The Contribution of the Crystalline Lens to Chromatic and Spherical Aberrations of the Eye

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Abstract

The longitudinal chromatic aberration of the eye is greater than expected from reduced eye calculations. Recent evidence shows that this is due to the fact that chromatic dispersion of the crystalline lens is greater than previous estimates, particularly at wavelengths below 500 nm. Measurements of spherical aberration of the lens indicate that the aberration is almost absent. Since the eye is known to be quite free of spherical aberration, both the cornea and the lens may be considered to have relatively constant focal lengths for incident light rays of varying separations.

Abrégé

L'aberration chromatique axiale mésurée de l'oeil est supérieure à celle résultant d'un calcul basé sur l'oeil reduit. Des études récentes démontrent que la dispersion chromatique du cristallin dépasse l'ancienne donnée surtout pours les longueurs d'ondes au dessous de 500 NM.

L'aberration spherique mésurée du cristallin est presque nulle. Conséquemment on peut conclure que la cornée et la cristallin maintiennent une distance focale constant pour des rayons incidents à differentes distance de l'axe optique.

Introduction

Numerous investigators, employing a variety of subjective and objective methods, have measured the chromatic and spherical aberration of the eye. Newton[1] is given the credit of being the first to measure longitudinal chromatic aberration. The more recent studies of Wald and Griffin[2], Ivanoff[3] and Bedford and Wyszecki[4] have confirmed that chromatic aberration is substantial and amounts to 2 — 2.5 dioptres between 400 and 700 nm.

Measurements of spherical aberration of the eye are more difficult and the results are less consistent than in the case of chromatic aberration, although efforts to measure it go back at least to the time of Young[5]. Nevertheless, the classic experiments of Ivanoff[6], Koomen et al[7]. and Schober et al.[8] are in agreement in concluding that spherical aberration is highly variable and relatively insignificant in amount. LeGrand[1] writes that "it seems illusory to speak of an average spherical aberration of the human eye; the only general conclusion is that in diurnal conditions spherical aberration reaches at most a few tenths of a diopter . . .". In fact, Jenkins[9] has calculated from schematic eye parameters that 10.0 dioptres of spherical aberration should exist for a 6 mm pupil. The reasons for the relative absence of spherical aberration will be discussed elsewhere in this paper.

Chromatic Aberration of the Crystalline Lens

The relative contributions of the lens and cornea to chromatic (and spherical) aberration is not clear despite the attention which these aberrations have received in studies dealing with the whole eye. In attempting to calculate the chromatic aberration expected from schematic eye values, LeGrand[1] was faced with the problem of assigning refractive indices for various wavelengths to the ocular media. Corneal constringence was assumed to be 56, that of water. The lens was more difficult to deal with. From the sparse data available in the literature[10,11], it appears that the lens is more dispersive than water and a constringence value of 50 was chosen. Even with this value, the calculated overall chromatic aberration of the eye is less than that measured experimentally, the difference being particularly noticeable at the blue end of the visible spectrum; ie. below 500 nm. LeGrand concludes that the lens must be still more dispersive in blue light.

Ivanoff[3] also considered that the lens contributes disproportionately to the eye's chromatic aberration. However, the amount of chromatic aberration which he measured in one aphakic subject (0.75D) is not strong evidence for this view since the average amount measured for normal eyes using the same experiment amounts to 1.25D. Sivak and Millodot[12] measured lens chromatic aberration of four subjects by eliminating the refractive contribution of the cornea. This is accomplished by submerging the front surface of the cornea in water (actually, a net refractive contribution of −1.5D results because the two corneal surfaces are not parallel). Corneal refractive power was replaced with an achromatic lens of appropriate power and location. The results indicate that the chromatic aberration of the lens amounts to 0.5D, or about one-third the average value of 1.5D measured for the same eyes without the water placed in front of the cornea. Since the power of the unaccommodated lens is approximately one-half that of the cornea, these results suggest that the chromatic aberration contributed by the two refractive structures of the eye are roughly proportional to their powers and a difference in dispersion is not indicated.

While these results are quite clear, there is one important flaw. LeGrand emphasizes that it is the blue end of the spectrum (below 500 nm) that is affected by enhanced

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lens dispersion. The Sivak and Millodot study stops at 486 nm due to limitations imposed by the experimental equipment. Thus the amount of chromatic aberration contributed by lens for the critical wavelengths below 486 nm was not measured.

Recently Palmer and Sivak measured chromatic dispersion of animal lenses and one human lens directly by the method of Pulfrich refractometry[13]. This method involves axially bisecting a freshly dissected lens and placing the cut edge on one side of a right angle glass prism. Refractive indices for a variety of wavelengths can be determined by noting the change in critical angle of the prism. Further, it is possible to differentiate between peripheral and central zones of the lens. This procedure included measurements made at short wavelengths (to 410 nm) and the results confirm the suspicions of LeGrand and Ivanoff. Lens dispersion values are consistently greater (or constringence values are consistently lower) than water, with dispersion increasing as a function of depth into the lens. Furthermore, dispersion increases asymptotically toward the blue wavelengths. In fact, the curve showing the change in refractive index between 700 and 550 nm is quite flat while the rate of change increases dramatically toward 400 nm.

A study carried out with two methods, Pulfrich and Abbe refractometry by Sivak and Mandelman[14] confirm these results on larger numbers of human and animal lenses. Constringence values for the lens nucleus can be as low as 35 (cat, human), substantially lower than the value of 50 used by LeGrand for the whole lens. In addition, measurements of corneal constringence are also lower than water although not as much as the lens (45, chicken) with the effect being particularly noticeable in blue light. In fact, corneal dispersion curves suggest that they are a combination of two separate functions, a flatter curve for the longer wavelengths and a steeper one for the short ones.

The results show that the greater dispersion of the lens (and the cornea to a lesser extent) in blue light is responsible for the larger than expected amounts of measured longitudinal chromatic aberration. Thus, one can argue that chromatic aberration, unlike the other aberrations of the eye, is not controlled and is, in fact, exaggerated somewhat. In this context it is important to note that the eye's substantial chromatic aberration is useful in that it is used as a means of sparing accommodation[15,16]. By using the chromatic aberration interval and focussing on long wavelengths with accommodation relaxed and short ones while accommodating, the effort exerted by the ciliary muscle-lenticular accommodative apparatus is minimized.

Spherical Aberration of the Crystalline Lens

That the eye is relatively free of spherical aberration has already been noted. The absence of spherical aberration is attributed to three factors; asphericity (peripheral flattening) of the cornea, asphericity of the surfaces of the crystalline lens[17] and the variation in refractive index of the lens from periphery to core. Little experimental attention has been paid to the relative importance of each of these factors in controlling spherical aberration. Bonnet[18] measured a small amount of positive spherical aberration (shorter posterior vertex distance for peripheral light rays) in one aphakic with a six mm pupil. This suggests that the lens alone must also have little spherical aberration. However, El Hage and Berny[19] concluded, on the basis of corneal topography, that the cornea contributes substantial quantities of positive spherical aberration and this must be neutralized by a lens with negative spherical aberration.

Millodot and Sivak[20] measured lens spherical aberration directly in an experiment in which corneal refractive power was virtually eliminated by means of a saline water-filled goggle. An aspheric glass lens (20D) appropriately placed in front of the eye replaced the cornea. The procedure was based on the Scheiner Disc principle. One eye was occluded while the other was partially occluded with a disc containing small apertures at varying eccentricities (1.4 — 3.6 mm) from a central aperture. Only the central and one of the peripheral apertures were open at a given time. A vertical target was seen as double by the subject when an ametropia existed. Loose prisms placed in front of the peripheral aperture to eliminate doubling of the target indicated the value of the ametropia. The magnitude and direction of spherical aberration was found by comparing the results for the different apertures.

The mean result for 20 subjects shows that the whole eye has a small amount (about 2/3 D for the greatest eccentricity) of positive spherical aberration. The amount and, in one case, the sign varies from one individual to another. The lens alone also exhibits slight positive spherical aberration although about half that of the whole eye. Here again, individual differences were noted. In two cases, the aberration was negative. These results indicate that the aberrations of the cornea and lens are not usually opposite in sign. Rather than neutralizing each other, the small aberrations of each structure summate. One can only conclude that both the lens and the cornea are remarkably free of spherical aberration and phenomena such as nocturnal myopia cannot be attributed to it.

Recently (Sivak and Kreutzer, in preparation), spherical aberration of excised human and other animal lenses were determined directly. The method involves projecting a split beam from a helium-neon laser through the lens and photographing its focal effect. By varying the separation of the entering beams it is possible to measure differences in focal length; ie. spherical aberration. Extensive variation in spherical aberration, both positive and negative, was noted for the 5 human lenses examined. Since the lenses were from individuals of relatively advanced age, it is possible that the ability of the lens to control its spherical aberration deteriorates with age.

Summary

1. The measured longitudinal chromatic aberration of the eye is greater than that calculated from reduced eye parameters.
2. This difference is due to the greater than expected chromatic dispersion of the crystalline lens.
3. Lens dispersion increases asymptotically below 500 mm and therefore the short wavelengths are major contributors to the eye's chromatic aberration.
4. The appreciable quantity of chromatic aberration exhibited by the eye is not necessarily detrimental to vision. For example, it has been shown that the chromatic aberration interval is used to spare accommodation.
5. The eye is relatively free of spherical aberration and it has been suggested that this is due to the fact that the positive spherical aberration of the cornea is neutralized by the negative aberration of the crystalline lens.
6. Measurement of the spherical aberration of the lens *in vivo* indicates that both the lens and the cornea are almost free of spherical aberration. In general, the slight positive aberration of both structures summate.
7. The relative absence of spherical aberration may be attributed to; peripheral flattening of the cornea, the variation in refractive index of the lens from the cortex to the core and the asphericity of the lens surfaces.
8. Direct measurement of spherical aberration of excised lenses from individuals of advanced age demonstrate large amounts of positive and negative aberrations. It is possible that the ability of the lens to control this aberration deteriorates with age.

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