Longitudinal Chromatic Aberration in Pseudophakia

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Abstract

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A computer operated Badal-type optometer was used to measure pseudophakic chromatic aberration in 4 observers aged between 62 and 70 years. Individuals were tested from 340 to 660 nm. Individual theoretical chromatic aberration was also calculated using ultrasound and keratometry readings and compared with the observed results. It was found that there was a significant difference between observers and that no correlations were found between the magnitude of chromatic aberration versus axial length and keratometry readings. A significant correlation was found between magnitude of chromatic aberration and anterior chamber depth. The average data were shown to be similar to theoretical data from 400 to 660 nm whereas below 400 nm there was an appreciable increase in chromatic aberration among the observed data. The results show that individual differences cannot be attributed to axial length or the power of the cornea but to anterior chamber depth. A major conclusion is that Cornu's formula cannot properly estimate the change in dispersion of the crystalline lens.

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Longitudinal Chromatic Aberration in Pseudophakia

The phenomenon of longitudinal chromatic aberration has been studied extensively ever since Newton proposed in 1730 that the eye's refraction is wavelength dependent. Strict empirical evaluations began to emerge only in the middle part of this century where the majority of studies addressed chromatic aberration in the phakic or intact eye. When the crystalline lens is removed the eye is opened to several perceptual and physical aberrations such as (1) excessive glare, (2) erythropsia, (3) retinal damage, as well as (4) ultraviolet (UV) light sensitivity, the latter being the focus of the present experiment. One consequence of this sensitivity to UV light is reduced visual acuity due to chromatic aberration (Rog, White, & Williams, 1986). Several studies have been done on aphakic chromatic aberration but none have concentrated their efforts on pseudophakic chromatic aberration from either an empirical or theoretical perspective.

Pseudophakia refers to the implantation of an intraocular lens (IOL) after the extraction of the crystalline lens. While previous studies have focussed on visible light they have ignored the important role of UV light and chromatic aberration. The purpose of this study is (1) to quantify longitudinal chromatic aberration in the pseudophakic eye, (2) extend measurements into the UV, and (3) to compare the obtained results with individual theoretical calculations of chromatic aberration for individual observers.

Chromatic aberration

The eye is far from being a perfect optical instrument. It accomplishes what it does due to many compensatory mechanisms without which vision would be rather unadaptable. For example, the crystalline lens, like the cornea, filters UV light and in addition it also exhibits chromatic aberration. Chromatic aberration is an inherent physical property of refracting surfaces. Intraocular lenses (IOLs) exhibit chromatic aberration similar to that of the crystalline lens but unlike the lens, they allow unfiltered UV light to be refracted as well.

The refractive functions of the optical media in the human eye are also wavelength dependent, which produces chromatic dispersion. These refracting media are the cornea, the lens, the aqueous and vitreous humour.

The refractive index of a transparent medium is the ratio of the sine of the angle of the incident ray to the normal and the sine of the angle between the refracted ray and the normal. This, and the fact that the incident and refracted rays and the normal to a surface all lie in the same plane, is referred to as the law of refraction or Snell's law, after its originator. When monochromatic light passes through a medium then the constant in Snell's law becomes the index of refraction, or the refractive index, and is usually designated as n. The refractive index of air at standard conditions is approximately 1.0003, therefore, it can be assumed to be unity. Typical indices of refraction for other substances are 1.52 for Crown glass and 1.333 for water measured at the recognized standard wavelength of 589 nm, yellow sodium light.

Theoretical and observed phakic chromatic aberration

Many investigators have attempted to quantify chromatic aberration of the human eye, and one of the earliest studies was conducted by Young in 1802. He found that the magnitude of chromatic aberration between the two ends of the spectrum was 1.30 diopters (D). A brief definition of diopter is in order. The reciprocal of the focal length of a lens is called power, and if the focal length is in meters then the power of the lens is denoted in diopters. For example the power of a positive lens whose focal length is 1 meter will be 1 diopter. If the focal length was 2 meters then the power would be 0.5 diopters.

Many of the other earlier studies, though, lacked clear descriptions of the methodologies used (Ames & Proctor, 1921; Polack, 1923; Pinegin, 1941). For example, Pinegin (1941) used only one observer and measurements were recorded from 300 to 700 nm but it is not clear whether the type of eye observed was phakic or aphakic.

Although refractive indices of optical materials are widely documented, the indices of the intraocular media are not as commonly known. Many investigators made use of sparse data from earlier studies to predict chromatic aberration (Polack, 1923; Tagawa, 1928). More recently, strict empirical measurements have been made of the eye's media of various species (Palmer & Sivak, 1981; Sivak & Mandelman, 1982; Campbell, 1984). This recent data has subsequently been used in the calculation of theoretical chromatic aberration.

Previous theoretical calculations of the chromatic aberration of the eye used a model of an eye that has the same posterior focal length as the human eye, but was composed entirely of distilled water with a single spherical refracting surface. The radius of curvature was assumed to be 5.719 mm similar to that of the reduced eye.

One important and concise study along these lines was carried out by Wald and Griffin (1947) who calculated the chromatic aberration of the water eye and compared the results to the data obtained from normal eyes.

They tested 14 observers at 9 different wavelengths ranging from 365 to 750 nm. They used a spectral stigmascope, and their target consisted of a black square-wave grating with a white background. The observer's eyes were not cyclopleged, therefore, their accommodation was fixed by having the eye not being tested to fixate at a far target. The magnitude of chromatic aberration was shown to be 3.25 D between 365 and 750 nm. When the theoretical curve was compared to the mean observed curve, it was found that chromatic aberration was less in the water eye than that of the normal eye. At the time, it was postulated that the difference in this aberration may have been due to the greater dispersion of the crystalline lens. Wald and Griffin further speculated that the cornea does not contribute much to the total dispersion of the eye. The reason given was that the cornea "is very thin and its outer and inner surfaces are not far from concentric" (Wald & Griffin, 1947, pg. 328).

A decade later, Bedford and Wyszecki (1957) conducted an experiment using a similar stigmascope. Twelve subjects between the ages of 23 and 40 years were tested and chromatic aberration was measured at thirteen wavelengths ranging from 389 to 700 nm. Five settings were made at each wavelength by each observer. The results were very similar to those of Wald and Griffin (1947), and the magnitude of chromatic aberration between 389 and 700 nm was shown to be 2.40 D. A few years later, Jenkins (1963) measured chromatic aberration, using a Badal-type optometer, in 32 subjects. The observers made 8 settings at 6 different wavelengths. The results, again, were relatively similar to those mentioned thus far.

LeGrand (1967) attempted to calculate theoretical chromatic aberration using a schematic model of the eye He calculated the chromatic aberration as the refraction of the eye measured from the first principal plane at any wavelength minus the refraction of the eye measured from the first principal plane at 590 nm. LeGrand also correctly observed that the dispersive nature of the lens is significantly greater than that of the cornea as opposed to earlier speculations.

Several years later, Tucker (1974) calculated theoretical chromatic aberration using the refractive indices of the reduced eye based on Houston's dispersion formula. The calculations were based on the power of the eye at 580 nm minus the power of the eye at all the other wavelengths. The results did not deviate appreciably from the calculations made by Legrand (1967) or those of Wald and Griffin (1947) for their water eye.

That same year, Millodot and Sivak (1974) measured chromatic aberration employing relatively simple optics, with trial lenses to measure the difference in refraction. Five subjects were tested and 2 measures were taken at each wavelength. The magnitude of chromatic aberration was found to be about 1.60 D between 486 and 656 nm. The data observed at the shorter wavelengths were different from the data predicted by theoretical studies. Again, it was speculated that this was due to the greater dispersion of the crystalline lens below 400 nm.

Millodot (1976) had conducted a follow-up study measuring chromatic aberration in 26 subjects, aged between 10 and 40 years of age using the same apparatus as Millodot and Sivak (1974). Here too the results were similar to those of previous studies by other experimenters.

Sivak and Millodot (1975) performed an experiment in order to answer the question of the separate contribution of the lens and cornea to chromatic aberration. It was shown that the dispersive nature of the lens does not differ significantly from that of the cornea and that the lens contributed one-third of the chromatic aberration and the cornea two-thirds.

With the advent of new technologies, researchers began to use new tools in their investigations. Retinoscopy had been used for many years to objectively measure the refractive state of the eye. This apparatus can be modified to measure chromatic aberration if the light leaving the eye is controlled. Sivak and Bobier (1978), and Bobier and Sivak (1980) conducted experiments where 13 observers (9 prepresbyopic and 4 presbyopic) were tested. The subjects fixated on a projected Snellen chart. Kodak Wratten filters No.25 (dominant wavelength 615 nm) and No.55 (dominant wavelength 530 nm) were used to measure chromatic aberration. The results showed that the average chromatic aberration was 0.78 D between the green and the red which was comparable to previous results. They also found that pupil size did not significantly alter the results. Although objective criteria were used, the apparatus proved to be inadequate for careful psychophysical measurement because only two dominant wavelengths were used.

Sound measurements were still not available regarding the refractive indices of eyes. Sivak and Mandelman (1981), though, attempted to gather measurements with a Pulfrich refractometer, making Abbe measurements which rely on variations in the critical angle of a prism to determine the refractive index. A variety of eyes of different species were used in this experiment, including humans, cows, pigs, cats, albino rats, frogs, and rock bass. The aqueous and the vitreous indices were not measured in the human eye. The cornea, peripheral lens, and the core of the lens were the only surfaces to be measured. Five lenses were from individuals of advanced age (59-78), two were from a 45-year-old, and two were from a 16-year-old. Palmer and Sivak (1981) had measured the crystalline lens dispersion from a 70 year old human eye using the same method as that of Sivak and Mandelman (1981). The results of both experiments and Cornu estimates are shown in Table 1. Cornu's formula is

Table 1

The chromatic dispersion of the ocular media reported by Palmer and Sivak (1981) (70 year old lens) and Sivak and Mandelman* (1981) (mean of several ages from 16-79 years) compared to Cornu formula calculations.

wavelength (nm)	cornea 1981*	cornea Cornu	lens 1981*	lens 1981	lens Cornu
410		1.388		1.410	1.433
440	1.380	1.385	1.416	1.407	1.430
470		1.384		1.405	1.427
486	1.376	1.382	1.410	1.403	1.426
500		1.381		1.402	1.425
530		1.380		1.400	1.423
560		1.378		1.399	1.421
590	1.370	1.377	1.375	1.396	1.420
620		1.376		1.394	1.419
650	1.368	1.375	1.371	1.394	1.418

represented by: n = nx + [K / (L - 130)], where n is the index of refraction, nx is a constant refractive index (cornea=1.3610, lens=1.3999), K is another constant (cornea=7.4147, lens 9.2492), L is the wavelength in question, and 130 is another constant being the same regardless of media. According to LeGrand (1967) Cornu's formula does not possess any theoretical basis. As shown in Table 1, there is a slight albeit negligible difference in the refractive indices in both experiments. The problem of comparison, though, is that one lens was compared to a mean of 9 lenses from subjects of various ages. It would be interesting to view the comparison of refractive indices of lenses of approximate ages. Sivak and Mandelman (1981) did report that the refractive indices all increase rather quickly at the violet end of the spectrum. They conclude that estimated chromatic aberrations cannot be adequately obtained from Cornu's formula which does not take this digression in refraction into account. This also suggests that the lens at the violet end of the spectrum exhibits greater dispersion than water.

From the data mentioned above, Mandelman and Sivak (1983) calculated the chromatic aberration of the eye using the method of LeGrand (1967). They confirmed that merely taking the difference of the power of the eye at 580 or 590 nm and at another wavelength was inaccurate due to the fact that longitudinal chromatic aberration is always less than the difference in total eye powers. As predicted, chromatic aberration was shown to be greater in the violet end of the spectrum than was previously shown. This increase in chromatic aberration, though, was not explained by any novel approach. The dispersive nature of the crystalline lens was again implicated as the source.

More recently, Howarth and Bradley (1986) using a Badal optometer measured the average chromatic aberration for 20 subjects between the ages of 23 and 43 years. The observers' eyes were cyclopleged to retard accommodation and an artificial pupil was used. Nine wavelengths were tested and at least 4 settings were made at each wavelength. The magnitude of aberration was about 1.85 D between 420 and 660 nm. In order to explain the large differences in chromatic aberration between observers, the axial length of the eye was measured and correlated with the magnitude of chromatic aberration. No significant correlation was found. The relationship between corneal power and chromatic aberration was also investigated and it was shown that the differences in corneal power did not greatly contribute to the observed differences in aberration. It was concluded that individual differences could be attributed to either differences in lens constringence or power, or differences in corneal constringence. Constringence (coefficient of

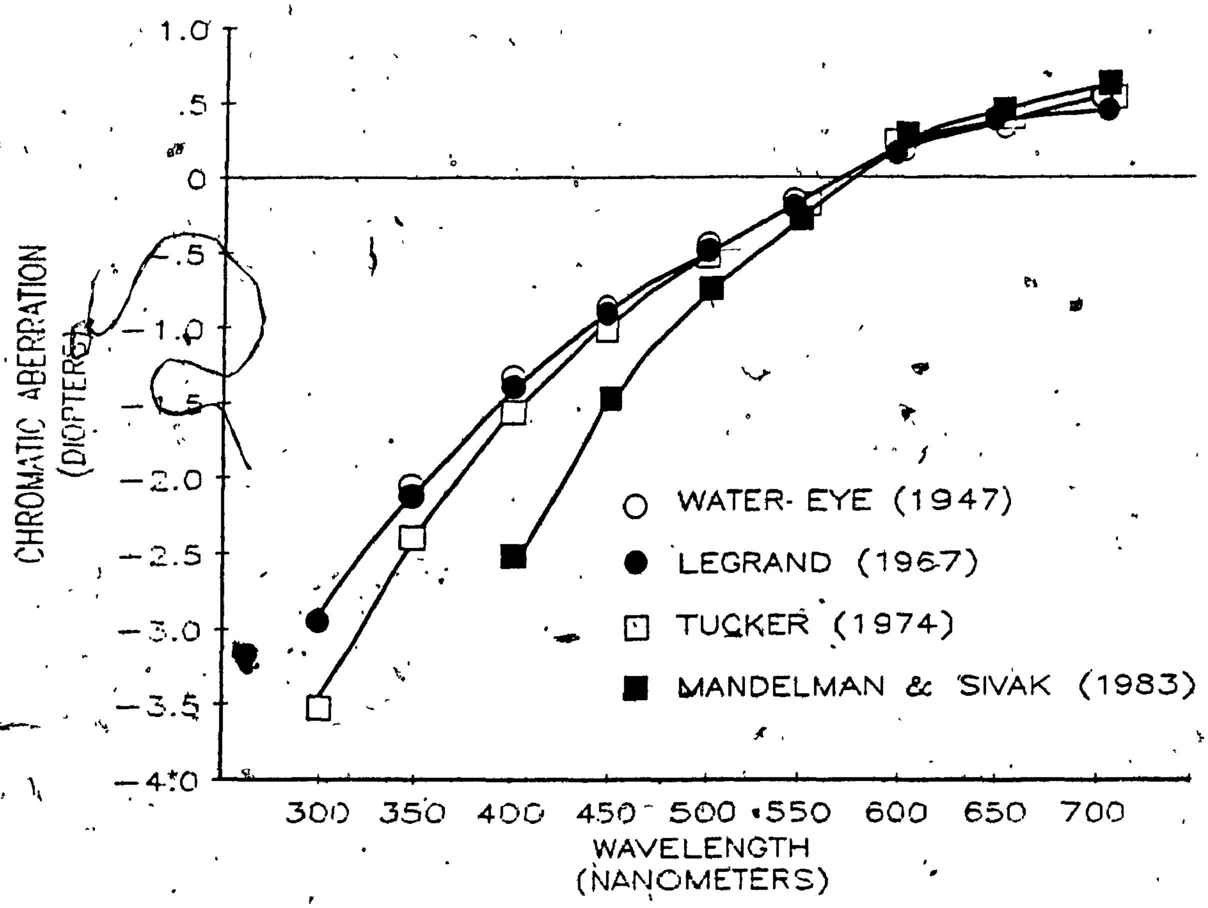

Figure 1. Theoretical chromatic aberration from different studies.

dispersion) is obtained by the formula: v = (nD - 1) / (nF - nC) whereby, n denotes index of refraction and F, D, and C denote Fraunhofer lines at wavelengths 486.1, 589.3, and 656.3 nm respectively. A substance in which the speed of a wave varies with wavelength is said to exhibit dispersion. Dispersion is also the reciprocal constringence.

In order to assimilate coherently the results of the many experiments presented thus far several figures will summarize the data. Figure 1 shows the data from the theoretical studies reviewed with a reference wavelength of 580 nm. The curves for the "water eye" (1947), LeGrand (1967), and Tucker (1974) are relatively similar whereas the values obtained by Mandelman and Sivak (1983) deviate considerably from the rest in the blue end of the spectrum. To reiterate, the refractive indices used by Mandleman and Sivak (1983) were from recent experimental data whereas the other studies were from previously known indices. Measurements of refractive indices, unfortunately, were not extended into the UV due to the limitations of the equipment used. Therefore, chromatic aberration could not be calculated in the UV by Mandleman and Sivak (1983).

The results of the experiments generating empirical data are presented in Figure 2. The results were adjusted so that all were normalized to the reference wavelength

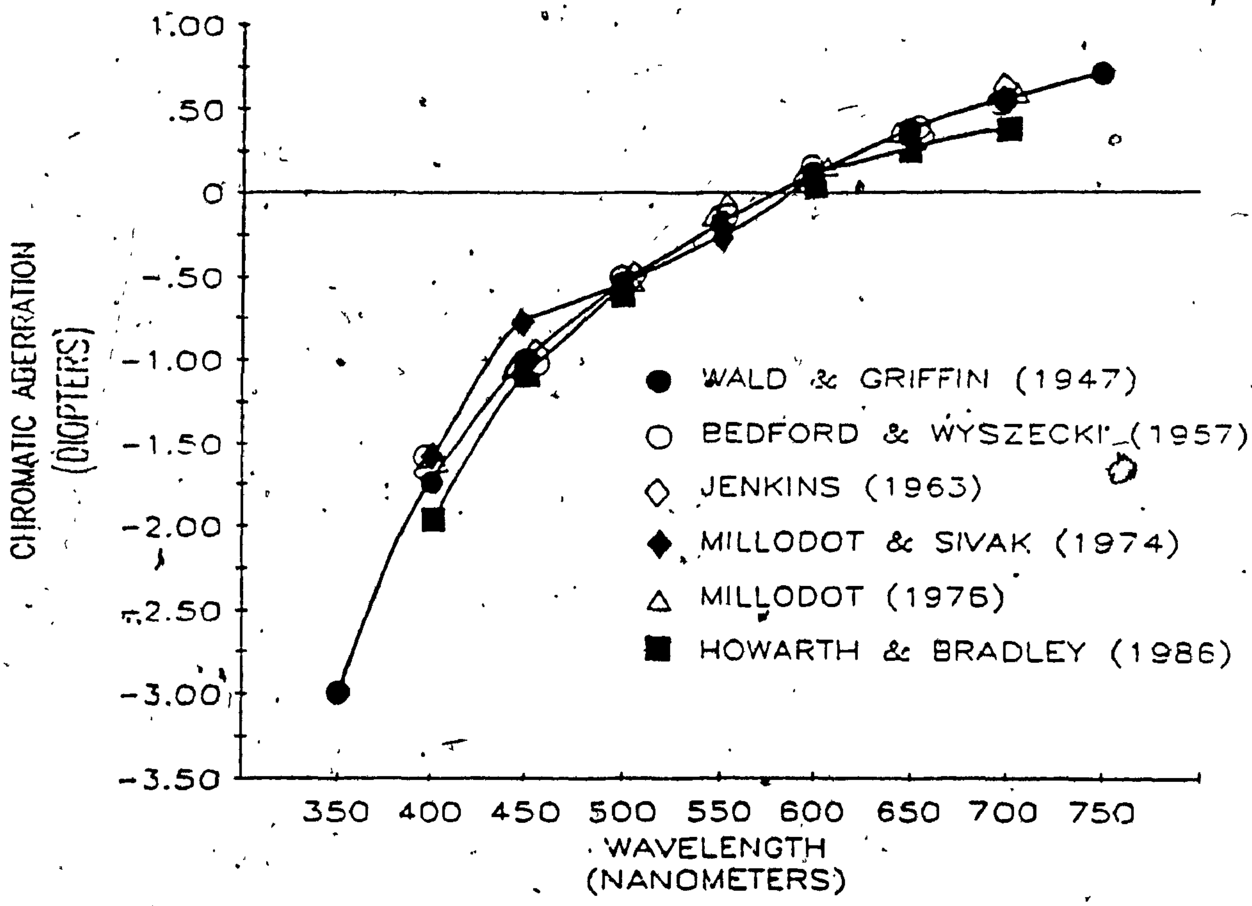

Figure 2. Observed data from experimental studies.

580 nm and as can be seen the data from the different investigations are in close agreement.

For comparison, Howarth and Bradley report chromatic aberration to be approximately -2.0 D at 400 nm whereas the theoretical values were about -1.50 D. The calculations by Mandelman and Sivak (1983) were adjusted so that all were normalized to the reference wavelength 580 nm.

<u>Aging effects</u>.

As pointed out above, the crystalline lens exhibits more dispersion in the blue and violet end of the spectrum than predicted by theoretical formulae, which produces greater chromatic aberration. The crystalline lens may also further exhibit a change in its optical characteristics due to age. This change could, therefore, alter the magnitude of chromatic aberration and explain individual differences found in previous experiments.

In order to investigate the possible change in chromatic aberration due to age, Millodot and Newton (1976) photographed Purkinje-Sanson images in red and blue light of the eyes of 10 young subjects (19-38 years of age) and old subjects (52-63 years of age) and made densitometeric examinations of the negatives. The data suggested the following: (1) the refractive index of the lens increases for red and decreases for blue light in aging eyes, (2) the refractive index of vitreous increases for blue and decreases for red light for aging eyes, and (3) the refractive index of the cornea does not change with age. The changes in the refractive indices for the lens and the vitreous were speculated to account for the decline of chromatic aberration in the aging eye.

To test the above assumption in a more conventional manner, Millodot (1976) measured the chromatic aberration of 58 observers aged between 10 to 80 years of age using a stigmascope. The observers' data were grouped into different age categories. The acuity target was a transparency made up of high contrast black text. Six wavelengths were tested and 2 measures were made at each wavelength. Chromatic aberration decreased as age increased even in aphakes. Thus, even when the crystalline lens was removed there was a decrement in chromatic aberration with age. It was concluded that the change in the refractive index of the vitreous was responsible for this reduction in chromatic aberration.

There has been opposition to the view that the eye's refractive media alters with age. Ware (1982) conducted an experiment using a modified stigmascope as initially utilized by Wald and Griffin (1947). Measurements were made at 10 different wavelengths with 6 settings at each wavelength. Twelve subjects participated in the experiment and an artificial pupil of 3 mm diameter was used. The observers were divided into two groups. One group was aged between 13 and 31 years of age, and the other group was aged 55-65 years of age. Two subjects from the older group had participated in a chromatic aberration study previously some thirty years prior (Bedford & Wyszecki, 1956).

The results of the experiment showed that there was no significant difference in the magnitude of chromatic aberration due to age. The results of the two subjects who had data from 1956 were also compared with the data from this experiment. There was no significant difference in their respective measurements of chromatic aberration. Ware concluded that perhaps Millodot's procedure and apparatus was not sufficiently controlled, such as the inconsistent fixation on the acuity target. The chromatic aberration measured, nonetheless, was similar to that of previous studies.

In response to Ware (1982), Mordi and Adrian (1985) conducted an experiment using an objective Rodenstock refractometer. Eight subjects of different ages ranging from 21 to 50 years participated in the experiment. The eyes being tested were cyclopleged and an artificial pupil of 5 mm was used. Nine wavelengths were used and 5 settings were made by each subject at each wavelength. In contrast to the results obtained by Ware, there was a statistically significant difference between the 21-30 year old group and the 31-50 year old group. One subject in the group participated in a chromatic aberration experiment 20 years previously using the same type of refractometer. The chromatic aberration for this subject was significantly different in the blue region of the spectrum with the magnitude of chromatic aberration less for the present data. Mordi and Adrian speculate that the yellowing of the cornea may play a major part in reducing chromatic aberration. My major criticism is that the yellowing of the cornea may reduce the consequences of longitudinal chromatic aberration, but does not reduce the aberration itself.

To summarize, three possible refractive indices could change due to age: the cornea, the lens, and the vitreous. From the evidence presented it is still difficult to conclude which refractive medium is responsible for age-related changes in chromatic aberration.

<u>Pseudophakia and aphakia</u>

The studies discussed thus far measured chromatic aberration in the intact or phakic eye. Very few studies have been done on aphakic eyes. Aphakia refers to the state of the eye after the crystalline lens is removed because of cataract or trauma. Also, no previous studies have used pseudophakic eyes, whereas pseudophakia refers to the implantation of a correcting intraocular lens (IOL) after the removal of the crystalline lens.

With the removal of the crystalline lens the eye loses approximately 16 Diopters (D) of focussing power. This, in turn, produces a blurred retinal image causing severe visual acuity loss. This loss in acuity can be corrected with contact lenses or extremely thick and heavy eye-glasses which cause many unwanted optical consequences such as a reduced visual field and severe curvature of the image plane (Benton & Welsh, 1966; Hvidberg & Jensen, 1977; Martin, Kracher, Stark & Maumenee, 1983). The wide-spread implantation of intraocular lenses (IOL) seems to indicate that pseudophakia is by far the better surgical choice over aphakia (Stark, et al., 1983).

Intraocular lenses

There are several reasons for the popularity of IOLs. The most important is the fact that IOLs allow patients to use their vision more efficiently with little or no correction, which avoids the necessity of low vision rehabilitation (Galin & Baras, 1978). Patient satisfaction is also of prime importance, and studies have indicated that pseudophakics are very content with their post-operative vision (Osher, 1976; Hiles, 1980).

There are a wide variety of IOL manufacturers and models to select from (Colenbrander, Woods, & Stampler, 1985). The most popular types of IOLs are shown in Figure 3. About two-thirds of all implants are posterior chamber IOLs and the remaining one-third are anterior

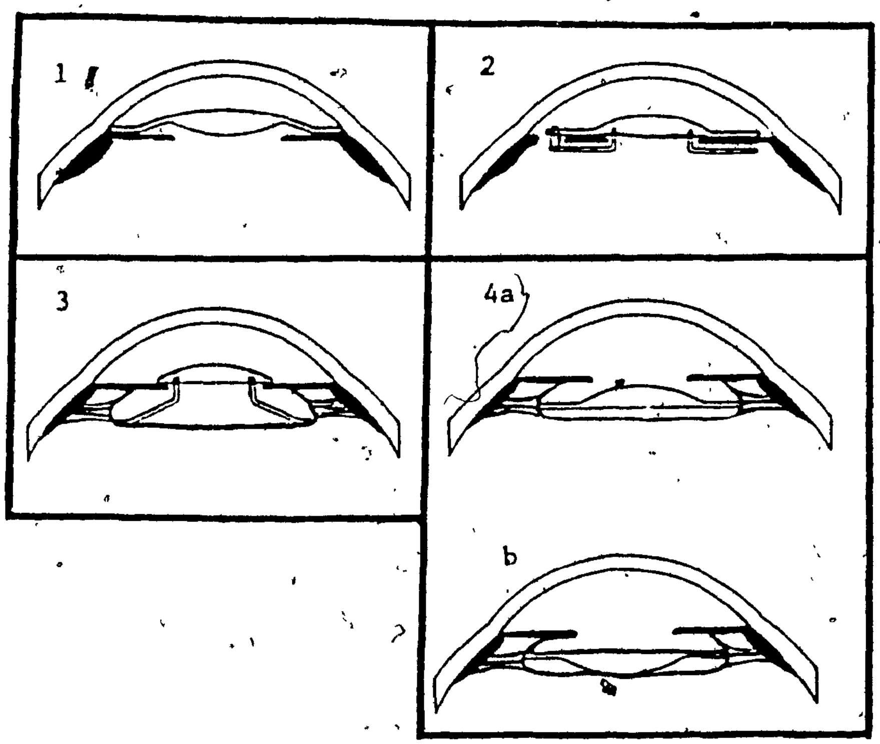

Figure 3. The different types of intraocular lenses in use today and their modes of implantation. (1, 2, 3) anterior chamber lenses (4a) posterior chamber lens with plano surface posterior (4b) posterior chamber lens with plano surface anterior.

chamber IOLs (Apple et al., 1984). Since more posterior chamber IOLs are implanted the most common form of surgery is extracapsular cataract extraction (ECCE). In ECCE a large portion of the anterior lens capsule is removed along with the lens nucleus. The maintenance of a separation between the anterior chamber and the vitreous is achieved by the posterior lens capsule. The majority of anterior implants are done after intracapsular cataract extraction (ICCE). In this form of surgery the lens capsule and the lens are completely removed. There are several advantages of ECCE such as the smaller incision at the corneoscleral limbus and the posterior lens capsule preventing any bulging of the vitreous (Jaffe et al., 1978).

Environmental and optical consequences of pseudophakia

There are several negative environmental and optical consequences associated with IOLs which differentiate them from the crystalline lens, the most notable being the lack of UV filtering. The crystalline lens is a natural filter of UV light. The visible spectrum extends from approximately 380 to 700 nm. Daylight is composed of a full spectrum which extends into the UV. The UV region of the spectrum is usually classified into two regions: UV-A and UV-B. The UV-B region (200-300 nm) is screened out by the cornea, and the crystalline lens absorbs the UV-A area (300-380 nm) of the spectrum. Some acrylic IOLs allow UV light to enter the eye and fall on the retina. As much as 70 to 90% of light between 300 and 700 nm is transmitted to the retina (Keates, Genstler, & Tarabichi, 1982; Thoms, Fishman, & Vander Meulen, 1983). More recently Mainster (1986) measuring the spectral transmittance of 16 different types of IOLs found that the lenses tested varied considerably in their transmittance. This lack of UV-filtering allows the pseudophakic individual to be highly sensitive to light between 300 - 380 nm with peak sensitivity at about 350 nm (Williams, White, & Stark, 1983). As shown in Figure 4, the scotopic sensitivity across the other part of the visible spectrum remained the same for aphakics, pseudophakics, and phakics.

Many recently developed IOLs have UV-absorbing properties. Even though these lenses are gaining in popularity, studies are still being conducted as to their safety (Clayman, 1984; Gupta, 1984a; Gupta, 1984b). The major considerations are whether or not the absorption properties remain constant with age and whether or not any toxicity occurs. Studies so far have shown that the lenses are safe and well tolerated in primate eyes (Peyman, Sloan, & Lim, 1982; Peyman, Zak, & Sloan, 1983). No long-term in vivo studies have yet been documented, as the practice of implanting UV absorbing IOLs is relatively recent.

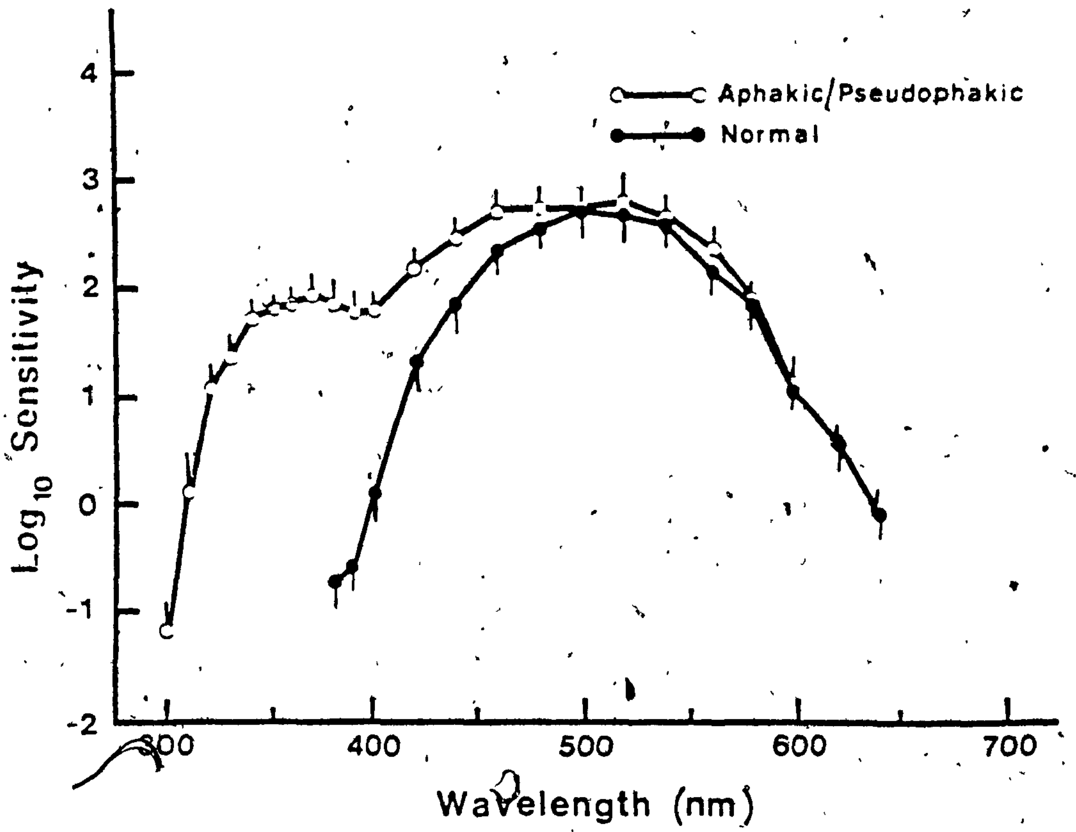

Figure 4. Scotopic sensitivity comparison between phakic and aphakic/pseudophakic data (Williams, White, & Stark, 1983).

The increased sensitivity to UV light gives rise to unique problems that aphakics and pseudophakics must endure such as (1) erythropsia, (2) retinal damage, and (3) reduced visual acuity.

Aphakic and pseudophakic erythropsia is the experiencing of "reddish" vision after prolonged exposure to bright outdoor light. It has been shown that erythropsia is primarily a glare phenomenon due to high luminance (Kamel & Parker, 1973; Saraux, Manent & Laroche, 1984). Mainster (1986) states, on the other hand, that it is still unclear whether severe erythropsia causes permanent damage to the retina that may not be initially observed by ophthalmoscopy. Mainster (1986) also states that erythropsia may also be the clinical analog of blue-sensitive cone photochemical damage observed in primates at very low levels of light (Sperling, Johnson, & Harverth, 1980).

A very serious consequence of UV exposure in aphakia and pseudophakia is retinal damage. Several studies have shown that prolonged undue exposure to hazardous outdoor UV light can cause irreversible photic maculopathy (Zigman & Vaughn, 1974; Mainster, 1978; Mainster, Ham, & Delori, 1983). Several investigators have implicated high intensity operating instrument light in the development of cystoid macular edema after cataract surgery (Berler & Peyser, 1983; Colvard, 1984). Jampol, Kraff, Sanders, Alexander, and Lieberman (1985), on the other hand, reported that the incidence of macular edema in pseudophakia is not significantly different between patients who had surgery performed with UV light filtered from the operating instruments and patients who had been operated on with no filtration of UV light. More recently, Robertson and Feldman (1986) produced lesions on the retina after a 60-minute exposure to light from an operating microscope. After a second exposure with the UV light filtered, similar lesions were also produced, therefore, light intensity and not simply UV light is implicated in retinal damage.

The third consequence of the use of IOLs is the artifact of reduced visual acuity due to UV light. Rog, White and Williams (1986) showed that when pseudophakic observers viewed a target illuminated by visible and UV light their acuity dropped by about one line on a conventional eye chart. The same was found for vernier acuity targets. The prediction that arose from this study, and which was corroborated by other investigators, stated that a UV blur circle is cast upon the retina preventing stimulus clarity (White & Wolbarsht, 1975; Zigman, 1982; Williams, White, & Stark, 1983).

<u>Aphakic chromatic aberration</u>

Aphakic chromatic aberration has not attracted as many investigations as the phakic eye. In fact, very few studies have attempted this task. Ivanoff (1947, 1953) measured chromatic aberration in two aphakic eyes. Two wavelengths were tested: 483 and 712 nm. The aberration was found to be -.41 and .18 D respectively.

Millodot (1976) measured the chromatic aberration, using a stigmascope, of 10 aphakic observers aged 19 to 79 years. The results were reported as the magnitude of chromatic aberration between 458 and 656 nm. Since the main objective of this experiment was to assess how chromatic aberration decreased with age, individual curves across the wavelength tested were not reported. Nevertheless, the average difference between the reference wavelengths was calculated to be 0.46 D with a standard deviation of 0.27 which. These results were very similar to those found by Ivanoff (1947) in his studies with aphakics.

The estimated chromatic aberration of the aphakic eye, though, can be derived theoretically by calculating the chromatic aberration of a schematic aphakic eye (Howarth, 1985; Rög, White, & Simonet, 1987). The parameters and equations employed by Rog et al. (1987) are shown in Appendix A. Shown in Figure 5 are the results that Ivanoff (1947) obtained for aphakic eyes and data from theoretical aphakic eyes. As shown, the aphakic data fall relatively close to the calculated theoretical data.

If the assumption is made that there are relatively

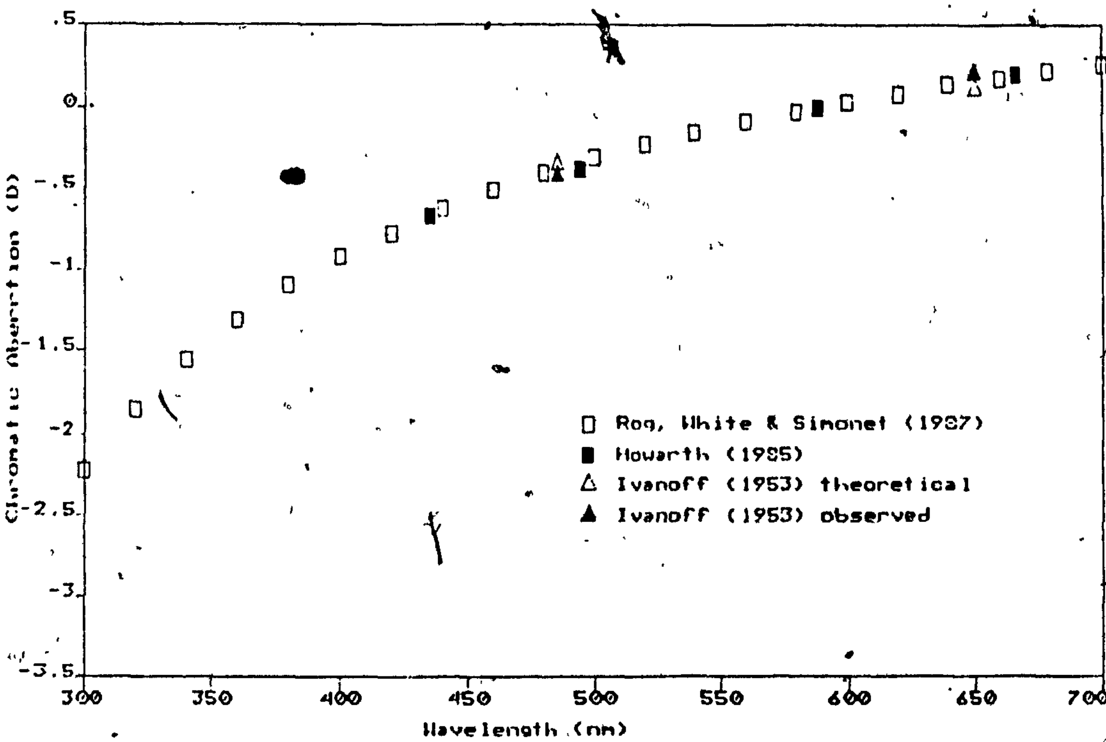

Figure 5. A comparison of theoretical and empirical aphakic data.

reliable data in phakic measurements and that the scarce aphakic data match theoretical predictions, where could the data of pseudophakic observers fall? If the PMMA lens is clear and allows more blue and UV light in, it should, therefore, act like an infant's lens which is void of any discoloring. The chromatic aberration should, logically, be less than phakic data if the argument is taken that chromatic aberration decreases due to age. But if it is assumed that chromatic aberration does not change with age then the measured pseudophakic aberration should be close to that of the phakic eye. Another consideration is the role of inter-observer differences which have consistently been observed in previous studies. Since all observers will be fitted with clear IOLs the differences between subjects should be attributed to variables other than the aging process of the lens, such as anterior chamber depth, IOL thickness and IOL type.

In summary, previous empirical research has consistently shown that there is agreement in the magnitude of chromatic aberration in the phakic eye. Theoretical studies show less agreement regarding the magnitude of chromatic aberration which is primarily attributed to the greater dispersion of the crystalline lens in the blue region of the spectrum. Theoretical aphakic calculations are in close agreement with the scant empirical measurements. If it is assumed that the IOL is as dispersive as the crystalline lens then pseudophakic chromatic aberration must be less than phakic chromatic aberration due to the fact that the IOL is not affected by aging. Therefore, the theoretical calculations should be similar to the observed data and any possible individual differences may be explained by different variables such as anterior chamber depth, axial length, and IOL type. Downing and Sayano (1983) speculated that by simply implanting a plano-convex lens with the plano surface forward may, in fact, decrease spherical and chromatic aberration.

The purpose of the present experiment is to quantify the amount of chromatic aberration in pseudophakic eyes implanted with clear PMMA IOLs, with measurements extending into the UV, and to explain any possible individual differences in relation to IOL type, anterior chamber depth, and axial length.

Method

Observers.

Four pseudophakic observers aged between 62 and 70 participated in this study. Individual characteristics of all observers can be found in Appendix B. They were recruited from a private ophthalmological practice. Willingness, good health, and a visual acuity of 20/40 or better, uncorrected, in the pseudophakic eyes were the requirements for participation with no ocular pathology in the pseudophakic eyes. Only one eye with the better acuity was tested per observer. The IOL was either a posterior chamber or anterior chamber type manufactured in polymethyl methacrylate, with no provisions for filtering ultraviolet light.

Participants were either paid $5.00 an hour for participating, or their transportation costs were reimbursed. Each experimental session lasted about 2 hours with appropriate rest periods. One observer required two visits but the other three required only one. All observers completed a consent form describing the experiment (Appendix C) and were told that they could withdraw from the experiment at any time and informed of the confidentiality of the results.

Apparatus.

Badal Optometer. The light source was a 75-watt xenon arc lamp housed in a Stabilarc 100 Lamphouse

(Ealing, Model 27-1411) and powered by a 250-watt Universal Arc Lamp Supply (Ealing Model 27-1015). An ultraviolet absorbing filter (Eastman Kodak, CP2B) was placed in front of the source for wavelengths above 380 nm to minimize exposure to UV light. The light source energy is shown in Figure 6. As shown, the light source resembles daylight and the UV filter blocks out light below approximately 380 nm. Appendix D shows the absolute corneal irradiance at the wavelengths tested at a bandwidth of 5 nm. A double-grating monochromator (Kratos, Model 200) was used to select the wavelength bands. An Apple II+ computer and a stepping motor (Ansi Corp., Model 82700) controlled the monochromator.

The optical system was a Badal-type optometer with a 10 D quartz lens (Badal, 1876). Other automated optometers were not suitable because the lenses must all be quartz to allow UV transmission. The advantages of the Badal system are that (1) image size does not change with distance and (2) the dioptric vergence varies with the axial position of the target. Therefore, the 10 D lens allows for a 1:1 ratio of diopters to distance the target was moved, i.e., 1 cm per diopter.

The experimental set-up is shown in Figure 7. The observer is positioned at the headrest and the eyepiece is adjusted to the position of the eye being tested. The observer's right hand is used to move the target with the

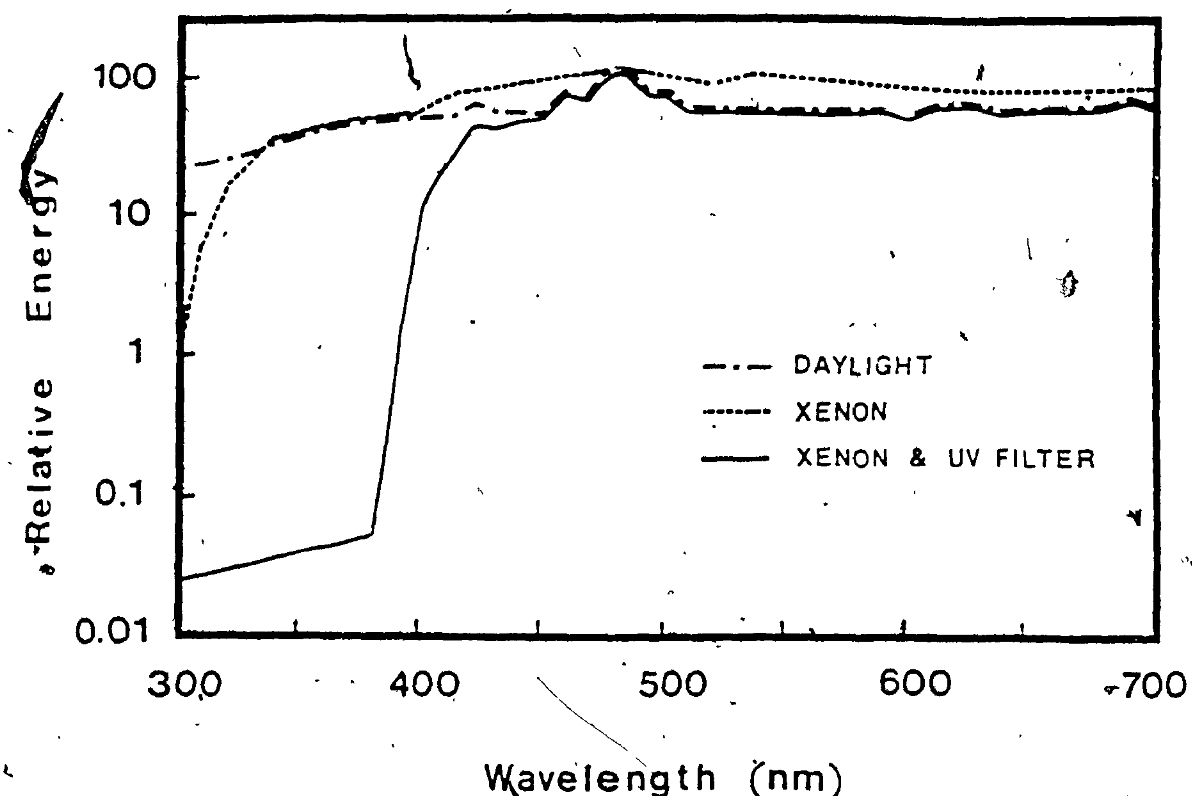

Figure 6. The energy distribution of the Xenon arc lamp used in the experiment. A comparison between the light source and outdoor light is also shown. The solid line represents the energy distribution with the Kodak UV-filter in place (Rög, White, & Williams, 1986).

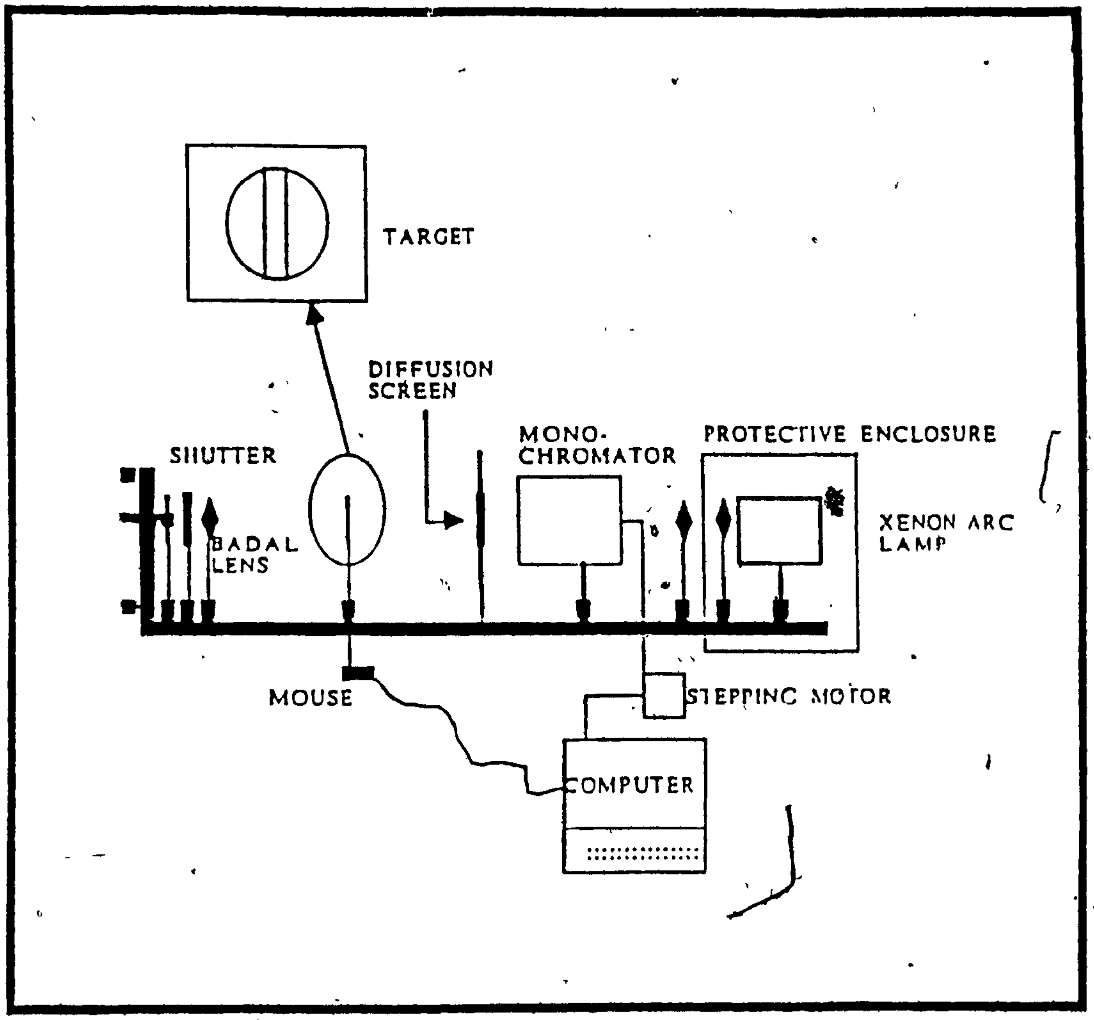

Figure 7. Schematic diagram of the automated Badal optometer used in this experiment is shown. The target shown consisted of 2 fine parallel hairs.

attached mouse and the left hand is used to open the shutter mechanism remotely.

A custom-made chin rest with velcro straps secured the position of the head comfortably. A bite-bar was not considered because of the likelihood that the participants might wear dentures. The eyepiece was 40 mm in focal length and 30 mm in diameter with a 3 mm artificial pupil. No cycloplegic agent was used. The shutter (Uniblitz, Model 225C) was positioned in front of the eyepiece and headrest. The Badal lens was mounted on the shutter enclosure. The shutter was powered by a drive unit (Uniblitz, Model 100-2B) which, in turn, was powered by a 12 VDC power supply (Micronta, Model 22-8224). The shutter opening was operated by the observer by a remote switch conveniently located by the headrest.

The target was similar to the one used by Howarth & Bradley (1986). Two fine vertical hairs 5 mm apart were positioned over an aperture of 14 mm diameter on a black piece of cardboard. The target was attached to a optical bench mounting bracket which slid freely on the optical bench. An Apple II mouse was attached to the mounting bracket so that the target's axial position could be transmitted to the microcomputer which printed the position of the target on an Apple Silentype printer. The print-out showed the wavelength and the position of the mouse at that wavelength. One centimetre (one diopter) equalled 37.8 mouse steps.

The light from the arc lamp was focussed through a series of two 8 D quartz lenses and an iris diaphragm through the monochromator. Light exiting from the monochromator was then projected onto a diffusion screen positioned on a black baffle. The baffle was 30 cm square with a centered aperture of 50 mm diameter. A piece of UV-transmitting plexiglass (Rohm and Haas), frosted by gentle abrasion, was placed on this opening.

A wooden ventilated enclosure was used to prevent any stray light from entering the laboratory as well as protecting the experimenter and observers from any possible malfunctions.

<u>Ultrasound</u>. Post-operative ultrasound measurements of axial length (A-scans) were made on two subjects at the Royal Victoria Hospital. The other two observers were not available for the post-operative A-scans. The data are reported in Appendix E.

<u>Keratometry</u>. Post-operative keratometry measurements (K-readings) were done by the ophthalmologist as a routine follow-up procedure (Appendix E).

<u>Theoretical pseudophakic calculations</u>. The results of the A-scans and k-readings were used in the calculation of individual pseudophakic chromatic aberratio[illegible]he thickness and the curvature of the IOLs used [illegible]obtained from IOLab Corporation. The Cilco lens was found to be

comparable to IOLab's model, therefore, IOLab's measurements were used for the CILCO lens. This information is confidential and, therefore, will not be reported. Theoretical calculations in phakia were also calculated..

Procedure.

The observers were first asked to sign the consent form that explained all the facets of the experiment. The subject's chart was examined and the pseudophakic eye with the better acuity was used in the experiment. Visual acuities are shown in Appendix B.

The observer was then seated at the chin rest. An eye patch was comfortably positioned over the eye not being used in the study. The chin rest was adjusted to fit comfortably and moved to accommodate either the left or right eye. Prior to this, the subject was given 15 minutes to adapt to the darkness. Several practice trials were then given to familiarize the observer with the task. The experiment began when the observer and the experimenter felt the task was sufficiently understood.

The experimenter then typed in the desired wavelength, the stepping motor dialed to that wavelength and the first focussing of the target was started. The observer opened the shutter with the use of the remote switch and began to focus the target by moving the mounting bracket with the target and mouse attached. One observer (AH) could not operate the shutter properly due to several aging problems, therefore, the experimenter took over the control. When the observer finished focussing the target and was satisfied that it was the clearest possible the shutter button was released by the observer or the experimenter and the computer registered the position of the mouse. The experimenter randomly moved the mouse away from the location before a next wavelength was tested. The monochromator was then dialed to another wavelength and the procedure was repeated.

The testing was done from 340 to 660 nm at intervals of 20 nm. Below 340 and above 660 nm the intensity of the arc lamp was not sufficient for the observer to make a response and it was not advisable to increase the intensity in the UV due to the pseudophakic's high sensitivity to these wavelengths.

There were a minimum of 6 and a maximum of 8 settings at each wavelength for each observer giving a minimum of 6 data points per wavelength.

When a spectral run was completed there were minor calibrations regarding the equipment. The mouse was checked and repositioned at the same spot nearest to the observer. The monochromator was constantly monitored as to whether any error in wavelength location was made.

The observers were also closely monitored to gauge their level of comfort and whether or not they were having any problems locating and focussing the target. The observers were not readily capable of withstanding long periods without rest. Every precaution was taken to make the observers as comfortable as possible during the experiment. This, in turn, produced lengthy, albeit, productive sessions.

Results

A comparison of all observers was plotted and is shown in Figure 8. The mean of all observers is also shown.

The results of the pseudophakic theoretical calculations and the experimental findings are presented for each observer in Figures 9 through 12. The normalization procedure was as follows: each deviation score (the mean for each observer minus each value for that observer) was subtracted from the mean of all observers at 580 nm, normalizing the data at that wavelength. Individual raw data can be found in Appendix F. The schematic representation of the eye, the equations used, and the parameters involved in the theoretical calculations can be found in Appendix G. The third order polynomial curve-fitting was accomplished by the use of computer software.

Figure 13 depicts the mean theoretical chromatic aberration and the mean observed chromatic aberration. As shown, the theoretical and observed values are relatively similar from 400 to 660 nm whereas below 400 nm there is an increase in chromatic aberration in the observed data.

Theoretical chromatic aberration was also calculated for phakic eyes, and the schematic representation of the eye and the parameters used in the calculations are found in Appendix H. The equation used

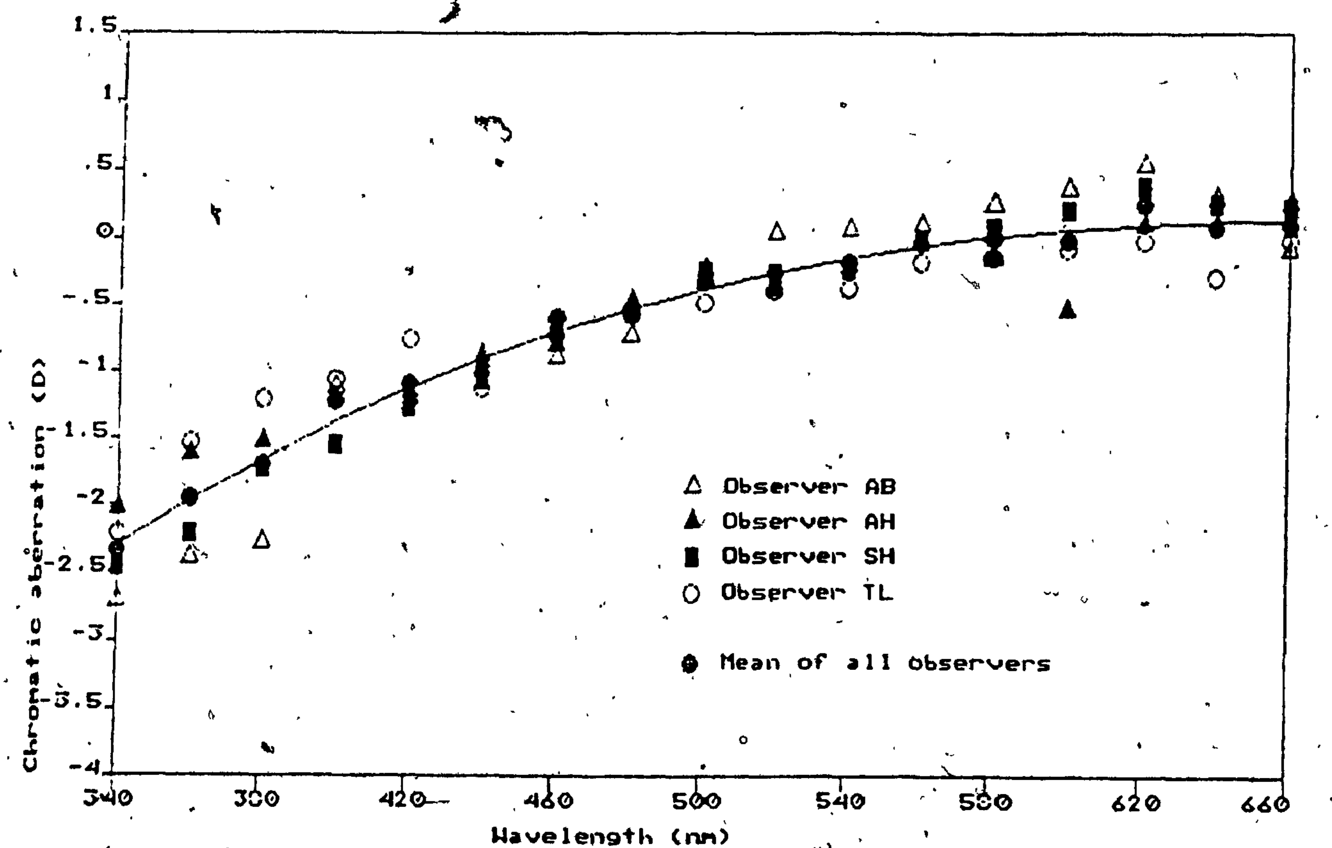

Figure 8. Comparison of data from all observers. The mean curve is the regression curve (polynomial of third order) of the average of all observers. The third order produced the best fitting curve without exaggerating the achromaticism found in the longer wavelengths.

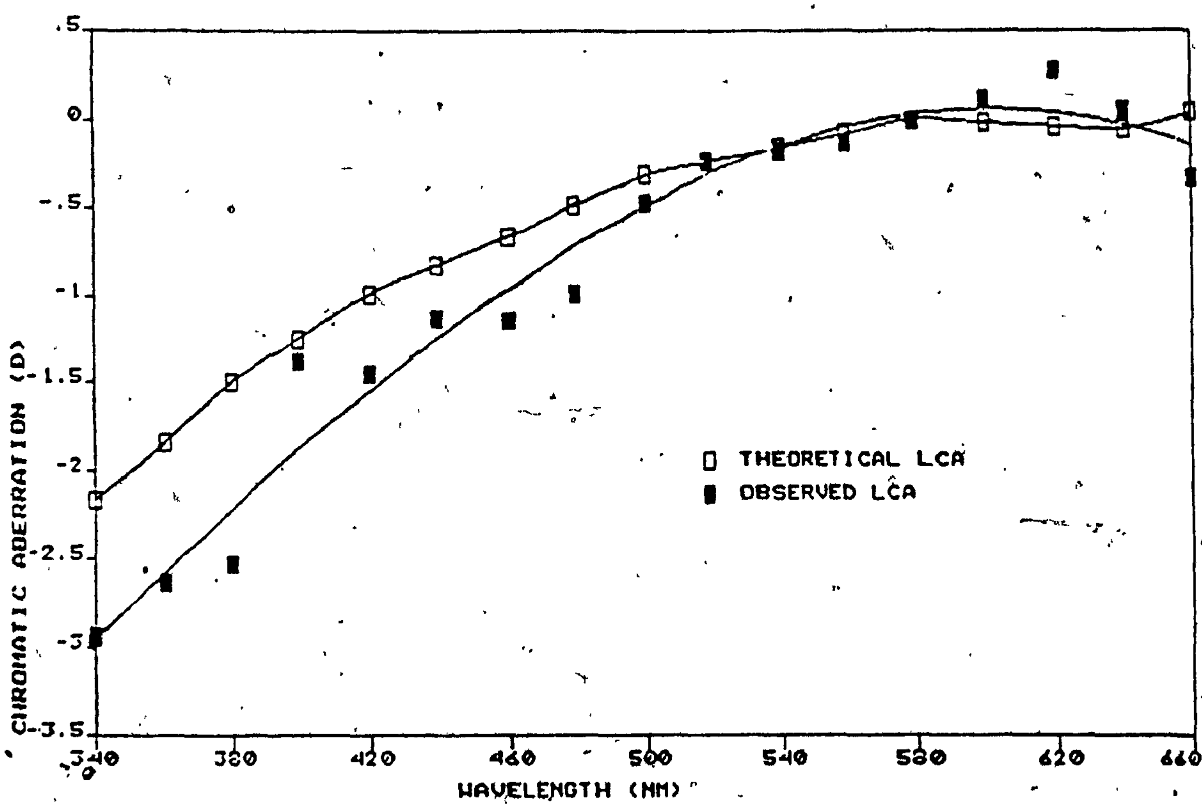

Figure 9. The theoretical and observed comparison for observer AB.

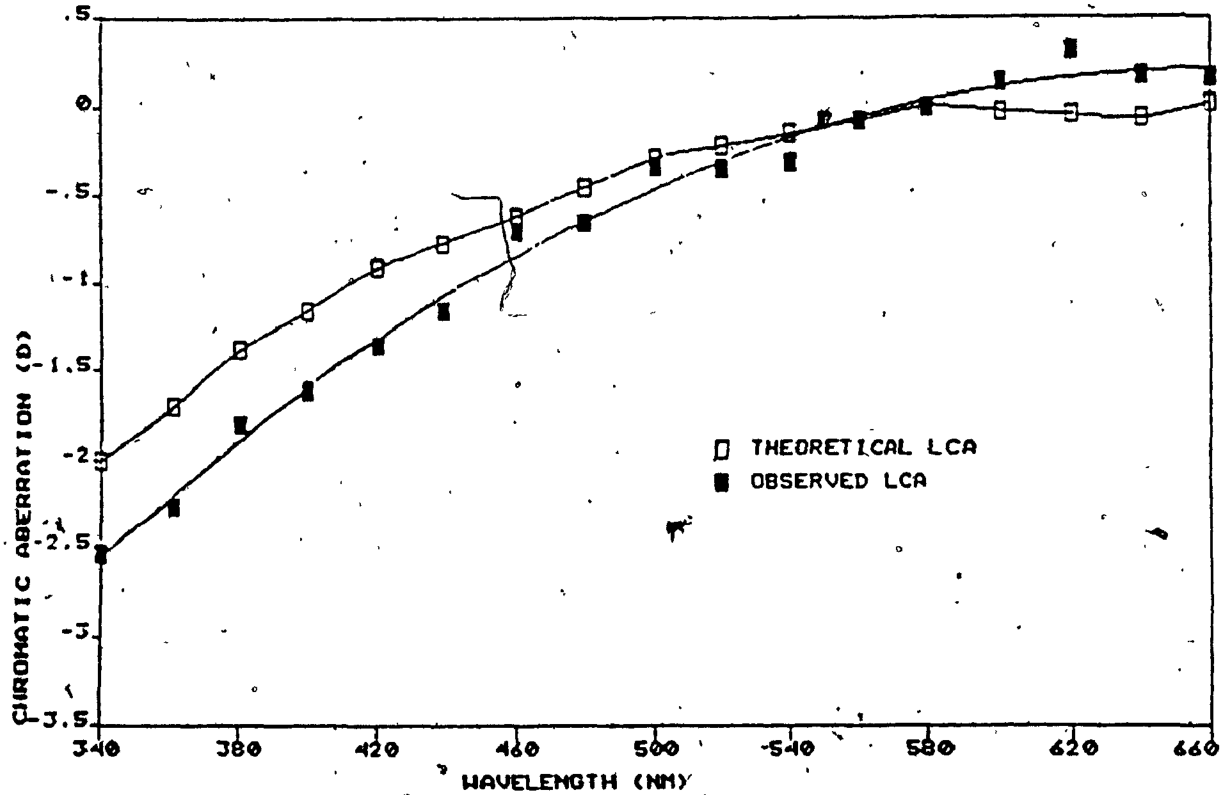

Figure 10. The theoretical and observed comparison for observer SH.

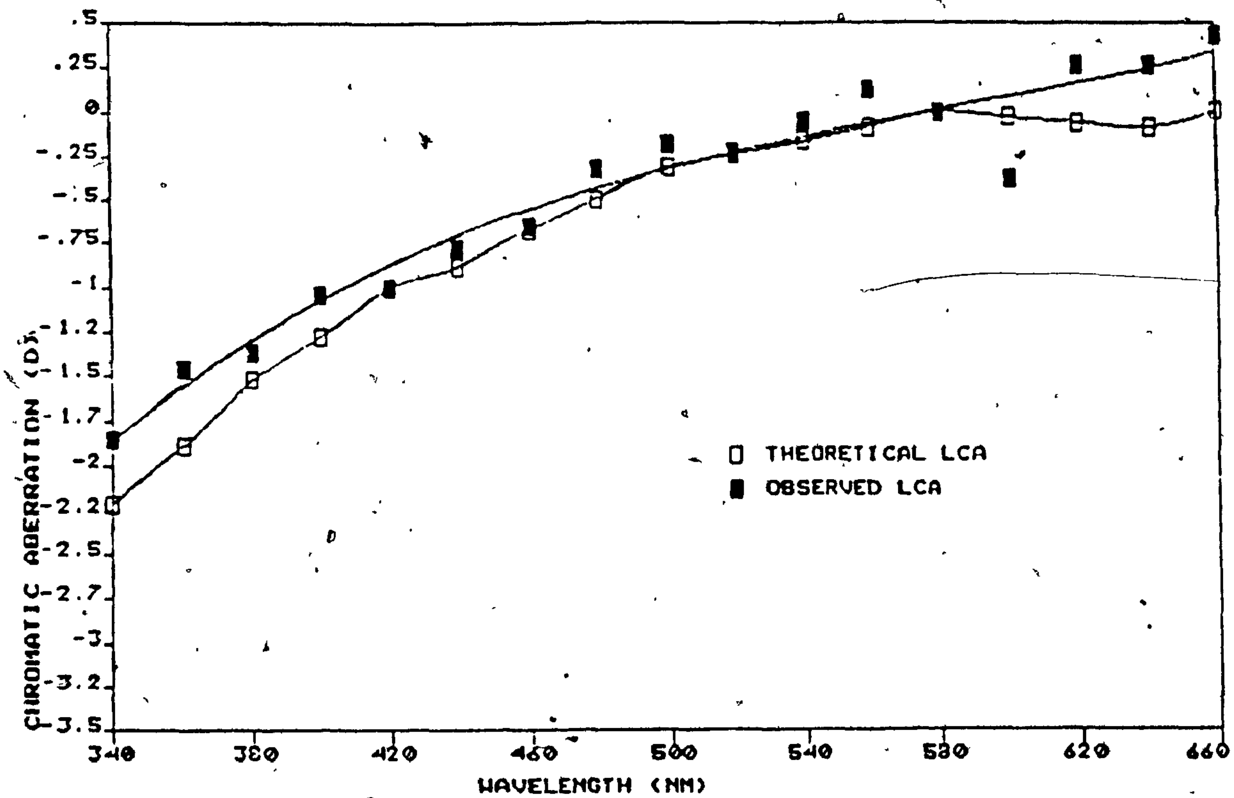

Figure 11. The theoretical and observed comparison for observer AH.

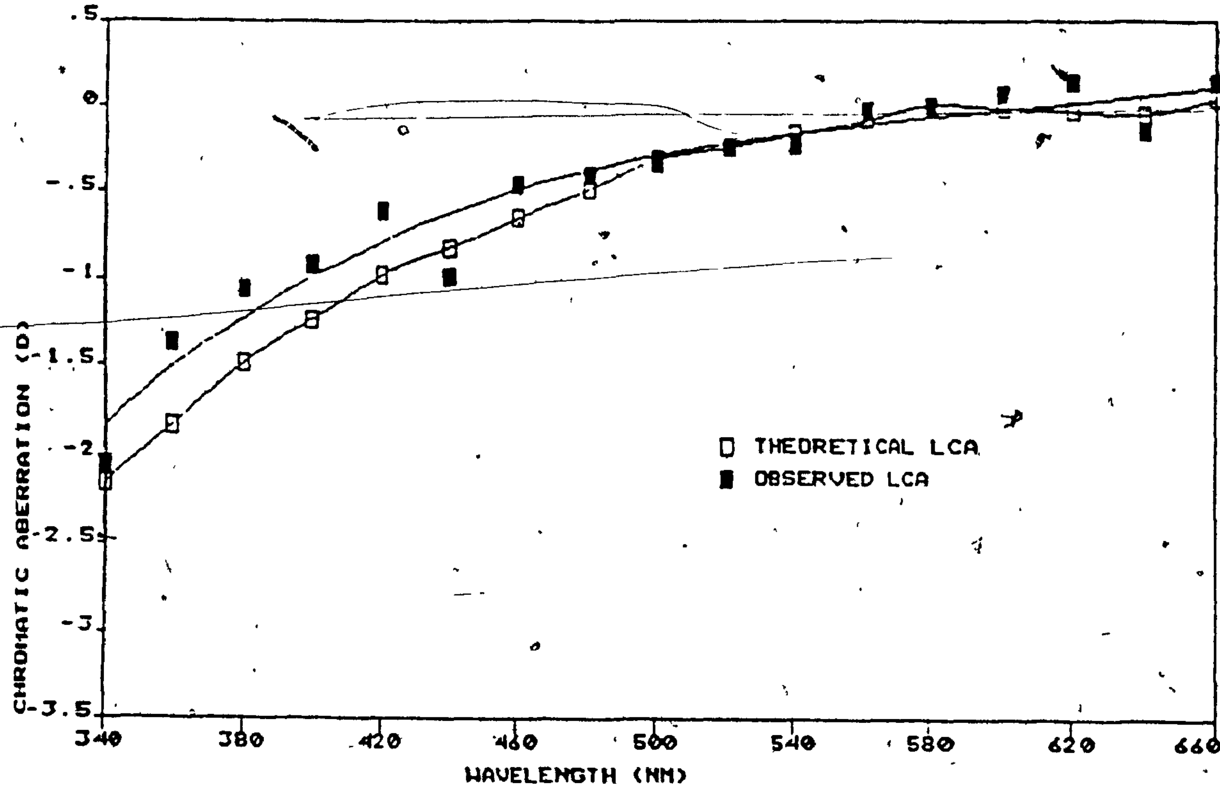

Figure 12. The theoretical and observed comparison for observer TL.

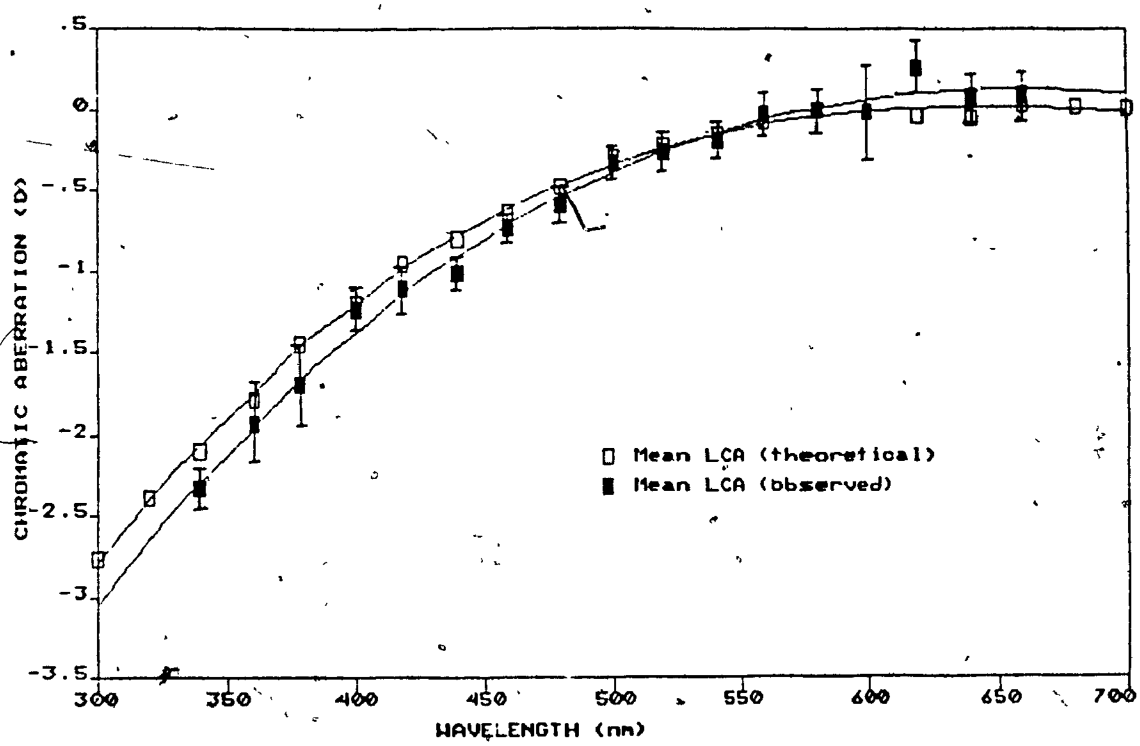

Figure 13. A comparison between mean theoretical and observed data.

is similar to that used in the calculation of pseudophakic chromatic aberration. It was found that the chromatic aberration was similar to previous findings except for the data reported by Mandleman and Sivak (1983) where the chromatic aberration was greater.

Figure 14 is a comparison of the different eye-types: phakic, aphakic, and pseudophakic. The mean theoretical pseudophakic, theoretical phakic, theoretical aphakic, and observed pseudophakic data represent the efforts of this study, whereas, the observed phakic data is taken from Howarth and Bradley (1986). The phakic curve exhibits the most chromatic aberration at 400 nm. Logically, the least is shown to be the aphakic curve. The observed pseudophakic curve fall relatively close to the theoretical phakic curve. The theoretical pseudophakic data fall above the theoretical below 400 nm and then remain relatively the same as the observed pseudophakic data. At the other end of the spectrum, the observed and theoretical pseudophakic data falls relatively close to zero diopters, whereas, the remaining curves are in close agreement at approximately 0.5 D.

To test whether individual observed data were different from the theoretical values a multiple regression analysis was calculated. It was found that individual data were not significantly different from theoretical values. An accompanying analysis of variance

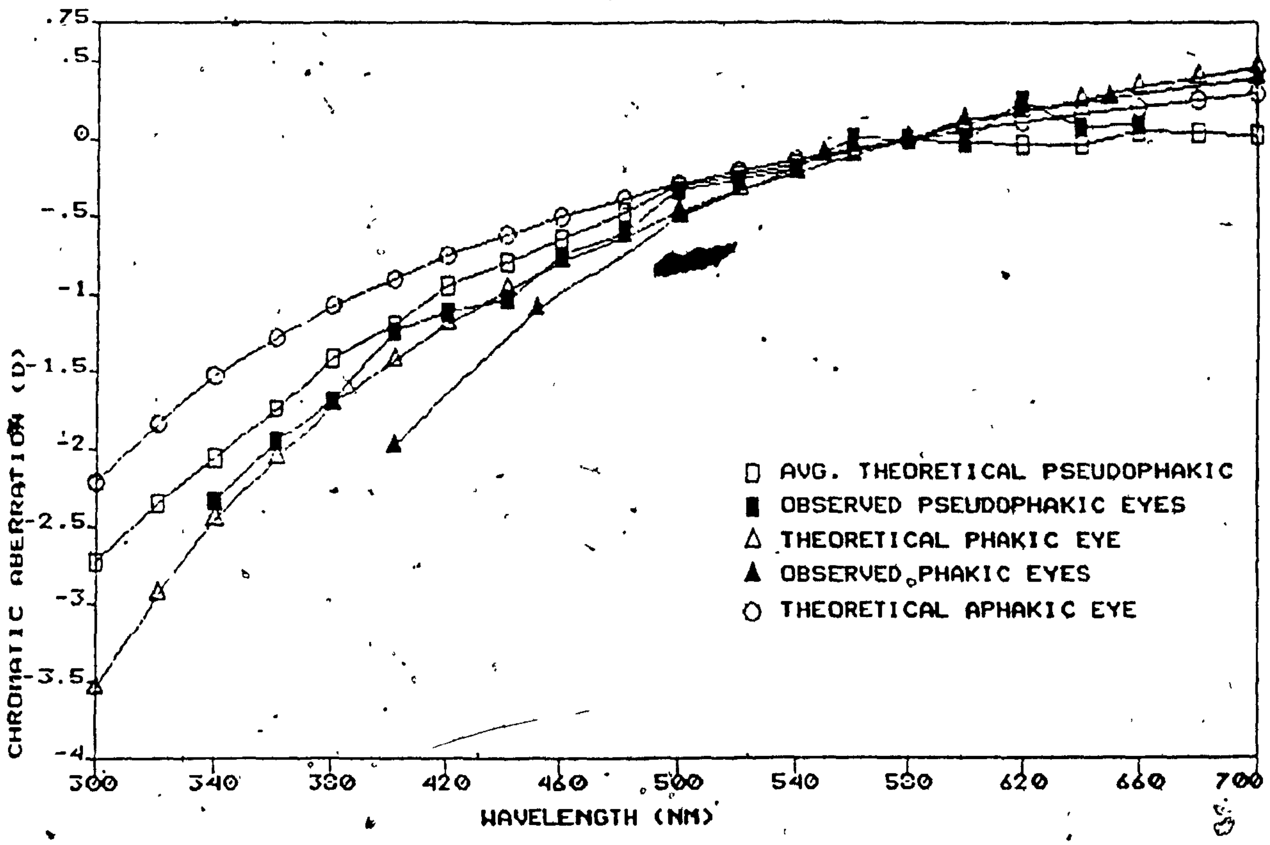

Figure 14. A comparison of chromatic aberration, both theoretical and observed, from different types of eyes. Filled triangles represent data from Howarth & Bradley (1986)

showed a significant model value, ($F = 8.09$, $p < .002$). The multiple regression and the accompanying analysis of variance reports are shown in Appendix I. The model, therefore, significantly fits the data.

Although it was shown that individual observers' data were good predictors of the theoretical values, more chromatic aberration was observed in observers with anterior placements as compared to theoretical values. A split-plot analysis of variance was, therefore, calculated. Appendix J shows the summary table for the analysis of variance and Figure 15 shows the anterior and posterior chamber data. No significance was observed between anterior and posterior chamber placements. Significance was observed in the wavelength (repeated measures) condition ($F = 77.72$, $p < .01$) and the interaction ($F = 4.40$, $p < .01$). The interaction shows that chromatic aberration is dependent on the anterior and posterior placement of the IOL. More short-wave chromatic aberration was observed in observers who were implanted with anterior chamber IOLs.

To summarize, pseudophakic chromatic aberration was shown to be less than empirical phakic chromatic aberration but similar to theoretical phakic values. The observed pseudophakic data were shown to be good predictors of the theoretical pseudophakic values.

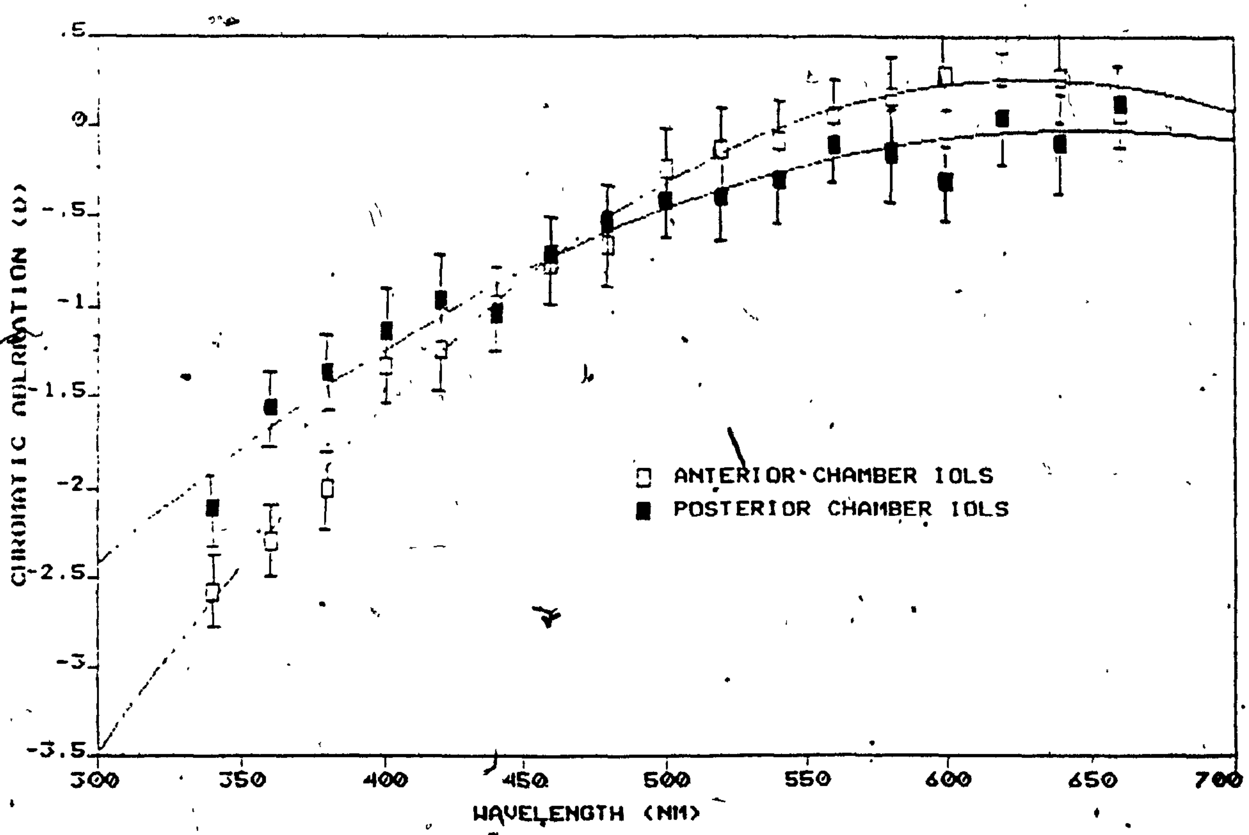

Figure 15. **Comparison between observers fitted with anterior and posterior chamber lenses. The solid lines represent the best-fitting polynomial regression.**

Discussion

As predicted, the pseudophakic chromatic aberration that was observed in the present study was less than that previously observed in phakic eyes (Howarth & Bradley, 1986).

Since observed values were good predictors of theoretical values no significant differences between observers can be concluded, which differs from previous findings that show individual differences. Howarth and Bradley (1986), in their experiment, attempted to implicate a structure or mechanism to account for individual differences. They found no significant correlations between the magnitude of chromatic aberration and either corneal power or axial length. In the present study, the differences between anterior chamber and posterior chamber placement of the IOL suggest that anterior chamber depth is a possible source of variability among observers.

To review this phenomenon, observer AB and SH had anterior chamber IOLs implanted. Analysis of their results shows a consistent trend: the observed chromatic aberration was greater than the calculated chromatic aberration. The only obvious difference between anterior and posterior chamber lenses is their physical placement in the eye. Therefore, the anterior chamber depth is less in the anterior chamber implants than in the posterior chamber implants. Does this difference in placement account for a change in chromatic aberration? Could the placement of the lens produce bulging of the vitreous outward, thereby creating an additional refractive surface which would increase chromatic aberration? The bulging of the vitreous could not produce a refractive surface of any significance. To elaborate, the front surface of the vitreous would be the posterior surface of the IOL, which is flat. Observers AH and TL had posterior chamber IOLs implanted. These two subjects showed a consistent pattern of less chromatic aberration than theoretical calculations. Therefore, the placement of the posterior chamber lens would not allow for bulging of the vitreous, producing no apparent increase in chromatic aberration.

There has been a consistent difference between theoretical and experimental data in phakia. This difference is most commonly in the blue and violet end of the spectrum. The general prediction is that the crystalline lens exhibits more dispersion than IOLs. The mean theoretical and the mean observed chromatic aberration as developed in this experiment show an interesting similar trend in the area below 400 nm. As shown in Figure 13, the observed data below 400 nm are greater than the theoretical data. The regression curves, though, meet at about 550 nm. An increase in dispersion of the crystalline lens is usually attributed to the normal aging of the lens. Does the IOL, which is manufactured from PMMA, possess the same optical qualities as does the crystalline lens? The IOL is a clear plastic, presumably not affected by the aging process especially in regards to yellowing. If it were, then logically a pseudophakic could develop IOL "cataracts". This is probably not the case. Therefore, some other mechanism must be responsible for the deviation of observed chromatic aberration from theoretical calculations in pseudophakia.

Phakic calculations employ Cornu's formula for the refractive indexes of the aqueous, vitreous, cornea, and lens without regard to any changes in the refractive index due to aging. The pseudophakic calculations use the same formula, but the refractive indices for PMMA were supplied by IOLab Corporation. The curves are similar, whereas, on visual inspection the chromatic aberration for the theoretical pseudophakic data is less than the observed pseudophakic data. Another point to consider regarding this discrepancy is that the constants for Cornu's formula were selected to fit dispersion in the visible and not the UV part of the spectrum.

There is one major difference between pseudophakic chromatic aberration, both observed and theoretical, and phakic and aphakic chromatic aberration, both observed and theoretical. This occurs in the red end of the spectrum.

The pseudophakic data falls about on the zero diopter level, whereas, the other data fall above that. The reason for this "achromaticism" is not quite clear. It could represent a property of the PMMA that is used in the manufacture of IOLs since both the experimental and calculated data exhibit the same pattern.

The debate as to whether or not chromatic aberration decreases with age is unresolved. Some studies have shown that chromatic aberration decreased with age (Millodot, 1976; Adrian & Mordi, 1985). Millodot (1976) tested aphakics of different ages and found that as age increased chromatic aberration decreased until an observer reached an age where there would not be any more chromatic aberration. The vitreous was then implicated as the reason for this decrease as opposed to the lens. Conversely, it has also been shown that chromatic aberration remains unchanged (Ware, 1982).

Considering that only elderly observers participated in the present experiment there could be a change in the dispersion of either the cornea, the vitreous, or possibly both. Testing younger observers would be recommended but locating such observers is difficult because a very young observer would probably be aphakic rather than pseudophakic. It is unlikely that chromatic aberration changes with age but more likely that the constants used in Cornu's formula must be re-evaluated in order to account for the greater dispersion of the crystalline lens in the blue and violet end of the spectrum.

One implication from the present experiment is that although there is less chromatic aberration in pseudophakia than phakia in the blue and violet end of the spectrum, the visual consequences of chromatic aberration may be greater in pseudophakia because of the increased UV transmission. Because more light is entering the pseudophakic's eye, this added component may cause the observed decrement in visual acuity (Rog, White, & Williams 1986).

In view of the present evidence, the use of UV-absorbing IOLs to reduce chromatic aberration would be advisable in addition to protecting the retina from hazardous UV levels. One benefit of this reduction in chromatic aberration would be clearer vision in the presence of UV light. Future research may address chromatic aberration in pseudophakes fitted with UV-absorbing IOLs.

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Appendix A

Aphakic Theoretical Calculations

nA : Index of aqueous
nC : Index of cornea
tC : thickness of cornea
D1 : Power of the anterior corneal surface = (nC - 1)/R1
D2 : Power of the posterior corneal surface = (nA - nC)/R2
R1 : Anterior corneal radius
R2 : Posterior corneal radius
FC : Power of the cornea = D1 + D2 - (tC/nC) x D1 x D2

H1H : position of the first principal plane from the corneal apex = tC/nC xD2/FC

H'2H' : position of the second principal plane from the back surface of the cornea =

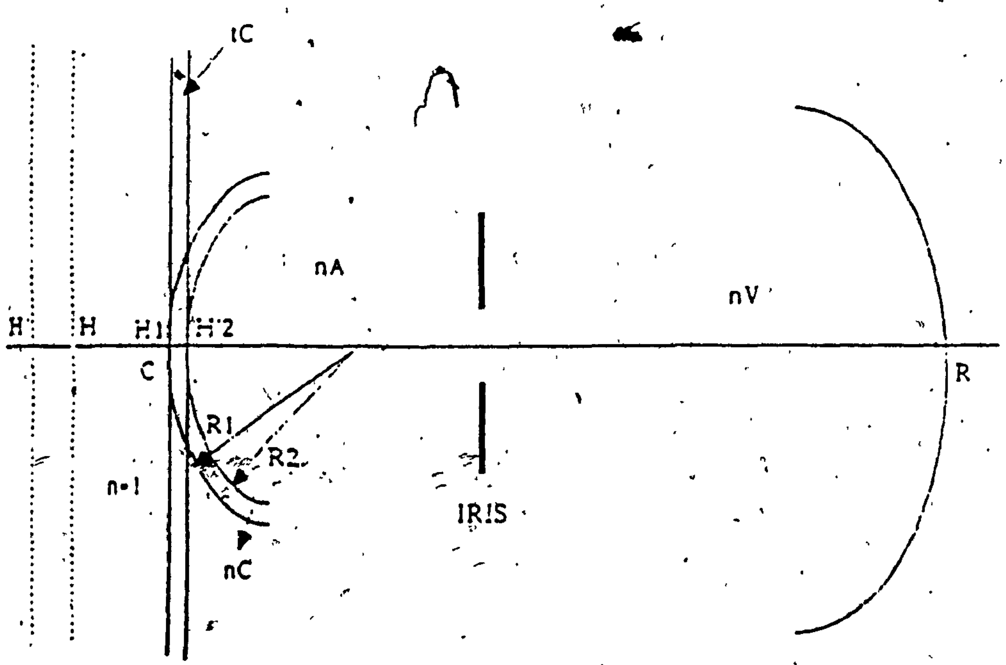
- nA x tC/nC x D1/Fc

H'C : position of the second principal plane from the apex of the cornea = tC +H'2..H

therefore:

H'R = l' = H'C..C + CR
n'A/l' = 1/l + FC
n'A/l = R + FC

R = (n'A/l') - FC



CORNU FORMULA CONSTANTS	CORNEA	AQUEOUS	VITREOUS
base index (n)	1.3610	1.3221	1.3208
constant (k)	7.4147	7.0096	6.9806
wavelength constant (lamda)	130	130	130

LEGRAND (1967)		m	mm	m
cornea ant. rad.	(rad1)	7.80E-03	7.8000	0.00780
cornea post. rad.	(rad2)	6.50E-03	6.5000	0.00650
Thickness of cornea (tc)		1.30E-03	1.3000	0.00130
Retina to cornea apex (CR)		2.42E-02	24.2000	0.02420

	(g)	(F)
WAVELENGTH	435.8	486.1
cornea index (nc)	1.3852	1.3818
aqueous index (na)	1.3450	1.3418
vitreous index (nv)	1.3436	1.3404
Power of ant. cornea (D1)	49.3906	48.9515
Power of post. cornea (D2)	-6.1846	-6.1596
Power of cornea (Fc)	43.4927	43.0[illegible]
Power of the eye (Fe)	43.4927	43.[illegible]
(tc/nc)	9.38E-04	9.41E-04
(D2/Fc)	-0.14220	-0.14300
(D1/Fc)	1.13561	1.13641
(H1 H)	-1.33E-04	-1.35E-04
(H'2 H')	-1.43E-03	-1.43E-03
(H' C)	-1.33E-04	-1.35E-04
(H' R)	2.4067E-02	2.4065E-02
n'a/H' R	55.8876	55.7556
R=n'a/H'R-Fc	12.3949	12.6800
NORMALIZED AT 589.6 NM	-0.6702	-0.3851
NORMALIZED AT 580 NM	-0.641929	-0.356796

(e) 546.1	(D) 589.6	(C) 656.3	300	320	340
1.3788	1.3771	1.3751	1.4046	1.4000	1.3963
1.3389	1.3374	1.3354	1.3633	1.3590	1.3555
1.3376	1.3360	1.3341	1.3619	1.3575	1.3540
48.5666	48.3504	48.0883	51.8738	51.2852	50.8087
-6.1344	-6.1202	-6.1030	-6.3512	-6.3126	-6.2814
42.7131	42.5095	42.2627	45.8275	45.2732	44.8245
42.7118	42.5079	42.2606	45.8318	45.2764	44.8268
9.43E-04	9.44E-04	9.45E-04	9.26E-04	9.29E-04	9.31E-04
-0.14362	-0.14397	-0.14441	-0.13859	-0.13943	-0.14013
1.13704	1.13740	1.13784	1.13194	1.13279	1.13350
-1.35E-04	-1.36E-04	-1.37E-04	-1.28E-04	-1.29E-04	-1.30E-04
-1.44E-03	-1.44E-03	-1.44E-03	-1.43E-03	-1.43E-03	-1.43E-03
-1.35E-04	-1.36E-04	-1.37E-04	-1.28E-04	-1.29E-04	-1.30E-04
2.4065E-02	2.4064E-02	2.4063E-02	2.4072E-02	2.4071E-02	2.4070E-02
55.6397	55.5746	55.4957	56.6363	56.4588	56.3151
12.9266	13.0651	13.2330	10.8087	11.1856	11.4907
-0.1385	0.0000	0.1679	-2.2563	-1.8795	-1.5744
-0.110241	0.028265	0.196179	-2.228078	-1.851232	-1.546143

360	380	400	420	440	460
1.3932	1.3907	1.3885	1.3866	1.3849	1.3835
1.3526	1.3501	1.3481	1.3463	1.3447	1.3433
1.3512	1.3487	1.3467	1.3449	1.3433	1.3420
50.4151	50.0845	49.8028	49.5600	49.3485	49.1627
-6.2556	-6.2339	-6.2154	-6.1995	-6.1857	-6.1735
44.4538	44.1424	43.8772	43.6485	43.4494	43.2744
44.4555	44.1436	43.8779	43.6488	43.4493	43.2740
9.33E-04	9.35E-04	9.36E-04	9.38E-04	9.39E-04	9.40E-04
-0.14072	-0.14122	-0.14166	-0.14203	-0.14236	-0.14266
1.13410	1.13461	1.13505	1.13543	1.13577	1.13607
-1.31E-04	-1.32E-04	-1.33E-04	-1.33E-04	-1.34E-04	-1.34E-04
-1.43E-03	-1.43E-03	-1.43E-03	-1.43E-03	-1.43E-03	-1.43E-03
-1.31E-04	-1.32E-04	-1.33E-04	-1.33E-04	-1.34E-04	-1.34E-04
2.4069E-02	2.4068E-02	2.4067E-02	2.4067E-02	2.4066E-02	2.4066E-02
56.1965	56.0969	56.0120	55.9388	55.8751	55.8192
11.7427	11.9544	12.1348	12.2903	12.4258	12.5448
-1.3224	-1.1106	-0.9303	-0.7748	-0.6393	-0.5203
-1.294096	-1.082365	-0.901992	-0.746492	-0.611051	-0.492023

480	500	520	540	560	580
1.3822	1.3810	1.3800	1.3791	1.3782	1.3775
1.3421	1.3410	1.3401	1.3392	1.3384	1.3377
1.3407	1.3397	1.3387	1.3378	1.3370	1.3363
48.9981	48.8512	48.7195	48.6006	48.4928	48.3945
-6.1627	-6.1531	-6.1444	-6.1366	-6.1296	-6.1231
43.1194	42.9811	42.8571	42.7451	42.6436	42.5510
43.1188	42.9803	42.8560	42.7439	42.6421	42.5495
9.41E-04	9.41E-04	9.42E-04	9.43E-04	9.43E-04	9.44E-04
-0.14292	-0.14316	-0.14337	-0.14356	-0.14374	-0.14390
1.13633	1.13657	1.13679	1.13699	1.13716	1.13733
-1.34E-04	-1.35E-04	-1.35E-04	-1.35E-04	-1.36E-04	-1.36E-04
-1.43E-03	-1.43E-03	-1.44E-03	-1.44E-03	-1.44E-03	-1.44E-03
-1.34E-04	-1.35E-04	-1.35E-04	-1.35E-04	-1.36E-04	-1.36E-04
2.4066E-02	2.4065E-02	2.4065E-02	2.4065E-02	2.4064E-02	2.4064E-02
55.7696	55.7254	55.6857	55.6499	55.6174	55.5879
12.6502	12.7442	12.8296	12.9048	12.9739	13.0368
-0.4149	-0.3208	-0.2364	-0.1603	-0.0912	-0.0293
-0.386595	-0.292563	-0.208172	-0.132013	-0.062937	0.000000

600	620	640	660	680	700
1.3768	1.3761	1.3755	1.3750	1.3745	1.3740
1.3370	1.3364	1.3358	1.3353	1.3348	1.3344
1.3357	1.3350	1.3345	1.3340	1.3335	1.3330
48.3046	48.2221	48.1460	48.0756	48.0104	47.9498
-6.1172	-6.1118	-6.1068	-6.1022	-6.0979	-6.0940
42.4664	42.3887	42.3170	42.2508	42.1894	42.1323
42.4647	42.3868	42.3151	42.2487	42.1872	42.1300
9.44E-04	9.45E-04	9.45E-04	9.45E-04	9.46E-04	9.46E-04
-0.14405	-0.14418	-0.14431	-0.14443	-0.14454	-0.14464
1.13748	1.13762	1.13774	1.13786	1.13797	1.13808
-1.36E-04	-1.36E-04	-1.36E-04	-1.37E-04	-1.37E-04	-1.37E-04
-1.44E-03	-1.44E-03	-1.44E-03	-1.44E-03	-1.44E-03	-1.44E-03
-1.36E-04	-1.36E-04	-1.36E-04	-1.37E-04	-1.37E-04	-1.37E-04
2.4064E-02	2.4064E-02	2.4064E-02	2.4063E-02	2.4063E-02	2.4063E-02
55.5608	55.5359	55.5130	55.4919	55.4722	55.4540
13.0944	13.1473	13.1960	13.2411	13.2828	13.3217
0.0293	0.0822	0.1309	0.1760	0.2178	0.2566
0.057582	0.110464	0.159199	0.204256	0.246038	0.284887

Appendix B

Observer Information

Ss	Age	Eye Tested	IOL Type	D	Time since operation (months)	Post-op acuity
AB	62	OD	CILCO AC Model 22723	20.0	24	20/40
SH	62	OS	IOLab AC Model 85JM	19.5	3	20/25
TL	70	OS	IOLab PC Model 706G	21.5	15	20/20
AH	63	OD	IOLab PC Model 706G	25.0	9	20/20

Appendix C

Observer Consent Form

OBSERVER CONSENT FORM
DEPARTMENT OF PSYCHOLOGY, CONCORDIA UNIVERSITY

NAME: ______________________ SEX: _____ AGE _____

ADDRESS: ______________________

____

TELEPHONE: ______________________

I HAVE VOLUNTEERED TO PARTICIPATE IN A STUDY DESIGNED TO MEASURE CHROMATIC ABERRATION AND HAVE BEEN FULLY INFORMED OF THE EXPERIMENTAL PROCEDURE WHICH INCLUDES:

(1) CHROMATIC ABERRATION WILL BE MEASURED USING AN OPTOMETER IN A DARKENED ENVIRONMENT.

(2) THE LIGHT SOURCE THAT IS DIRECTED TOWARDS THE TARGET IS COMPRISED OF THE FULL VISIBLE SPECTRUM PLUS A SMALL UV COMPONENT (FAR LESS THAN OUTDOOR LIGHT) FROM A XENON ARC LAMP.

(3) THE EXPERIMENTAL SESSION WILL LAST ABOUT TWO HOURS INCLUDING REST PERIODS.

(4) YOU WILL BE REIMBURSED TAXI FARE (RETURN) OR $5.00 PER HOUR FOR PARTICIPATING.

(5) UNCONDITIONAL WITHDRAWAL FROM THE STUDY CAN BE MADE AT ANY TIME AND THE RESULTS OF YOUR TESTS WILL BE KEPT CONFIDENTIAL.

(6) YOU WILL RECEIVE A SUMMARY OF THE RESULTS AT THE CONCLUSION OF THE STUDY.

DATE: ______________________ SIGNATURE: ______________________

EXPERIMENTER: ______________________

Appendix D

Corneal Irradiance

Wavelength	corneal irradiance (microwatts/cm2)
340	.006586
360	.007616
380	.020314
400	.030634
420	.038983
440	.033630
460	.029708
480	.019138
500	.028913
520	.029740
540	.021217
560	.016262
580	.012541
600	.008359
620	.006006
640	.003443
660	.001241

Appendix E

Results of A-scans and K-readings

ULTRASOUNDS (A-SCANS)

Observer	Axial length (mm) pre/post	A.C. depth (mm) pre/post	lens thickness (mm) pre/post
AB	22.65/22.28	3.00/2.70	5.25/.833
SH	23.47/23.30	2.85/2.76	4.65/.813
TL	22.70/22.42*	2.25*/3.95*	5.50*/.881
AH	21.92/21.66*	2.30/4.00*	5.41/1.001

* Approximate values were estimated by examining the ratio of pre and post A-scans for known values.

KERATOMERY (K-READINGS)

Observer	keratometry (diopters)
AB	45.31
SH	41.56
TL	45.00
AH	44.06

Appendix F

Individual data for all observers

Observer: AH

WAVELENGTH	TRIALS 1	2	3	4	5	6	7	8	MEAN
340	2.59	2.51	3.36	4.31	3.94	2.99	3.99	3.57	3.41
360	2.83	3.84	3.17	3.31	3.94	4.26	3.99	4.58	3.80
380	2.86	3.17	3.28	4.15	3.94	4.81	3.99	4.92	3.89
400	3.39	4.44	3.28	4.31	3.94	5.00	4.29	5.05	4.21
420	3.44	4.44	3.10	4.31	3.78	5.29	4.52	5.16	4.26
440	3.44	4.34	3.33	4.31	4.66	5.66	4.81	5.29	4.49
460	3.25	4.34	3.89	4.47	4.79	5.66	4.81	5.66	4.61
490	3.99	5.16	4.29	4.47	4.97	5.66	5.05	5.93	4.94
500	3.52	5.95	4.42	4.55	4.97	5.66	5.05	6.53	5.09
520	2.99	5.69	4.42	4.74	5.34	5.66	5.05	6.35	5.03
540	3.69	6.06	4.50	4.67	5.45	5.55	5.56	5.96	5.21
560	4.18	6.96	4.66	4.87	5.45	5.56	5.56	5.77	5.37
580	4.18	5.71	4.92	5.19	5.19	5.56	5.56	5.77	5.26
600	4.66	5.82	4.92	5.19	5.42	5.56	5.77	5.77	5.39
620	4.50	6.53	5.29	5.19	5.42	5.56	5.93	5.77	5.52
640	4.21	6.06	5.69	5.19	5.42	5.56	5.93	6.11	5.52
660	4.63	6.72	5.69	5.34	5.37	5.56	6.06	6.11	5.68

Observer: SH

WAVELENGTH	TRIALS 1	2	3	4	5	6	7	8	MEAN
340	3.23	4.47	3.54	3.70	2.96	3.44	3.44	3.36	3.52
360	3.86	3.94	3.73	3.78	3.23	4.26	3.65	3.65	3.76
380	4.15	4.47	4.42	4.87	3.70	4.18	4.13	4.05	4.25
400	3.97	4.31	4.76	4.81	4.42	4.68	4.31	4.13	4.42
420	4.66	5.03	4.84	4.34	4.63	4.84	4.44	4.74	4.69
440	5.16	5.03	4.55	4.42	4.63	5.34	4.97	5.00	4.89
460	4.69	6.14	5.77	5.79	5.03	5.26	5.16	4.92	5.34
480	4.95	5.42	5.53	6.01	5.21	5.45	5.26	5.32	5.39
500	6.16	5.67	5.58	6.19	5.21	5.58	5.79	5.34	5.72
520	6.11	5.82	5.71	5.79	5.34	5.74	5.34	5.71	5.70
540	5.69	5.90	5.79	6.38	5.48	5.53	5.58	5.53	5.73
560	5.69	6.08	6.11	6.27	5.74	5.50	6.69	5.63	5.97
580	6.22	6.08	6.32	6.11	5.74	5.69	6.43	5.77	6.04
600	6.11	6.64	6.51	6.51	5.71	6.06	6.08	5.74	6.17
620	6.80	6.69	6.53	6.96	5.71	6.01	6.38	5.77	6.36
640	6.46	7.28	6.53	6.32	5.82	5.58	6.14	5.61	6.22
660	6.59	5.87	6.85	6.32	5.85	6.27	6.40	5.45	6.20

Observer: AB

	TRIALS						
	1	2	3	4	5	6	MEAN
WAVELENGTH							
340	3.04	1.38	2.06	2.20	1.51	0.79	1.83
360	2.65	2.70	2.06	2.38	1.51	1.51	2.13
380	2.65	2.39	2.06	2.38	1.51	2.49	2.24
400	3.52	3.36	3.62	2.79	3.26	3.76	3.40
420	3.52	3.31	3.15	2.88	3.36	3.76	3.33
440	3.99	3.97	3.15	3.20	3.73	3.76	3.63
460	3.99	3.76	3.15	3.36	3.73	3.76	3.62
480	3.99	4.02	2.94	4.29	3.73	3.76	3.79
500	5.48	4.18	3.31	4.79	4.26	3.76	4.29
520	4.60	4.34	4.31	4.79	4.26	4.89	4.53
540	4.89	4.97	4.31	4.26	4.23	4.89	4.59
560	4.89	4.97	4.31	4.52	4.23	4.89	4.64
580	4.89	5.40	4.31	5.13	4.02	4.89	4.78
600	5.00	5.40	4.89	5.03	4.07	4.89	4.88
620	5.42	4.47	5.66	5.45	4.42	4.89	5.05
640	5.05	3.84	5.29	5.45	4.42	4.89	4.82
660	5.16	3.49	3.12	5.24	4.71	4.99	4.44

Observer: TL

	TRIALS								
WAVELENGTH	1	2	3	4	5	6	7	8	MEAN
340	1.69	3.36	2.43	2.62	4.39	2.46	3.86	2.88	2.96
360	2.72	4.31	2.62	3.79	4.39	3.20	4.50	3.68	3.65
380	3.25	4.60	2.72	4.52	4.39	4.15	4.02	3.94	3.95
400	3.25	4.60	3.04	4.37	4.58	4.66	4.34	3.94	4.10
420	3.89	4.60	2.99	4.58	4.52	4.97	3.86	4.84	4.39
440	4.29	4.60	3.99	4.81	4.81	4.84	3.86	4.84	4.51
460	4.29	4.97	3.81	4.79	5.08	4.84	3.86	4.84	4.56
480	4.29	4.97	3.81	5.37	5.08	4.67	3.86	4.63	4.61
500	4.31	4.97	3.81	5.79	5.26	5.00	3.86	4.42	4.68
520	4.31	4.97	3.81	5.79	5.32	5.74	3.86	4.42	4.78
540	4.18	4.97	3.81	5.79	5.61	5.58	3.89	4.42	4.78
560	4.84	4.97	4.15	5.79	5.63	5.56	4.13	4.81	4.99
580	4.84	4.97	3.78	5.79	5.77	5.93	3.70	5.34	5.02
600	4.34	5.08	4.44	5.79	5.90	5.77	4.47	4.89	5.09
620	4.34	5.08	4.63	5.79	6.19	5.71	4.95	4.47	5.15
640	4.34	5.08	4.71	5.79	4.78	6.09	4.26	3.94	4.87
660	5.45	5.08	4.81	5.79	6.67	4.29	5.58	3.47	5.14

Appendix G

Theoretical Pseudophakic Chromatic Aberration Parameters

$$R = \frac{1}{\dfrac{tC}{nC} \times \dfrac{D1}{FC} + \dfrac{tL}{nL} \times \dfrac{D4}{FL} + \dfrac{tAC}{nA} \times \dfrac{FC}{Fe} + \dfrac{}{\dfrac{tL}{nL} \times \dfrac{D3}{FL} + \dfrac{CR - tC - tAC - tL}{nV}} - Fe}$$

nC : index of cornea
nA : index of aqueous
nV : index of vitreous

nL : index of intraocular lens

tC : thickness of cornea
tAC: thickness of the anterior chamber
tL : thickness of IOL

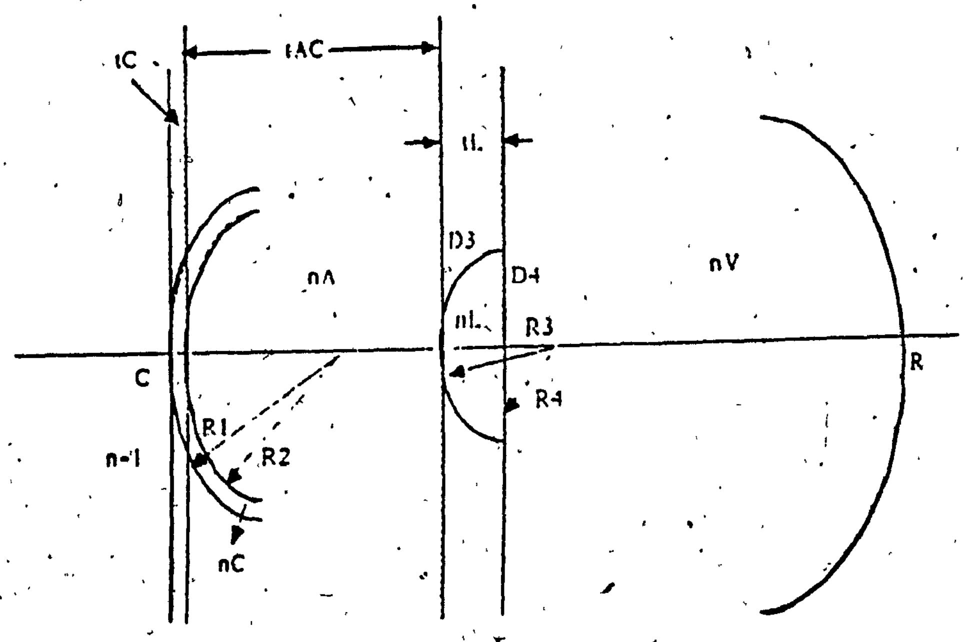
FC : power of the cornea = $D1+D2 - tC/nC \times D1 \times D2$

FL : Power of the IOL = $D3+D4 - tL/nL \times D3 \times D4$

Fe : Power of the eye =

$FC+FL-FC \times FL \times (nA \times tC/nC \times D1/FC)+tAC+(nA \times tL/nL \times D3/FL)/nL$

D1 : Power of the anterior corneal surface = $(nC - 1)/R1$
D2 : Power of the posterior corneal surface = $(nA - nC)/R2$
D3 : Power of the anterior lens surface = $(nL - nA)/R3$
D4 : Power of the posterior lens surface = $(nV - nL)/R4$
R1 : Anterior corneal radius
R2 : Posterior corneal radius
R3 : Anterior lens radius
R4 : Posterior lens radius



CORNU FORMULA CONSTANTS		CORNEA	AQUEOUS	VITREOUS
base index (n)		1.3610	1.3221	1.3208
constant (k)		7.4147	7.0096	6.9806
wavelength constant (lamda)		130	130	130
		m	mm	m
cornea ant. rad.	(rad1)	8.58E-03	8.5800	0.00858
cornea post. rad.	(rad2)	6.50E-03	6.5000	0.00650
IOL ant. rad.	(rad3)	7.23E-03	7.2300	0.00723
IOL post. rad.	(rad4)	0.00E+00	0.0000	0.00000
Thickness of cornea (tc)		1.30E-03	1.3000	0.00130
Thckrss of ant. ch. (tac)		3.35E-03	3.3500	0.00335
Thickness of IOL (tL)		8.82E-04	0.8820	0.000882
Retina to cornea apex (CR)		2.24E-02	22.4200	0.02242

WAVELENGTH	(g) 436	(F) 486
cornea index (nc)	1.3852	1.3818
aqueous index (na)	1.3450	1.3418
IOL index (nl)	1.5010	1.4970
vitreous index (nv)	1.3436	1.3404
Power of ant. cornea (D1)	44.9006	44.5014
Power of post. cornea (D2)	-6.1884	-6.1596
Power of cornea (Fc)	38.9729	38.5996
Power of ant. IOL (D3)	21.5737	21.4683
Power of post. IOL (D4)	0.0000	0.0000
Power of IOL (FL)	21.5737	21.4683
Power of the eye (Fe)	57.8555	57.4079
(tc/nc * D1/Fc)	0.001081	0.001085
(tac/na)	0.002491	0.002497
(Fc/Fe)	0.673625	0.672375
Solution 1	0.002406	0.002408
(t1/nl * D3/F1)	0.000588	0.000589
Solution 2		
(CR-tc-tac-t1/nv)	0.012569	0.012599
Solution 3		
Solution 1+2+3	0.015563	0.015596
1/Solution 1+2+3	64.2563	64.1175
Above ÷ Fe = R(lamda)	6.4008	6.7096
NORMALIZED AT 589.6 NM	-0.7844	-0.4756
NORMALIZED AT 580 NM	-0.9934	-0.6846

(e) 546	(D) 590	(C) 656	300	320	340
1.3788	1.3771	1.3751	1.4046	1.4000	1.3963
1.3389	1.3374	1.3354	1.3633	1.3590	1.3555
1.4930	1.4910	1.4890	1.5240	1.5190	1.5150
1.3376	1.3360	1.3341	1.3619	1.3575	1.3540
44.1515	43.9549	43.7166	47.1580	46.6229	46.1898
−6.1344	−6.1202	−6.1030	−6.3512	−6.3126	−6.2814
38.2724	38.0886	37.8658	41.0840	40.5836	40.1785
21.3076	21.2515	21.2422	22.2223	22.1310	22.0638
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
21.3076	21.2515	21.2422	22.2223	22.1310	22.0638
56.9548	56.7306	56.5110	60.4318	59.8767	59.4331
0.001088	0.001089	0.001091	0.001062	0.001067	0.001070
0.002502	0.002505	0.002509	0.002457	0.002465	0.002471
0.671979	0.671395	0.670061	0.679841	0.677786	0.676029
0.002412	0.002419	0.002412	0.002393	0.002394	0.002394
0.000591	0.000592	0.000592	0.000579	0.000581	0.000582
0.012626	0.012641	0.012659	0.012401	0.012440	0.012472
0.015629	0.015646	0.015664	0.015372	0.015415	0.015449
63.9847	63.9158	63.8420	65.0527	64.8736	64.7299
7.0299	7.1852	7.3310	4.6209	4.9969	5.2968
−0.1553	0.0000	0.1458	−2.5643	−2.1883	−1.8884
−0.3643	−0.2090	−0.0632	−2.7733	−2.3973	−2.0974

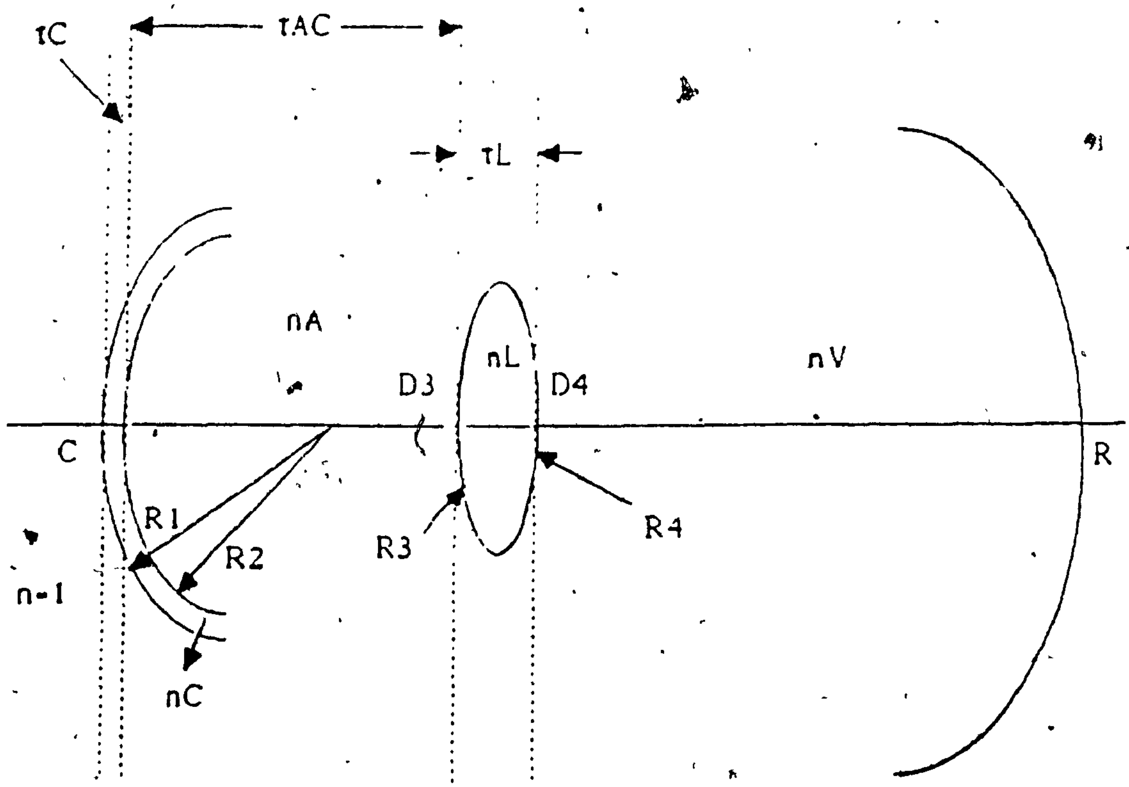
360	380	400	420	440	460
1.3932	1.3907	1.3885	1.3866	1.3849	1.3835
1.3526	1.3501	1.3481	1.3463	1.3447	1.3433
1.5110	1.5070	1.5040	1.5010	1.4990	1.4970
1.3512	1.3487	1.3467	1.3449	1.3433	1.3420
45.8319	45.5313	45.2753	45.0545	44.8623	44.6933
−6.2556	−6.2339	−6.2154	−6.1995	−6.1857	−6.1735
39.8438	39.5628	39.3233	39.1169	38.9371	38.7791
21.9120	21.6959	21.5683	21.4010	21.3400	21.2529
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
21.9120	21.6959	21.5683	21.4010	21.3400	21.2529
58.9814	58.5233	58.1829	57.8387	57.6140	57.3868
0.001073	0.001076	0.001078	0.001080	0.001082	0.001083
0.002477	0.002481	0.002485	0.002488	0.002491	0.002494
0.675533	0.676017	0.675856	0.676310	0.675827	0.675750
0.002398	0.002405	0.002408	0.002413	0.002415	0.002417
0.000584	0.000585	0.000586	0.000588	0.000588	0.000589
0.012499	0.012521	0.012541	0.012557	0.012572	0.012585
0.015481	0.015511	0.015535	0.015558	0.015575	0.015591
64.5958	64.4688	64.3697	64.2749	64.2062	64.1402
5.6144	5.9455	6.1868	6.4362	6.5922	6.7535
−1.5708	−1.2397	−0.9985	−0.7490	−0.5930	−0.4317
−1.7798	−1.4487	−1.2075	−0.9580	−0.8020	−0.6407

480	500	520	540	560	580
1.3822	1.3810	1.3800	1.3791	1.3782	1.3775
1.3421	1.3410	1.3401	1.3392	1.3384	1.3377
1.4950	1.4930	1.4920	1.4910	1.4900	1.4890
1.3407	1.3397	1.3387	1.3378	1.3370	1.3363
44.5437	44.4102	44.2904	44.1824	44.0843	43.9950
-6.1627	-6.1531	-6.1444	-6.1366	-6.1296	-6.1231
38.6392	38.5144	38.4024	38.3013	38.2096	38.1261
21.1442	21.0173	21.0134	20.9963	20.9680	20.9299
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
21.1442	21.0173	21.0134	20.9963	20.9680	20.9299
57.1574	56.9262	56.8164	56.7053	56.5932	56.4800
0.001084	0.001085	0.001086	0.001087	0.001088	0.001089
0.002496	0.002498	0.002500	0.002501	0.002503	0.002504
0.676014	0.676567	0.675903	0.675445	0.675164	0.675038
0.002420	0.002424	0.002424	0.002424	0.002425	0.002426
0.000590	0.000591	0.000591	0.000592	0.000592	0.000592
0.012596	0.012606	0.012615	0.012623	0.012631	0.012638
0.015606	0.015621	0.015630	0.015639	0.015648	0.015656
64.0767	64.0150	63.9779	63.9422	63.9077	63.8742
6.9193	7.0888	7.1615	7.2369	7.3146	7.3942
-0.2659	-0.0964	-0.0237	0.0517	0.1294	0.2090
-0.4749	-0.3054	-0.2327	-0.1573	-0.0797	0.0000

600	620	640	660	680	700
1.3768	1.3761	1.3755	1.3750	1.3745	1.3740
1.3370	1.3364	1.3358	1.3353	1.3348	1.3344
1.4890	1.4890	1.4890	1.4880	1.4880	1.4880
1.3357	1.3350	1.3345	1.3340	1.3335	1.3330
43.9133	43.8382	43.7691	43.7051	43.6458	43.5907
-6.1172	-6.1118	-6.1068	-6.1022	-6.0979	-6.0940
38.0497	37.9795	37.9149	37.8551	37.7996	37.7481
21.0216	21.1058	21.1834	21.1168	21.1833	21.2452
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
21.0216	21.1058	21.1834	21.1168	21.1833	21.2452
56.4890	56.4974	56.5051	56.3891	56.3958	56.4020
0.001090	0.001090	0.001091	0.001092	0.001092	0.001092
0.002506	0.002507	0.002508	0.002509	0.002510	0.002510
0.673577	0.672235	0.670999	0.671319	0.670256	0.669269
0.002422	0.002418	0.002415	0.002417	0.002414	0.002411
0.000592	0.000592	0.000592	0.000593	0.000593	0.000593
0.012644	0.012650	0.012655	0.012660	0.012664	0.012669
0.015658	0.015660	0.015662	0.015670	0.015671	0.015673
63.8648	63.8561	63.8481	63.8176	63.8108	63.8044
7.3757	7.3587	7.3430	7.4285	7.4150	7.4025
0.1905	0.1735	0.1578	0.2438	0.2298	0.2172
-0.0185	-0.0355	-0.0512	0.0343	0.0208	0.0082

Appendix H

Theoretical Phakic Chromatic Aberration Parameters


τC
τAC
τL
nA
nL
D3
D4
nV
C
R
R1
R2
R3
R4
n=1
nC

	LENS
	1.3999 (general index)
	9.2492
	130

CORNU FORMULA CONSTANTS	CORNEA	AQUEOUS	VITREOUS
base index (n)	1.3610	1.3221	1.3208
constant (k)	7.4147	7.0096	6.9806
wavelength constant (lamda)	130	130	130

LEGRAND (1967)		m	mm	m
cornea ant. rad.	(rad1)	7.80E-03	7.8000	0.0078
cornea post. rad.	(rad2)	6.50E-03	6.5000	0.0065
lens ant. rad.	(rad3)	1.02E-02	10.2000	0.0102
lens post. rad.	(rad4)	-0.0060	-6.0000	-0.0060
Thickness of cornea (tc)		1.30E-03	1.3000	0.0013
Thickns of ant. ch. (tac)		3.60E-03	3.6000	0.0036
Thickness of lens (tL)		0.004000	4.0000	0.004000
Retina to cornea apex (CR)		2.42E-02	24.2000	0.0242

WAVELENGTH	(g) 435.8	(F) 486.1
cornea index (nc)	1.3852	1.3818
aqueous index (na)	1.3450	1.3418
lens index (nl)	1.4301	1.4259
vitreous index (nv)	1.3436	1.3404
Power of ant. cornea (D1)	49.3906	48.9515
Power of post. cornea (D2)	-6.1846	-6.1596
Power of cornea (Fc)	43.4927	43.0756
Power of ant. lens (D3)	8.3455	8.2440
Power of post. lens (D4)	14.4193	14.2451
Power of the lens (FL)	22.4286	22.1597
Power of the eye (Fe)	60.8384	60.2412
(tc/nc * D1/Fc)	0.001066	0.001069
(tl/nl * D4/FL)	0.001798	0.001803
(tac/na)	0.002677	0.002683
(Fc/Fe)	0.714888	0.715052
Solution 1	0.003961	0.003972
(tl/nl * D3/Fl)	0.001041	0.001044
Solution 2		
(CR-tc-tac-tl/nv)	0.011387	0.011414
Solution 3		
Solution 1+2+3	0.016389	0.016431
1/Solution 1+2+3	61.0181	60.8621
Above - Fe = R(lamda)	0.1797	0.6210
NORMALIZED AT 589.6 NM	-1.0412	-0.5999
NORMALIZED AT 580 NM	-0.9971	-0.555[illegible]

(e) 546.1	(D) 589.6	(C) 656.3	300	320	340
1.3788	1.3771	1.3751	1.4046	1.4000	1.3963
1.3389	1.3374	1.3354	1.3633	1.3590	1.3555
1.4221	1.4200	1.4175	1.4543	1.4486	1.4439
1.3376	1.3360	1.3341	1.3619	1.3575	1.3540
48.5666	48.3504	48.0883	51.8738	51.2852	50.8087
-6.1344	-6.1202	-6.1030	-6.3512	-6.3126	-6.2814
42.7131	42.5095	42.2627	45.8275	45.2732	44.8245
8.1551	8.1052	8.0446	8.9190	8.7831	8.6730
14.0920	14.0060	13.9017	15.4075	15.1733	14.9839
21.9239	21.7914	21.6308	23.9485	23.5884	23.2968
59.7201	59.4272	59.0721	64.1853	63.3925	62.7501
0.001072	0.001074	0.001076	0.001048	0.001052	0.001055
0.001808	0.001810	0.001814	0.001770	0.001776	0.001782
0.002689	0.002692	0.002696	0.002641	0.002649	0.002656
0.715221	0.715320	0.715443	0.713983	0.714173	0.714333
0.003983	0.003989	0.003996	0.003897	0.003912	0.003924
0.001046	0.001048	0.001049	0.001024	0.001028	0.001031
0.011439	0.011452	0.011469	0.011225	0.011270	0.011300
0.016468	0.016489	0.016514	0.016156	0.016210	0.016255
60.7251	60.6481	60.5546	61.8976	61.6897	61.5211
1.0050	1.2208	1.4825	-2.2877	-1.7028	-1.2290
-0.2158	0.0000	0.2617	-3.5085	-2.9236	-2.4498
-0.1718	0.0440	0.3058	-3.4645	-2.8796	-2.4057

360	380	400	420	440	460
1.3932	1.3907	1.3885	1.3866	1.3849	1.3835
1.3526	1.3501	1.3481	1.3463	1.3447	1.3433
1.4401	1.4369	1.4342	1.4318	1.4297	1.4279
1.3512	1.3487	1.3467	1.3449	1.3433	1.3420
50.4151	50.0845	49.8028	49.5600	49.3485	49.1627
-6.2556	-6.2339	-6.2154	-6.1995	-6.1857	-6.1735
44.4538	44.1424	43.8772	43.6485	43.4494	43.2744
8.5821	8.5057	8.4407	8.3846	8.3357	8.2928
14.8272	14.6957	14.5837	14.4871	14.4030	14.3291
23.0559	22.8535	22.6810	22.5324	22.4029	22.2890
62.2191	61.7727	61.3922	61.0641	60.7782	60.5268
0.001058	0.001061	0.001063	0.001065	0.001066	0.001069
0.001786	0.001790	0.001793	0.001796	0.001799	0.001801
0.002662	0.002666	0.002671	0.002674	0.002677	0.002680
0.714472	0.714595	0.714703	0.714799	0.714885	0.714962
0.003934	0.003943	0.003950	0.003956	0.003962	0.003967
0.001034	0.001036	0.001038	0.001040	0.001041	0.001042
0.011324	0.011344	0.011361	0.011377	0.011390	0.011401
0.016291	0.016323	0.016349	0.016372	0.016393	0.016410
61.3818	61.2646	61.1646	61.0784	61.0033	60.9372
-0.8373	-0.5081	-0.2276	0.0143	0.2251	0.4104
-2.0581	-1.7289	-1.4484	-1.2065	-0.9957	-0.8104
-2.0141	-1.6849	-1.4044	-1.1624	-0.9516	-0.7664

480	500	520	540	560	580
1.3822	1.3810	1.3800	1.3791	1.3782	1.3775
1.3421	1.3410	1.3401	1.3392	1.3384	1.3377
1.4263	1.4249	1.4236	1.4225	1.4214	1.4205
1.3407	1.3397	1.3387	1.3378	1.3370	1.3363
48.9981	48.8512	48.7195	48.6006	48.4928	48.3945
-6.1627	-6.1531	-6.1444	-6.1366	-6.1296	-6.1231
43.1194	42.9811	42.8571	42.7451	42.6436	42.5510
8.2548	8.2209	8.1904	8.1630	8.1381	8.1154
14.2636	14.2052	14.1528	14.1055	14.0626	14.0236
22.1882	22.0983	22.0176	21.9447	21.8787	21.8195
60.3041	60.1055	59.9271	59.7661	59.6201	59.4870
0.001069	0.001070	0.001071	0.001072	0.001073	0.001073
0.001803	0.001805	0.001806	0.001808	0.001809	0.001810
0.002682	0.002684	0.002686	0.002688	0.002690	0.002691
0.715032	0.715095	0.715153	0.715206	0.715255	0.715300
0.003971	0.003975	0.003979	0.003982	0.003985	0.003987
0.001043	0.001044	0.001045	0.001046	0.001047	0.001047
0.011412	0.011421	0.011429	0.011436	0.011443	0.011449
0.016426	0.016440	0.016453	0.016464	0.016475	0.016484
60.8787	60.8264	60.7796	60.7372	60.6988	60.6638
0.5746	0.7210	0.8524	0.9711	1.0787	1.1768
-0.6463	-0.4998	-0.3684	-0.2497	-0.1421	-0.0440
-0.6022	-0.4558	-0.3243	-0.2057	-0.0981	0.0000

600	620	640	660	680	700
1.3768	1.3761	1.3755	1.3750	1.3745	1.3740
1.3370	1.3364	1.3358	1.3353	1.3348	1.3344
1.4196	1.4188	1.4180	1.4174	1.4167	1.4161
1.3357	1.3350	1.3345	1.3340	1.3335	1.3330
48.3046	48.2221	48.1460	48.0756	48.0104	47.9498
-6.1172	-6.1118	-6.1068	-6.1022	-6.0979	-6.0940
42.4664	42.3887	42.3170	42.2508	42.1894	42.1323
8.0946	8.0756	8.0580	8.0417	8.0267	8.0127
13.9878	13.9550	13.9247	13.8967	13.8708	13.8467
21.7634	21.7128	21.6662	21.6231	21.5831	21.5459
59.3652	59.2534	59.1503	59.0550	58.9666	58.8843
0.001074	0.001075	0.001075	0.001076	0.001076	0.001077
0.001811	0.001812	0.001813	0.001814	0.001815	0.001815
0.002693	0.002694	0.002695	0.002696	0.002697	0.002698
0.715341	0.715380	0.715415	0.715449	0.715480	0.715509
0.003990	0.003992	0.003994	0.003996	0.003998	0.004000
0.001048	0.001049	0.001049	0.001050	0.001050	0.001050
0.011455	0.011460	0.011465	0.011470	0.011474	0.011477
0.016493	0.016501	0.016508	0.016515	0.016522	0.016528
60.6317	60.6023	60.5752	60.5501	60.5268	60.5052
1.2665	1.3489	1.4249	1.4951	1.5603	1.6208
0.0457	0.1281	0.2041	0.2743	0.3394	0.4000
0.0897	0.1722	0.2481	0.3184	0.3835	0.4441

Appendix I

Multiple Regression and Analysis of Variance

Summary Tables

Multiple regression report for 4 observers and theoretical observations.

Obs.	Parameter Estimate	Sx	t value (b=0)	Prob. (b=0)	Sequential R-squared	Simple R-Sq.
Const	-.1964					
SH	.3359	.8158	0.41	.688	.6809	.6809
AB	.5507	.4558	1.21	.250	.7127	.7121
TL	-.5813	.6966	-0.83	.420	.7282	.5828
AH	.1556	.6433	0.24	.813	.7295	.6482

Analysis of variance report

Source	df	Sums of Squares (Sequential)	Mean Square	F
Constant	1	4.1902	4.1902	
Model	4	6.4333	1.6084	8.09 *
Error	12	2.3856	.1988	
Total	16	8.8190	.5512	

* $p < .002$

Appendix J

Analysis of Variance Summary Table

Split plot analysis of variance between anterior and posterior chamber placement

Source	SS	df	MS	F
Between SS	3.97	3		
IOL	.00000132	1	.00000132	1.0
SS Within Gr.	.00000264	2	.00000132	
Within SS	42.68	64		
Wavelength	39.43	16	2.46	77.72 *
Interaction	2.23	16	.1396	4.40 *
Error-W	1.01	32	.0317	

* $p < .01$