tests. *Ophthalmic Physiol Opt* 1994;14:233–8.
- Lakowski R, Bryett J, Drance SM. A study of colour vision in ocular hypertensives. *Canad J Ophthalmol* 1972;7:86–95.
- Moreland JD. Analysis of variance in anomaloscope matches. *Doc Ophthalmol Proc Ser* 1984;39:111–19.
- Pokorny J, Smith VC, Verriest G, et al. *Congenital and acquired colour vision defects*. New York: Grune and Stratton, 1979.
- Sample PA, Weinreb R, Boynton RM. Acquired dyschromatopsia in glaucoma. *Surv Ophthalmol* 1986;31:54–64.
- King-Smith E. Psychophysical methods for the investigation of acquired colour vision deficiencies. In: Foster DH, ed. *Inherited and acquired colour vision deficiencies*. London: MacMillan Press, 1991:38–55.
- Ing EB, Parker JA, Emerton LA. Computerized colour vision testing. *Can J Ophthalmol* 1994;29:125–8.
- Hoffmann A, Menozzi M. Computer-based determination of red/green color vision defects. *Biomed Tech (Berl)* 1998;43:124–32.
- Falcao-Reis FM, O'Sullivan F, Spileers W, et al. Macular color contrast sensitivity in ocular hypertension and glaucoma—evidence for 2 types of defect. *Br J Ophthalmol* 1991;75:598–602.
- Yu TC, Falcao-Reis FM, Spileers W, et al. Peripheral color contrast—a new screening-test for preglaucomatous visual-loss. *Invest Ophthalmol Vis Sci* 1991;32:2779–89.
- Devos M, Devos H, Spileers W, et al. Quadrant analysis of peripheral color contrast thresholds can be of significant value in the interpretation of minor visual-field alterations in glaucoma suspects. *Eye* 1995;9:751–6.
- Felius J, van den Berg TJ, Spekreijse H. Peripheral cone contrast sensitivity in glaucoma. *Vis Res* 1995;35:1791–7.
- Fristrom B. Peripheral colour contrast thresholds in ocular hypertension and glaucoma. *Acta Ophthalmol Scand* 1997;75:376–82.
- Alvarez SL, Pierce GE, Vingrys AJ, et al. Comparison of red-green, blue-yellow and achromatic losses in glaucoma. *Vis Res* 1997;37:2295–301.
- Stiles WS. *Mechanisms of colour vision*. London: Academic Press, 1978.
- Reffin JP, Astell S, Mollon JD. Trials of a computer-controlled colour vision test that preserves the advantages of pseudoisochromatic plates. In: Drum B, Moreland JD, Serra A, eds. *Colour vision deficiencies X*. Amsterdam: Kluwer Academic Publishers, 1991:69–76.
- Birch J, Barbur JL, Harlow AJ. New method based on random luminance masking for measuring isochromatic zones using high resolution colour displays. *Ophthalmic Physiol Opt* 1992;12:133–6.
- Verriest G. Les defences acquises de la discrimination chromatique. *Memoires Academie Royale de Medecine de Belgique* 1964;III/IV:5.
- Austin DJ. Acquired color vision defects in patients suffering from chronic simple glaucoma. *Trans Ophthalmol Soc UK* 1974;94:880–3.
- Kalmus H, Luke I, Seeburgh D. Impairment of colour vision in patients with ocular hypertension and glaucoma. *Br J Ophthalmol* 1974;58:922–6.
- Quigley HA, Sanchez RM, Dunkelberger GR, et al. Chronic glaucoma selectively damages large optic nerve fibers. *Invest Ophthalmol Vis Sci* 1987;28:913–20.
- Kolb H, Goede P, Roberts S, et al. Uniqueness of the S-cone pedicle in the human retina and consequences for color processing. *J Comp Neurol* 1997;386:443–60.
- Calkins DJ, Tsukamoto Y, Sterling P. Microcircuitry and mosaic of a blue-yellow ganglion cell in the primate retina. *J Neurosci* 1998;18:3373–85.
- Gunduz K, Arden GB, Perry S, et al. Color vision defects in ocular hypertension and glaucoma. Quantification with a computer-driven color television system. *Arch Ophthalmol* 1988;106:929–35.
- Sample PA, Boynton RM, Weinreb R. Isolating the color vision loss in primary open-angle glaucoma. *Am J Ophthalmol* 1988;106:686–91.
- Greenstein VC, Halsey D, Zaidi Q, et al. Chromatic and luminance systems deficits in glaucoma. *Vis Res* 1996;36:621–9.
- Kalloniatis M, Harwerth RS, Smith EL, et al. Color-vision anomalies following experimental glaucoma in monkeys. *Ophthalmic Physiol Opt* 1993;13:56–67.
- Drance SM, Lakowski R. Colour vision in glaucoma. In: Kriegstein G, Leydhecker W, eds. *Glaucoma update*. Berlin: Springer-Verlag, 1983;II:117–21.
- Yamazaki Y, Drance SM, Lakowski R, et al. Correlation between color vision and highest intraocular pressure in glaucoma patients. *Am J Ophthalmol* 1988;106:397–9.
- Yamazaki Y, Lakowski R, Drance SM. A comparison of the blue color mechanism in high-tension and low-tension glaucoma. *Ophthalmology* 1989;96:12–15.
- Yamagami J, Koseki N, Araie M. Color vision deficit in normal-tension glaucoma eyes. *Jap J Ophthalmol* 1995;39:384–9.

- 63 Lachenmayr BJ, Drance SM. Central function and visual field damage in glaucoma. *Int Ophthalmol* 1992;16:203-9.
- 64 Trick GL. Visual dysfunction in normotensive glaucoma. *Doc Ophthalmol* 1993;85:125-33.
- 65 Lakowski R, Drance SM. Acquired dyschromatopsias. The earliest functional losses in glaucoma. *Doc Ophthalmol Proc Ser* 1979:159-65.
- 66 Breton ME, Krupin T. Age covariance between 100-hue color scores and quantitative perimetry in primary open angle glaucoma. *Arch Ophthalmol* 1987;105:642-5.
- 67 Adams AJ, Rodic R, Husted R, et al. Spectral sensitivity and color discrimination changes in glaucoma and glaucoma-suspect patients. *Invest Ophthalmol Vis Sci* 1982;23:516-24.
- 68 Barbur J, Birch J, Harlow J. Colour vision testing using spatiotemporal luminance masking: psychophysical and pupillometric methods. In: Drum B, ed. *Colour vision deficiencies XI*. Amsterdam: Kluwer Academic Publishers, 1993:417-26.
- 69 Pacheco-Cutillas M, Sahraie A, Edgar DF, et al. Assessment of chromatic discrimination loss in glaucoma. *Ophthalmic Physiol Opt* 1998;18:381.
- 70 Airaksinen PJ, Lakowski R, Drance SM, et al. Color vision and retinal nerve fiber layer in early glaucoma. *Am J Ophthalmol* 1986;101:208-13.
- 71 Flammer J. Psychophysics in glaucoma, a modified concept of the disease. *Doc Ophthalmol Proc Ser* 1985;43:11.
- 72 Heron G, Adams AJ, Husted R. Central visual fields for short wavelength sensitive pathways in glaucoma and ocular hypertension. *Invest Ophthalmol Vis Sci* 1988;29:64-72.
- 73 Johnson CA, Adams AJ, Casson EJ, et al. Blue-on-yellow perimetry can predict the development of glaucomatous visual-field loss. *Arch Ophthalmol* 1993;111:645-50.
- 74 Johnson CA, Adams AJ, Casson EJ, et al. Progression of early glaucomatous visual field loss as detected by blue-on-yellow and standard white-on-white automated perimetry. *Arch Ophthalmol* 1993;111:651-6.
- 75 Wild JM, Moss ID, Whitaker D, et al. The statistical interpretation of blue-on-yellow visual-field loss. *Invest Ophthalmol Vis Sci* 1995;36:1398-410.
- 76 Sample PA, Johnson CA, Haegerstrom-Portnoy G, et al. Optimum parameters for short-wavelength automated perimetry. *J Glaucoma* 1996;5:375-83.
- 77 Sample PA, Weinreb R. Color perimetry for assessment of primary open-angle glaucoma. *Invest Ophthalmol Vis Sci* 1990;31:1869-75.
- 78 Wild JM, Cubbidge RP, Pacey IE, et al. Statistical aspects of the normal visual field in short-wavelength automated perimetry. *Invest Ophthalmol Vis Sci* 1998;39:54-63.
- 79 Bengtsson B, Olsson J, Heijl A, et al. A new generation of algorithms for computerized perimetry SITA. *Acta Ophthalmol* 1997;75:368-75.
- 80 Gray LS, Heron G, Cassidy D, et al. Comparison of age-related changes in short-wavelength sensitive cone thresholds between normals and patients with primary open-angle glaucoma. *Optom Vis Sci* 1995;72:205-9.
- 81 Haegerstrom-Portnoy G, Hewlett SE, Barr SAN. S cone loss with aging. In: Drum B, Verriest G, eds. *Colour vision deficiencies IX*. Amsterdam: Kluwer Academic Publishers, 1989.
- 82 Gutierrez P, Wilson MR, Johnson C, et al. Influence of glaucomatous visual field loss on health-related quality of life. *Arch Ophthalmol* 1997;115:777-84.
- 83 Parrish RK 2nd, Gedde SJ, Scott IU, et al. Visual function and quality of life among patients with glaucoma. *Arch Ophthalmol* 1997;115:1447-55.
- 84 Lee BL, Gutierrez P, Gordon M, et al. The glaucoma symptom scale. A brief index of glaucoma-specific symptoms. *Arch Ophthalmol* 1998;116:861-6.



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