J. Indian Inst. Sci., 66, May 1986, pp. 307–316
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On chromatic aberration in the cornea

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Received on April 7, 1986.

Abstract

The effects of ocular disturbances on the chromatic aberration produced at the cornea are studied. The variation of refractive index with the wavelength of incident light are determined for the rat cornea and aqueous humor from enucleated eyes by interference microscopy and refractometry using a monochromator light source. By computing the separation of a blue (475 nm) and a red (650 nm) ray of light simultaneously projected at either corneal surface, the effect of distorting the normal index profile is examined. Hypothetical refractive index profiles are developed for the cornea and aqueous humor that make the cornea totally achromatic.

Key words: Cornea, refractive index, chromatic aberration.

1. Introduction

It is well known in optics that lens systems refract light of different wavelengths to different extents such that their points of focus are displaced longitudinally with respect to each other and this is known as chromatic aberration. The amount of chromatic aberration depends on the nature of the refractive medium. It is found for most materials, excepting certain conjugated protein solutions and others with absorption bands in the visible region, that the refractive index decreases with increasing wavelength of visible light used. The higher refractive index at the short wavelengths of the visible spectrum causes its focal point to form closer to the lens system than the longer wavelength counterparts. The nature of the variation of refractive index with wavelength (index profile) therefore determines the extent of chromatic aberration displayed by an optical system, and empirical relationships have been developed for the index profile (*e.g.*, Cauchy 4-point formula[1]).

The substantial amount of chromatic aberration present in the human eye (2.0–2.5 D between 400–700 nm) has been confirmed through many studies[2–6]. Studies on other vertebrates have concluded similarly[7]. Since the source of the chromatic error must be the optical interfaces of the cornea and crystalline lens, the above conclusions invite a further analysis of the underlying mechanisms and influences of the ocular media at these surfaces upon the development of chromatic aberration.

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This paper examines chromatism at the anterior and posterior surfaces of the cornea and how it may conceivably be influenced by certain pathological conditions. The analysis can be developed from simple theoretical considerations to which actual refractive index data are applied. Previous studies by Chaudhuri *et al*[8] have provided carefully controlled data on the refractive indices of the ocular components in the rat eye across the visible spectrum. With the assumption that the refractive parameters of human and rat cornea are not too dissimilar, the data from the above study are used in the present analysis with the proviso that the results are merely scaled proportional to the size differences of the two eyes. It should also be pointed out that only the thin lens approximation has been used in the analysis. Though the thick lens formulas are the appropriate relationships that should be used, given the dimensions of the system under consideration, it is sufficient to use thin lens approximations. Also, we are only interested in the general form of the refractive index profiles rather than actual computed values, and thus these thick lens relationships are not utilized in these computations.

Within the framework of the overall dioptrics of the rat eye, the cornea is responsible for about 25% of the total chromatic aberration[8]. As noted earlier, the extent of this contribution could vary with changes in the index profiles of the system. The index profiles are susceptible to conditions such as undue accumulation of protein in the aqueous humor following ocular injury or to changes in corneal hydration which may be caused by various factors, *e.g.*, endothelial dystrophy. The present approach allows us to evaluate the consequent changes in chromatic aberration arising in the cornea.

2. Theoretical background

The system to be considered schematically will be spherical surfaces representing the anterior and posterior corneal surfaces (fig. 1). A blue (B) and a red (R) ray, the exact wavelengths of which will be specified later, are projected simultaneously upon either surface. We wish to estimate the angular separation between the blue and red ray after refraction at a particular surface. This can be most conveniently specified by the difference in the refracted angles with respect to the normal, and can be determined using Snell's law:

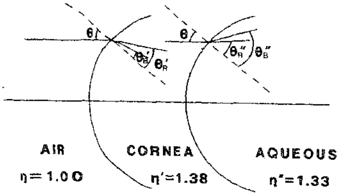

FIG. 1. Schematic representation of the cornea (not to scale) showing the conventions used in the paper.

$$\text{Ray B:}\quad \sin\theta'_B = (n_B/n'_B)\sin\theta \tag{1}$$

$$\text{Ray R:}\quad \sin\theta'_R = (n_R/n'_R)\sin\theta. \tag{2}$$

The angular separation (δ) is defined for the anterior corneal surface as:

$$\delta = (\sin\theta'_B - \sin\theta'_R) = (n_B/n'_B - n_R/n'_R)\sin\theta \tag{3}$$

with

$$n_B = n_R = 1.00;\ \sin\theta = \text{a constant} = c. \tag{3a}$$

Equation (3) reduces to:

$$\delta = c(1/n'_B - 1/n'_R). \tag{4}$$

Since δ represents the angular separation and is the parameter of interest, the present report examines how it is affected by disturbing the index profiles of the cornea and aqueous. We are only concerned with the relative sign and magnitude of δ and therefore the constant c, will be dropped in subsequent analysis since it only acts as a proportionality constant which merely scales δ. A negative value of δ implies positive chromatic aberration whereby the blue focus forms closer to the surface than the red one. Alternatively, negative or reverse chromatic aberration, which may occur in certain situations will result in the opposite effect and will be indicated by a positve value of δ.

A similar analysis can be applied to the posterior corneal surface, giving a result similar to equation 4:

$$\delta' = (n'_B/n''_B - n'_R/n''_R). \tag{5}$$

At this surface the angular separation refers again to a mixture of blue and red light striking the interface and being dispersed as it passes into the aqueous medium. Here also the constant of proportionality has been dropped. The total amount of chromatic dispersion in the cornea can then be shown to be the sum of the angular separation at the anterior and posterior surfaces as follows: The original incident light is dispersed by an amount δ. On striking the posterior surface, it is again dispersed by an amount δ', due to the refractive index change between the cornea–aqueous interface. Therefore, the total amount of chromatic dispersion (when compared to the original incident beam) is:

$$\delta_{\text{Tot}} = \delta + \delta'. \tag{6}$$

In this study we are concerned with how this dispersion will be modified if the normal refractive index values are perturbed. With regard to the cornea, these changes, which may be brought about by certain pathological conditions can be of a proportional nature, whereby the refractive index values at all wavelengths are affected equally. The refractive index profile will therefore result in an equal vertical shift, the direction and extent of which will depend on the nature of the disturbance. Alternatively, the condition may bring about a skew in the profile, whereby one end of it is affected to a greater extent such that the profile either becomes flatter or steeper. The effects of both of these conditions will be examined.

Proportional refractive changes in the cornea may result from increased hydration, *e.g.*, endothelial dystrophy. The consequent effect on thickness and its relation to refractive index by way of the Gladstone–Dale law was shown by Fatt and Harris[9] to be negligible for interference with pachometry. Although their clinically observed, above normal range of thickness rarely affected refractive indices by more than 1%, the present study examines the consequences of up to a 4% change in this parameter. Furthermore, it is proposed that such a disturbance affects refractive indices equally at all wavelengths since only the concentration of dissolved substances in the cornea is being affected and not the differential interaction of light of different wavelengths with this substance.

The angular separation (δ) is evaluated for proportional index changes of the cornea mathematically by adding a constant to the refractive parameters of equations 4 and 5, giving the following relations for the anterior and posterior surfaces respectively:

$$\delta = (1/(n'_B + k) - 1/(n'_R + k)), \tag{7}$$

$$\delta' = ((n'_B + k)/n''_B - (n'_R + k)/n''_R). \tag{8}$$

Skew changes of the refractive index profiles of both cornea and aqueous humor may occur as a result of ocular injury or inflammation whereby plasma protein concentration within these components increases. The angular separation for this condition affecting the cornea is evaluated mathematically by multiplying a constant k' to the refractive parameters of equations 4 and 5, giving the following relations for the anterior and posterior surfaces respectively:

$$\delta = (1/k')\,(1/n'_B - 1/n'_R), \tag{9}$$

$$\delta' = k'\,(n'_B/n''_B - n'_R/n''_R). \tag{10}$$

Skew changes on the aqueous index profile affecting the posterior corneal surface are given by

$$\delta' = (1/k')\,(n'_B/n''_B - n'_R/n''_R). \tag{11}$$

3. Methods

Refractive indices of the rat cornea and aqueous humor were determined using incident light of wavelengths in the range of 475–650 nm at 25 nm intervals. The ocular components were taken from enucleated eyes of female, retired breeder rats of the Long Evans strain. Discrete wavelengths in the above range were isolated using JENA interference filters (half-width = 6–7.5 nm) with a quartz-iodine lamp. A Bausch and Lomb monochromator (half-width = 4.8 nm) was also used to provide more regular intervals of incident light wavelengths.

The refractive index of the ocular components were obtained with an Abbe refractometer and a JENA interference microscope. It was found that the refractometer provided a more accurate estimation of the refractive index of a standard control (water) whose refractive parameters are well known[10] at all the wavelengths measured. Nevertheless, results from both were combined and scaled by the control correction factor as well as one that represented the standard deviations of the samples.

4. Results and discussion

The refractive indices for rat cornea and aqueous are provided in Table 1. Graphical profiles of these values are shown by the dashed curves in fig 2. In the following we will discuss the effects of proportional and skew changes on the refractive index profile.

4.1. Proportional refractive index change

The effect of changing the proportional parameter, k, from -0.06 to $+0.06$ is shown in fig 3. Although the values of δ are not exact, since the first order or paraxial

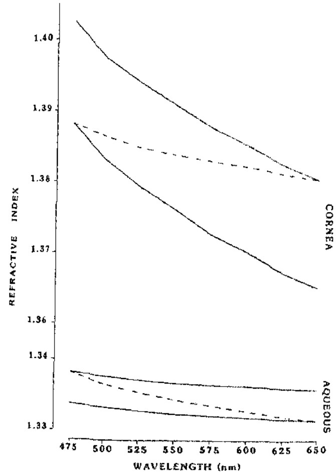

FIG. 2. Actual 'index profiles' (dashed curves) of the cornea and aqueous humor and hypothetical profiles (solid curves) that make the cornea entirely achromatic.

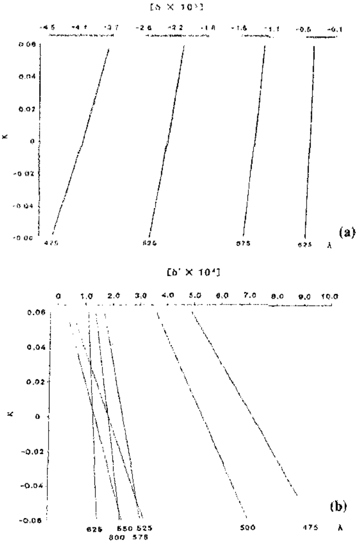

FIG. 3. Effect of proportional refractive index disturbances of the cornea on the angular separation (δ) for the anterior (a) and posterior (b) corneal surfaces. The angular separations are computed for rays of light at the indicated wavelengths from light of 650 nm.

Table I
Refractive index of rat cornea and aqueous humor (Temperature corrected values)

λ (nm)	Refractive index	
	Cornea	Aqueous
475	1.3882	1.3381
500	1.3864	1.3366
525	1.3848	1.3355
550	1.3838	1.3346
575	1.3829	1.3336
600	1.3821	1.3329
625	1.3812	1.3321
650	1.3804	1.3315

approximation is used, the trend is for chromatic aberration at the corneal surfaces to be inversely proportional to changes in the refractive index of that component. Therefore, increases in corneal hydration, as implied by a negative value of k, since refractive index will decrease, will result in increased chromatism at both the surfaces. However, since chromatism at the anterior surface is opposite in sign to that at the posterior surface, the two effects will tend to offset each other. The negative value of δ at the anterior surface implies that the shorter wavelengths converge more than the longer wavelength counterparts. The negative power posterior surface diverges shorter wavelengths more (δ positive by our convention). This effect is one order of magnitude less than the effect produced at the anterior surface. Total corneal chromatic aberration will therefore follow that which was produced at the anterior surface.

So far actual values of wavelengths have not been used in considering chromatic aberration. Traditional accounts involve use of Fraunhofer lines. In this study, we consider a continuous description whereby the red end ($\lambda = 650$ nm) is fixed and we compute the aberration of shorter wavelengths at 25 nm intervals starting at 475 nm. n'_B and n''_B take on values corresponding to the wavelength under consideration, and n'_R and n''_R represent the refractive indices at 650 nm of the cornea and aqueous humor respectively. Naturally, the chromatic error would be expected to successively decrease as the value of the lower wavelength is increased (fig. 3a). However, at the posterior corneal surface (fig. 3b) it is seen that chromatism at 550 nm can be lower than all other wavelengths considered.

FIG. 4: Effect of skew refractive index disturbances of the cornea on the angular separation (δ) for the anterior (a) and posterior (b) corneal surfaces (dashed lines). Skew change effects of the aqueous humor for the posterior surface are shown by solid lines in(b). Both figures also show the relation between angular separation and wavelength of light that is compared to 650 nm. Note the dip at 550 nm at the posterior surface.

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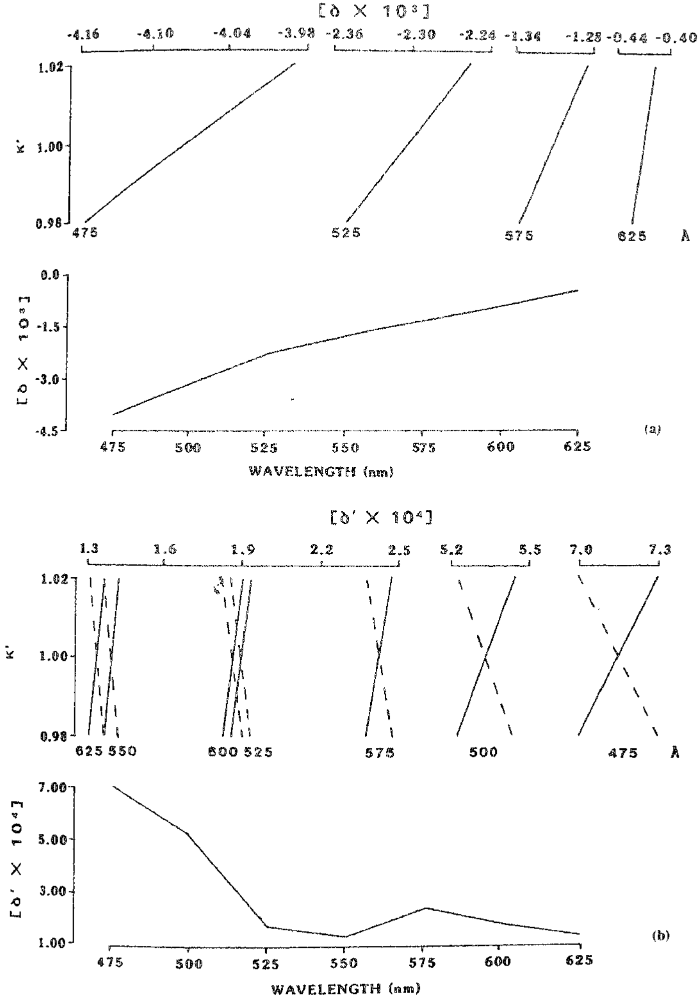
[$\delta \times 10^3$]
-4.16
-4.10
-4.04
-3.98
-2.36
-2.30
-2.24
-1.34
-1.28
-0.44
-0.40
1.02
1.00
0.98
K'
475
525
575
625
Å
0.0
-1.5
-3.0
-4.5
[$\delta \times 10^3$]
475
500
525
550
575
600
625
WAVELENGTH (nm)
(a)
[$\delta' \times 10^4$]
1.3
1.6
1.9
2.2
2.5
5.2
5.5
7.0
7.3
1.02
1.00
0.98
K'
625
550
600
525
575
500
475
Å
7.00
5.00
3.00
1.00
[$\delta' \times 10^4$]
475
500
525
550
575
600
625
WAVELENGTH (nm)
(b)

4.2. *Skew refractive index change*

The effect of changing the skew parameter, k', from 0.98 to 1.02 is shown in fig. 4. As with proportional changes, chromatic aberration is found to be inversely proportional to the change in refractive index of the cornea for both anterior and posterior surfaces. However, decreases in the skew parameter for the aqueous humor (or a flattening of its index profile) are accompanied by reduced angular separation and consequently chromatic aberration. The magnitude of these effects decreases with increasing wavelength. That is, as shown in the lower part of fig. 4a, angular separation decreases as one considers shorter and shorter intervals of the visible spectrum with the red end fixed at 650 nm. There is a peculiar dip in the relation for the posterior corneal surface (fig. 4b) which suggests that chromatic defocus between light of 550 and 650 nm to be smaller than light of any other wavelength up to 625 nm when compared with 650 nm. However, as noted before, total corneal chromatic aberration is composed almost entirely of the chromatic contribution of the anterior surface. The dip in the posterior surface is therefore masked and does not show up in a similar relation for the entire cornea (fig. 5).

The notion of total chromatic aberration in the cornea being the sum of the contributions of the anterior and posterior surfaces leads to the development of a series of index profiles for the cornea and aqueous humor that would entirely eliminate this aberration in the cornea. The dashed lines in fig. 2 show the actual index profile of the cornea and aqueous, whereas the solid lines represent index profiles that these components would have to possess independently for the condition of corneal

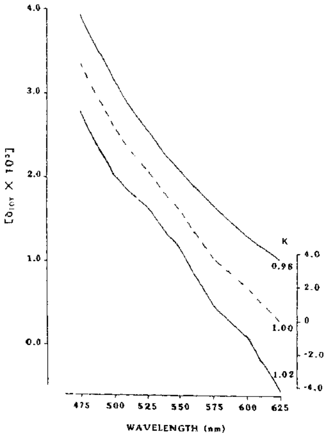

FIG. 5. Total angular separation (δ_{tot}) shown as a function of wavelength for three values of the skew parameter. The angular separation decreases for shorter intervals of the visible spectrum with the red end fixed at 650 nm.

achromatism. In fact, any curve similar to the solid ones and within those boundaries could result in the same condition.

5. Conclusion

The effect on chromatic aberration at the anterior and posterior corneal surfaces was examined by altering the index profiles of the cornea and aqueous humor. Such changes may occur naturally due to pathology or due to ocular injury. It is found that the bulk of corneal chromatic aberration occurs at the anterior surface and this serves to mask a chromatic peculiarity that arises in the posterior surface. Hypothetical index profiles of the cornea and aqueous humor that could make the cornea totally achromatic were determined.

Acknowledgements

The data used in this study were collected as part of an M.Sc. thesis by A.C. in the laboratory of P. E. Hallet, Dept. of Physiology, University of Toronto, Toronto, Canada.

V.L. would like to acknowledge an award from the Regents of the University of California and partial support from National Eye Institute research grant EYO 3674, from the National Institutes of Health, Bethesda, Maryland, USA.

Partial results from this study were presented at the annual meeting of the Association for Research in Vision and Ophthalmology, Sarasota, Florida, May, 1984 (*Invest. Ophthalmol. Vis. Sci.*, 1984, **25**, 182).

References

1. JENKINS, F. A. AND WHITE, H. E. *Fundamentals of optics*, III edition, McGraw-Hill, New York, 1976.
2. WALD, G. AND GRIFFIN, D. R. The change in the refractive power of the human eye in dim and bright light, *J. Opt. Soc. Am.*, 1947, **37**, 321–336.
3. IVANOFF, A. Les aberrations de l'oeil, *Rev. d'optique*, Paris, 1953, 1–80.
4. BEDFORD, R. E. AND WYSZECKI, G. Axial chromatic aberration of the human eye, *J. Opt. Soc. Am.*, 1957, **47**, 564–565.
5. CHARMAN, W. N. AND JENNINGS, J. A. M. Objective measurements of the longitudinal chromatic aberration of the human eye, *Vision Res.*, 1976, **16**, 999–1005.
6. SIVAK, J. G. AND MANDELMAN, T. Chromatic dispersion of the optical media, *Vision Res.*, 1982, **22**, 997–1003.
7. HUGHES, A. A useful table of reduced schematic eyes for vertebrates which includes computed longitudinal chromatic aberrations, *Vision Res.*, 1979, **19**, 1273–1275.

8. Chaudhuri, A., Hallett, P. E. and Parker, J. A. — Aspheric curvatures, refractive indices and chromatic aberration of the ra eye, *Vision Res.*, 1983, **23**, 1351–1363.

9. Fatt, I. and Harris, M. G. — Refractive index of the cornea as a function of its thickness, *Am. J. Optom.* 1973, **50**, 383–386.

10. Eisenberg, H. — Equation for the refractive index of water, *J. Chem. Phys.*, 1965, 43 3887–3892.