THE LIGHT SCATTERING CHARACTERISTICS OF THE NORMAL AND CONTACT LENS-WEARING EYE

Volume II

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CHAPTER 8

The light scattering characteristics of abnormalities affecting the cornea

8.1 Introduction

Ocular abnormalities known to increase intraocular light scatter include cataract, corneal scarring and vitreous opacities (Miller and Benedek 1973). These ocular pathologies may cause the sufferer to become abnormally sensitive to glare.

A variety of studies have investigated the effect of ocular pathology on glare sensitivity. Amongst these, Verriest and Uvijls (1989) investigated normal and abnormal eyes using simultaneous and successive disability glare in conjunction with Snellen VA. The equivalent luminance method was used, with the assumption that any disability glare was due to scattered light. Several conditions were found to cause a significant elevation in increment threshold in the presence of glare - aphakia, cataract, corneal opacification, macular oedema, myopia of 6D or greater, pseudophakia and vitreous opacities. However, there was a poor correlation between VA and the rise in increment threshold due to glare. This showed that the results of testing VA may not correlate with patients' symptoms and if VA alone is used as an indicator of disability glare, the detection or progression of abnormalities may be missed. Assessment of scattered light in abnormal eyes may help diagnosis and more adequately reflect the quality of vision experienced by the patient.

The aim of the experiments described in Chapter 8 was to evaluate the light scattering profiles of subjects with corneal abnormalities associated with high levels of intraocular scatter. The effect of keratoconus (prior to and following surgery) and other corneal abnormalities on measurements of visual function was investigated using the P_SCAN 100 scatter apparatus and CS. Investigation of these subjects will allow quantification of the effect of a range of corneal abnormalities, with varying levels of severity, on measures of forward light scatter and the CSF. These findings, together with those from normals, will have particular relevance to the investigation into the effects of long-term contact lens wear, on scatter and CSF, by allowing comparison of the magnitude of the effects between lens wearers, normals and those with corneal abnormalities.

8.2 Keratoconus

Keratoconus is a corneal ectasia in which there is progressive development of irregular astigmatism, corneal steepening and thinning, and apical scarring. It is a predominately bilateral disorder, which may be sporadic or genetically determined (Bron 1988). The severity of the condition may be asymmetrical and may stabilise at any time. The prevalence of keratoconus is reported as 54.5 per 100,000 (Hofstetter 1959; Duke-Elder and Leigh 1965; Franceschetti 1965; Krachmer et al 1984; Kennedy et al 1986). In some instances it is hereditary, with a recessive transmission. Keratoconus affects all races, but Asians have been reported to have a four fold higher incidence, compared to Caucasians (Pearson et al 1999). There are three stages in the progression of keratoconus - incipient (Grade 1), moderate (Grade 2) and advanced (Grade 3).

Developmental, degenerative, malnutritional, and endocrine aetiologies have been proposed as being causative for keratoconus. However, despite extensive investigation, the aetiology of keratoconus remains unclear (Bron 1990; Rabinowitz 1998). Biochemical studies have suggested increased collagenase activity (Kao et al 1982; Rehany et al 1982; Krachmer et al 1984; Ihalainen et al 1986), a reduced number of collagen cross-links (Oxlund and Simonsen 1985), increased levels of proteases and other catabolic enzymes (Sawaguchi et al 1989) and a loss of keratocytes through apoptosis (e.g. resulting from eczema, allergies or trauma from contact lenses) (Wilson et al 1996). In addition, increased lysosomal enzyme levels have also been demonstrated in the corneal epithelium of keratoconics (Fukuchi et al 1994). Keratoconus has a number of systemic and ocular associations (e.g. Marfan's syndrome, Ehlers-Danlos syndrome and Down's syndrome).

Histologically, during the primary stages of keratoconus there is loss of epithelial basement membrane (Teng 1963; Kato et al 1997), a reaggregation of the irregularly arranged collagen fibrils of Bowman's layer and an alteration of the keratocytes into active fibroblast-like cells (McTigue 1967). In addition, the collagen fibril orientation in the stroma becomes completely disrupted (Daxer and Fratzl 1997). Clinically, vertical folds (Vogt's lines) can be seen in the early stages at the level of the stroma and Descemet's membrane. Thinning of the stroma occurs within the apex of keratoconic corneas, due to a reduction in the number of interlacing collagen lamellae. This altered collagen arrangement influences the biochemical properties of the cornea, and may result in further propagation of the condition, independent of its primary pathogenesis (Radner et al 1996). Thinning of Descemet's membrane, the stroma and Bowman's membrane may also occur (Probst 1996) and may be observed using pachometry. The normal CT (approximately 0.530 mm) becomes progressively reduced to 0.523 $\pm$ 0.037 mm, 0.488 $\pm$ 0.052 mm and finally 0.456 $\pm$ 0.059 mm in stages 1, 2, and 3 respectively (Yamamoto et al 1996). As the thinning progresses further, the corneal cone can be seen to angulate the lower lid (Munson's sign), and central striae appear. However, there is some dispute as to whether this is a characteristic of the disease, or a result of RGP lens wear. For instance, Davis et al (1993) found that in early cases of keratoconus, the striae may be a result of the rigid lens used to correct the astigmatism.

Clusters of activated keratocytes result in fragmentation and scarring of Bowman's layer, which may also affect the dermal portion of the cornea. It is thought that this dermal disturbance causes extensive interference with VA (Radner et al 1996). This theory is disputed by Kaushansen (1993), who found no correlation between histopathological findings and loss of VA. Keratoconus also causes significant damage to the endothelium, with corneas demonstrating endothelial cell pleomorphism, and polymegethism, endothelial cell degeneration, and evidence of anterior chamber inflammation (Sturbaum et al 1996).

Clinical signs of keratoconus vary depending on the severity of the disease, and also on the particular stage of disease progression (Rabinowitz 1998). Keratoconus can essentially be characterised by four disease processes (Bron 1988), namely, (i) corneal thinning; CT reduces with duration of disease (Woodward 1980), (ii) corneal stretching; reduction of tensile strength (Andreassen et al 1980), (iii) increased corneal curvature; irregular astigmatism and eventually Munsen's sign (Bron 1988) and (iv) increased corneal surface area; Fleischer's ring, fibrillary lines (Bron et al 1975) and endothelial polymegethism (Laing et al 1979b). In addition, the corneal nerves become increasingly visible and folds appear in the posterior stroma (Bron 1988). Therefore, in moderate to advanced disease any one or combination of clinical signs may be detectable (table 8.1).

Table 8.1 - Signs of keratoconus (Rabinowitz 1998).

External signs	Munson's sign Rizzuti phenomenon
Slit lamp findings	Stromal thinning Posterior stress line (Vogt's striae) Iron ring (Fleischer ring) Scarring - epithelial or subepithelial
Retroillumination signs	Scissoring on retinoscopy Oil droplet sign (Charleaux)
Photokeratoscopy signs	Compression of mires inferotemporally Compression of mires inferiorly or centrally
Videokeratography signs	Localised increased surface power Inferior/superior dioptric asymmetry Relative skewing of the steepest radial axes above and below the horizontal meridian

In advanced cases of keratoconus, ruptures in Descemet's membrane may occur. These ruptures are acute hydrops and result in leakage of aqueous into the corneal stroma and epithelium, producing a marked increase in CT. The corneal oedema clears, but scarring of the stroma occurs, which once detrimental to vision, or when the astigmatism is too great, limits treatment to penetrating keratoplasty.

8.2.1 Effect of keratoconus on visual performance

Keratoconic patients characteristically exhibit progressive myopia and irregular astigmatism, leading to decreased VA (Krachmer 1984). One of the first symptoms noted in keratoconus is impaired vision due to irregular astigmatism, which is often seen in one eye only, with subsequent progression to the other eye. This change can be clearly seen as an irregular reflex on retinoscopy, and is confirmed by keratometry and Placido disk. When acuity decreases and the amount of astigmatism increases, the initial form of correction is with RGP lenses, which usually provide optimal correction in early keratoconus and in certain more advanced patients (Smiddy et al 1988). Much has been claimed for the role of RGP lenses in keratoconus, including retardation, remission, or even reversal of the disease. Other studies, however, have suggested that contact lens wear may induce the condition (Macsai et al 1990). Such studies may be flawed, as they have all been based upon keratometry, which may be misleading because contact lens wear can produce a temporary flattening of the cornea. As keratoconus is essentially a disease of corneal thinning, it can only be accurately monitored using serial topographical pachometry. When serial topographical pachometry is performed contact lenses have been shown not to affect disease progression (Woodward 1991).

Although the clinical signs of keratoconus are well documented (Krachmer 1984), the visual problems (apart from VA) caused by this abnormality have not been investigated extensively using modern methods (Mannis et al 1984; Edrington et al 1999). The more recent studies have either used CS or indirect methods of measuring forward light scatter to assess the effect of keratoconus on visual performance. No previous studies have investigated the effect of keratoconus on direct measures of scattered light.

8.2.1.1 Effect of keratoconus on glare measurements

Edrington et al (1999) investigated the relationship between baseline corneal scarring with patient-reported and clinician-assessed variables in 1,206 keratoconics. After statistically adjusting for age, contact lens wearing time, and disease severity, the multivariate analysis showed a positive correlation between corneal scarring, VA and patient-reported effects of glare on their vision. However, the patient-reported glare complaints were not quantified.

Gray and Barrett (1999) investigated the effect of disability glare in 20 keratoconus patients wearing RGP lenses and normal subjects. Monocular high and low contrast logMar acuities and Pelli-Robson CS were measured with and without the BAT on the maximum setting. The study reported no significant differences in high contrast acuity (either with or without glare) between the two subject groups. In the absence of disability glare, a significant reduction in low contrast VA and CS was demonstrated by the keratoconic subjects. The presence of disability glare caused a significant reduction in low contrast VA ($p = 0.0001$) and CS ($p = 0.0001$) in all subjects. However, there was no significant difference in the effect of disability glare between the two subject groups.

8.2.1.2 Effect of keratoconus on the contrast sensitivity function

Contrast attenuation has been shown to occur in keratoconic eyes before VA loss occurs (Hess and Carney 1979; Carney 1982a, b; Mannis et al 1984; Zadnik et al 1987). Hess and Carney (1979) investigated the effect of unilateral (three subjects) and bilateral keratoconus (three subjects) on Landolt C and CSF measurements. The subjects were optically corrected, although the type of correction was not stated. The results from the unilateral keratoconics revealed no low frequency loss, even when there were gross forms of high frequency loss. Bilateral keratoconics revealed loss over all spatial frequencies. The presence of a low frequency abnormality appeared to partially depend on the severity of medium to high frequency degradation. Opacities were present in more advanced keratoconic cases, and correlated well with the presence of a low frequency abnormality. The study suggested that in cases of keratoconus it is the degree of opacification that determines the spatial frequency at which the loss occurs. Low frequency abnormalities were found to correlate with opacification, which is known to occur in well-established keratoconus (Reinke 1975).

Although rigid lens wear improves both VA and CS, residual CS losses are still often found in keratoconics (Carney 1982a, b). Carney (1982a, b) investigated five bilateral keratoconics wearing spectacles and RGP lenses. Even though CS improved following fitting with RGP lenses, there still remained attenuation of low spatial frequencies, and in general, CS was reduced at all spatial frequencies compared to normal subjects. In contrast, Mannis et al (1984) reported CS deficits in seven unilateral keratoconics at all but low spatial frequencies. This was confirmed by Zadnik et al (1987) who investigated 12 keratoconic patients (18 eyes) using the Vistech and Regan multi-contrast charts. The authors reported a preferential loss of sensitivity at medium and high spatial frequencies. A later study by Carney and Lembach (1991), investigated six bilateral keratoconus patients wearing rigid lenses and reported that the CSF was reduced for all spatial frequencies tested. The severity of the CSF loss was not exacerbated by the addition of a glare source. The study concluded that significantly reduced functional visual performance may exist, despite only moderate VA losses. Therefore, in cases of keratoconus with reasonably good Snellen acuity, a reduced CSF is a reliable indicator of visual dysfunction, and may substantiate the patient's complaints, thus documenting the indications for surgical intervention.

8.3 Surgical management of keratoconus

Surgical intervention is required for the visual rehabilitation of contact lens intolerant keratoconus in 10% of cases. The outcome is usually satisfactory, although RGP contact lenses will be needed by around a half of patients (Buckley 1998). Historically, lamellar or penetrating keratoplasty have been the surgical procedures of choice. Penetrating keratoplasty is technically easier than lamellar keratoplasty and it offers a better visual prognosis (Kaufman 1980; Steinert and Wagoner 1988; Goosey et al 1991). However, disadvantages of this surgical procedure include graft failure or immune rejection. Radial keratotomy has also been used in cases of keratoconus (Durand et al 1992). Although numerous improvements have been made to the procedure, there still exist a number of disadvantages (e.g. excessive scarring, unplanned over-and undercorrection, glare and visual fluctuation) (Arrowsmith and Marks 1987; Waring et al 1987). Epikeratophakia avoids some of the technical difficulties associated with lamellar keratoplasty, and the procedure also minimises risk of immune rejection and maintains the host endothelium. When used as an onlay technique to flatten and reinforce the ectatic host cornea, it is referred to as epikeratoplasty (Waring et al 1991). However, the inevitable interface opacities cause a loss of visual function (Buckley 1998).

8.3.1 Effect of surgical intervention on visual performance

A number of researchers have attempted to investigate the consequences of surgical intervention following keratoconus on visual performance (Carney and Kelley 1991; Hovding and Bertelsen 1992; Wicker et al 1992; Khong et al 1993; Parmley et al 1994; Waller et al 1995). Most studies have evaluated subjects following either penetrating keratoplasty, radial keratotomy or epikeratoplasty and used either CS or indirect methods of measuring forward light scatter to assess visual performance.

8.3.1.1 Effect of surgical intervention on glare measurements

Parmley et al (1994) investigated six cases of penetrating keratoplasty that were performed for complications of radial keratotomy in advanced keratoconus. Following radial keratotomy, symptoms of glare were reported in all cases, but quantitative measurements were not taken. The glare caused by the radial keratotomy was thought to be due to subepithelial scarring. Hovding and Bertelsen (1992) investigated 16 patients who had received epikeratoplasty for keratoconus (mean follow up period 27.8 months) and reported a significant improvement of VA, compared to pre-operative measurements. Fourteen of the 16 eyes investigated achieved a corrected VA of at least 6/12. Seven of these patients complained of glare, but unfortunately glare tests were not employed to ascertain the true extent of their symptoms. Waller et al (1995) also found VA to be substantially improved following epikeratoplasty for keratoconus five years after surgery. The mean spectacle acuity improved from 3/30 to 6/9. Again, no glare measurements were taken.

8.3.1.2 Effect of surgical intervention on the contrast sensitivity function

Mannis et al (1987) reported that although optically successful penetrating keratoplasty in patients with bilateral corneal disease tended to improve CS in the operated eye, CS curves were abnormal compared to those of normal subjects (except at 0.5 cpd). Wicker et al (1992) have shown that the amount of CS loss following penetrating keratoplasty for keratoconus is dependant upon the patient's optical correction. Seven subjects were evaluated and the time lapse between testing and surgery was 8 - 160 months. CS was significantly higher for middle and high spatial frequencies in patients wearing RGP lenses than spectacle wearers, even when the Snellen acuity was identical for both forms of correction. The CS losses observed were associated with subjective assessments of poor vision. The study suggested that CS losses were produced by mild irregularities in graft contour.

Khong et al (1993), employed VA, CS and computerised topographical analysis of the cornea to investigate eight keratoconic patients who had undergone penetrating keratoplasty. Data were collected pre-operatively and at one week, one month, two months, three months and six months post-operatively. The CSF was initially depressed post-operatively, but improved to well above pre-operative values by one month. The CSF continued to show gradual improvement at six months which paralleled the improvement in the surface indices and VA. The type of optical correction worn by the subjects was not stated. The study suggested that topographical analysis provided a good indication of the rate and optical stabilisation of corneal healing following penetrating keratoplasty.

Carney and Kelley (1991), tested CSF with and without a glare source, in an attempt to compare the beneficial effects of radial keratotomy following advanced keratoconus (33 months post surgery) with patients who had undergone epikeratoplasty for myopia (28 months post surgery) and bilateral keratoconic (wearing RGP lenses) patients prior to surgery. Seven patients were tested in each group and each revealed CS loss at the medium spatial frequencies (4 and 12 cpd). Compared with control groups, the epikeratoplasty and keratoconic patients had statistically significant CS losses. Radial keratotomy patients exhibited less reduction in CS compared to the other patient groups, a finding that is in agreement with Carney and Lembach (1991).

8.4 Other corneal abnormalities

Hess and Carney (1979) suggested that corneal abnormalities may be considered in terms of one or more basic causes of visual degradation, despite the fact that such abnormalities are highly diverse in appearance and pathophysiological basis. One such classification might include the distinction between the visual effects resulting from corneal distortion and corneal scattering. Certain conditions will clearly involve an interaction between both of these extreme components of degradation (i.e. in the case of corneal scarring) (Hess and Carney 1979). As a result, conditions affecting the cornea are difficult to classify. For brevity, only those conditions which have direct relevance to the subjects tested in the present study (corneal dystrophies and corneal guttatae) will be discussed presently.

8.4.1 Corneal dystrophies

Most corneal dystrophies are bilateral inherited abnormalities, which tend to develop slowly from early life onwards. Corneal dystrophies may affect the anterior limiting membrane, Bowman's layer, the stroma, and/or the posterior limiting membrane, and the effect on visual function will vary according to the extent and nature of the dystrophy.

8.4.2 Corneal guttatae

Corneal guttatae are associated with a number of degenerative corneal diseases, dystrophies and inflammations. They may also be seen as a secondary condition in keratoconus, iritis, anterior chamber haemorrhage, and deep corneal inflammation. Corneal guttatae are often the primary cause of graft failure (Christopoulos and Garner 1996).

Corneal guttatae specifically affect the endothelium of the cornea and they are defined as focal excrescences of altered basement membrane material that consist of accumulations of collagen (Adamis et al 1996). The guttatae are noted in the zone of specular reflection as round, dark areas located in the normal endothelial mosaic. Most often noted in women over sixty years of age, the condition may be stable for long periods, however, continued deterioration results in impairment of the metabolic pump action of the endothelium, resulting in epithelial dystrophy. Whilst stable, the corneal guttatae may not result in decreased VA, but accumulation of melanin pigment on the endothelium, which is often associated with this condition, will lead to a reduction in VA.

The severity of guttatae is not evenly distributed throughout the cornea (Bluthner et al 1996). In more advanced cases, the guttatae have a 'beaten metal' appearance, and the endothelial cells overlying the area are attenuated. As a consequence, the abnormal endothelium exhibits cells of different size and shape, and loss of regular definitions.

8.4.3 Effect of corneal abnormalities on visual performance

Unfortunately, few studies have investigated the affect of corneal irregularities on visual function, as it is logical that corneal opacities will result in degraded visual performance. Studies that have investigated subjects with corneal irregularities have reported either an increase in light scatter (van den Berg 1986), or a reduction in the CSF (Hess and Carney 1979), compared to normal subjects.

8.4.4 Effect of corneal abnormalities on measures of forward light scatter

van den Berg (1986) used the direct compensation technique in conjunction with CS testing, to investigate seven patients with various types of corneal dystrophy. All subjects revealed increased levels of light scatter, when compared to normals. One subject suffering from a crystalline corneal dystrophy revealed a 20-fold increase in scattered light with only moderate VA loss (0.8 - 6/7.5). The CS loss amounted to a factor of 10 compared to normal subjects.

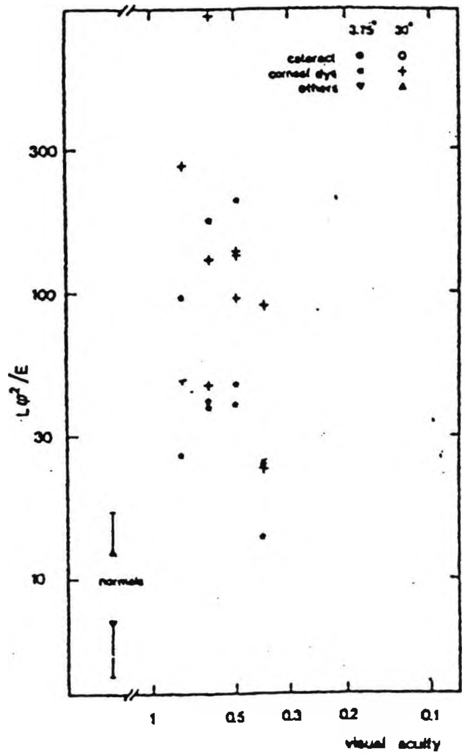


Figure 8.1 - Relation between decimal acuity (horizontally) and strength of the light scatter (vertically) over 3.75 and 30 degrees. Data are plotted for 10 corneal dystrophic eyes. Not all eyes were measured at 3.75 degrees scatter distance (van den Berg 1986).

8.4.5 Effect of corneal abnormalities on the contrast sensitivity function

Hess and Carney (1979) examined the relationship between visual loss from induced corneal distortion (three subjects wore a tight-fitting haptic lens over which 100% oxygen was passed), induced corneal oedema (three subjects wore a sealed, tightly fitting haptic lens filled with distilled water) and corneal pathology (two subjects) using Landolt C targets and CS testing (computer generated). The results of induced corneal distortion (no appreciable CT change but irregular topography change) revealed that contrast thresholds were affected only for a limited band of medium to high frequencies. Induced corneal oedema (marked CT change, but with minor distortion) produced depression of contrast thresholds for low as well as high frequency gratings. To support the findings of induced corneal abnormalities, the same study investigated two subjects with corneal pathology. One subject had unilateral epithelial pitting, whilst the other suffered from a bilateral corneal dystrophy. Each patient exhibited a contrast loss only for high to medium spatial frequencies, mimicking corneal distortion. This was not predictable on the basis of the experimentally-induced corneal distortion and oedema results, however, this may have been due to the small number of subjects investigated. The study illustrates the importance of individually assessing the nature of CS loss for diverse types of visual disturbance.

8.5 Summary of introduction

Patients with keratoconus suffer:-

- degraded visual performance when compared to normal subjects, and patient-reported effects of glare correlate with corneal scarring (Edrington et al 1999).
- attenuation of CS with relative sparing of low spatial frequencies, despite normal Snellen acuity (Mannis et al 1984; Zadnik et al 1987). However, once scarring occurs, low spatial frequencies also become attenuated (Hess and Carney 1979).
- loss at all spatial frequencies (Carney 1982a, b; Carney and Lembach 1991).

Consequently, CS testing at a number of spatial frequencies is a useful method of following the progression of keratoconus, although, as discussed in section 3.5, the test is often subject to other influences (e.g. neuronal interactions). The direct measurement of forward light scatter used in this study is independent of neuronal interactions and may provide an explanation for the poor visual function of keratoconics as measured by CS.

Surgical intervention for keratoconus may also have a detrimental affect on visual performance, with glare problems and CS losses often reported following penetrating keratoplasty, radial keratotomy and epikeratoplasty (Carney and Kelley 1991; Hovding and Bertelsen 1992; Wicker et al 1992; Khong et al 1993; Parmley et al 1994; Waller et al 1995).

The effect of corneal abnormalities on visual function has not been studied extensively.

- Hess and Carney (1979) attempted to define the effect of corneal abnormalities by inducing corneal oedema and distortion and investigating the affect of these on the CSF. Corneal oedema was shown to reduce performance at all spatial frequencies whilst corneal distortion only affected a limited band of medium to high frequencies.
- van den Berg (1986) later showed a large increase in light scatter for a subject with a crystalline corneal dystrophy compared to normal subjects.

These studies have demonstrated that as corneal problems vary in location and severity, the measurement of forward light scatter is an important tool in evaluating the cause of reduced visual function in such cases.

It is clear that the majority of previous work investigating the effect of corneal abnormalities has generally concentrated on measures of CS. The P_SCAN 100 scatter apparatus was used in the present study investigating corneal abnormalities in order to obtain a measure of the full forward scatter function. A further level of investigation is introduced in the current study by recording the extent of backscatter (grading of the condition as seen with the slit lamp biomicroscope) caused by keratoconus, in order to allow a comparison to be made between forward light scatter and backward light scatter. To summarise, the availability of a researcher who could devote the long periods of time required to collect and analyse the data generated by the P_SCAN 100 scatter apparatus has allowed the current study to:-

- obtain a direct measure of forward light scatter
- measure k', in addition to n and k
- compare measurements of scatter and the CSF over a wide range of spatial frequencies
- compare measurements of backscatter and forward scatter in cases of keratoconus.

8.6 Aims

One of the principal aims of the thesis is to investigate the light scattering characteristics of contact lens wearers, in an attempt to elucidate whether corneal changes occur following long term wear. In order to assess the extent of any changes that may occur in response to lens wear, it is useful for comparison purposes to determine the amount of forward light scatter caused by pathological corneal opacitites/changes. Therefore, the aim of the studies described in Chapter Eight was to investigate the effect of corneal abnormalities on measures of light scatter.

8.7 Subjects

Subjects were recruited from the City University Eye Clinic, or were referred by the External Eye Disease Department at Moorfields Eye Hospital. Wherever possible, male subjects were chosen due to the increased variability noted in female subjects in Chapter 6 and 7. However, in order to complete the data set, four females were included but all were above the age of 40 years. As females are known to have reduced levels of oestrogen during middle age, the results from these five subjects are unlikely to be as variable as those found in younger females in Chapter 7. The keratoconic patients were examined using the slit lamp biomicroscope and graded according to the severity of the condition. Although corneal topographical measurements would have provided greater information regarding the severity of keratoconus, lack of instrumentation precluded such measures. As discussed in section 8.2, any one or a combination of the clinical findings can be observed, depending on the stage of progression of the disease. Depending on the severity of the clinical observations, the subjects were classified as:-

Table 8.2 - Table to show the grading scheme employed to classify subjects with keratoconus.

Grading	Slit-lamp biomicroscopy signs
Grade 1	Increased visibility of corneal nerves Distortion of keratometry mires Scissoring on retinoscopy
Grade 2	Vogt's striae Fleischer ring Bowing of cornea+-++ Central / paracentral scarring+
Grade 3	Vogt's striae Fleischer ring Bowing of cornea++-+++ Central / paracentral scarring ++-+++

As the clinical signs of Grade 1 keratoconus do not necessarily constitute a clear diagnosis of the disease, only keratoconics with a grading of at least 2 were included in the study. In total, eleven subjects with keratoconus (eighteen eyes), three subjects who had received penetrating keratoplasties (three eyes), (of which one was also examined pre-operatively), one subject who had received Excimer laser treatment and a superficial keratectomy for keratoconus (one eye), one subject who had received an epikeratophakia for keratoconus (one eye) and three subjects with corneal abnormalities (six eyes) were examined.

8.8 Methods

Before inclusion in the study, the subject's VA, corneal integrity and fundus health were examined to exclude other pathologies. All subjects wore their best refractive correction and had been examined recently either in the City University Clinic or at Moorfields Eye Hospital. Measurements were taken in the afternoon to avoid variability caused by the effects of overnight sleep (as discussed in section 6.13). Both eyes were examined, if VA permitted, and the subjects were asked about their perceived visual disability. Results were excluded if other pathology was detected, or the VA was too low to complete the investigation. In addition, each subject's lens was graded using LOCS II in order to exclude cataract. All subjects underwent scatter and CS testing following the methods described in section 5.7.

8.9 Results

Tables 8.3, 8.4, 8.5, 8.6 and 8.7 show the mean values of n, k and k' (as defined in chapter one) in subjects with varying ocular pathology. The k'-$k'(age)$ value was obtained by subtracting the age-matched k' values from the value obtained from the subject with ocular abnormality. The mean value from three experimental runs was then calculated. Subjects reporting symptoms of glare are indicated by * in the tables.

8.9.1 Results for keratoconic subjects

Table 8.3 - Scatter results from 11 keratoconics [Grade 2 (moderate), and 3 (advanced)].

Subject	Gender	Age (years)	Eye	n	k	k'	k'-$k'(age)$	s.d.	Grading
NT*	Male	46	RE	1.42	31.99	54.68	45.48	2.34	3
			LE	1.63	44.19	41.25	32.05	4.90	3
SH*	Female	43	RE	1.72	52.81	41.03	32.57	0.58	2
			LE	1.69	50.10	43.86	35.40	3.46	3
DA*	Male	19	RE	2.02	45.99	20.97	14.46	1.98	2
			LE	2.80	289.95	38.63	32.12	0.73	3
GE*	Male	47	RE	1.69	35.31	32.74	23.25	4.90	3
AF*	Male	42	LE	1.64	30.78	28.15	19.88	5.37	3
BB*	Male	45	RE	2.20	73.46	23.79	14.86	4.41	3
			LE	1.82	44.77	28.48	19.55	1.09	3
ML*	Male	45	RE	2.23	51.03	19.79	10.86	1.03	2
			LE	1.62	20.73	15.96	7.03	2.41	3
GO*	Male	33	LE	2.07	38.53	15.09	7.97	0.85	2
MP*	Male	29	RE	1.79	16.23	11.03	4.17	1.02	3
MR*	Male	30	RE	2.52	31.79	9.65	2.74	0.63	2
			LE	2.42	67.06	15.24	8.33	0.64	3
AD*	Male	25	RE	2.09	25.80	10.07	3.39	1.04	2
			LE	1.88	16.34	8.81	2.13	0.42	2

** Subject reporting symptoms of glare*

Subject NT reveals the greatest increase in light scatter, when compared with age-matched normals in this group of keratoconic patients. The right eye shows a greater increase in scatter (k' = 54.68) than the left (k' = 41.25), compared to an age-matched normal (k' = 9.20). Figure 8.2a, b shows the angular distribution of scattered light for this keratoconic subject who obtained VAs of 6/9. Due to the low n values obtained in the right eye (1.42), the light scatter has a wider angular distribution than the left (1.63). In both eyes, the CSF is reduced at all spatial frequencies (figure 8.2c, d).

Subject SH shows high levels of scatter in both eyes, compared to age-matched normals. The greatest increase in light scatter is seen for the left eye which also demonstrates a greater reduction in the CSF (figure 8.3a, b, c, d). Due to the low n values obtained (1.72 and 1.69, respectively), both eyes reveal a wide angular distribution of light scatter. The VA for this eye is slightly better than the right eye (6/9 compared to 6/12-1).

Subject DA exhibits increased levels of light scatter in both eyes compared to age-matched normals (6.51), with the left eye showing particularly increased levels of scattered light (38.63), compared to the right eye (20.97) (figure 8.4a, b). Due to the high n values obtained in the left eye (2.80), most of the scatter is close to the fovea and hence is less spread than the right eye (2.02). The level of forward light scatter found in both eyes is accompanied by a reduced CS at all spatial frequencies (figure 8.4c, d) and a reduction in the level of acuity. A greater reduction in VA and a greater loss of CS is observed in the left eye, compared with the right eye.

The right eye of subject GE shows high levels of scatter (k' = 32.74) compared to age-matched normals (k' = 9.49). The CSF reveals loss at all spatial frequencies, which is accompanied by a VA of 6/9+1 (figure 8.5a, b, c, d). No data were recorded for the left eye, due to the subject's low VA (3/60). The left eye of subject AF exhibits a similar increase in light scatter (28.15), compared to age-matched normals (8.27). Again, this is accompanied by a loss of CSF at all spatial frequencies and a VA of 6/9 (figure 8.6b, d). The right eye, which has received a penetrating keratoplasty, is discussed in section 8.9.2.

Subject BB reveals increased light scatter in both eyes, with the left eye showing the greatest increase (k' = 28.48). The right eye reveals higher n values (2.20) than the left

(1.82), which indicates that the light scatter in the right eye has a narrower distribution of scattered light than the left. This is reflected in figure 8.7a, b. This is accompanied by a loss of CS at all spatial frequencies and a reduced level of VA (figure 8.7c, d).

The right eye of subject ML reveals a greater increase in light scatter compared to age-matched normals than the left eye. The right eye reveals higher *n* values (2.23) than the left (1.62), which indicates that this eye has a narrower distribution of scattered light. This is reflected in figure 8.8a, b. A similar CS loss is observed in both eyes but the right eye shows a greater reduction in VA (figure 8.8c, d).

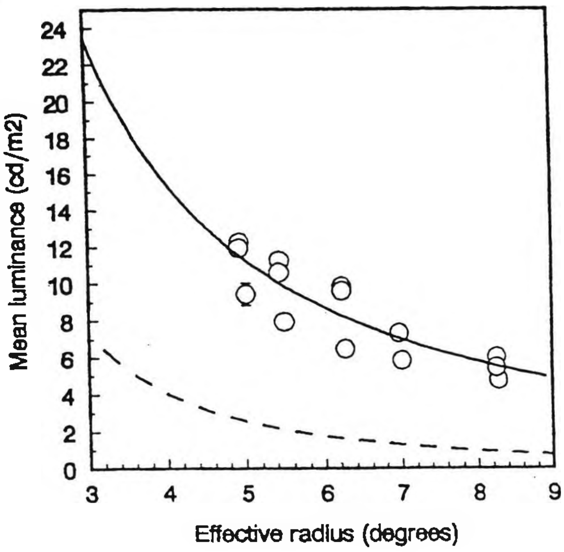
Testing subject GO reveals high levels of scatter in the left eye compared to age-matched normals (15.09 compared to 7.12). The CSF is reduced at all spatial frequencies compared to age-matched normals (figure 8.9b, d) and the eye has a VA of 6/18-2. The results obtained from the right eye are discussed in section 8.9.3, as this eye has received a penetrating keratoplasty following advanced keratoconus.

The right eye of subject MP reveals an increase in light scatter ($k'-k'(age)$ = 4.17) and a reduction in CS across all spatial frequencies (figure 8.10a, c) compared to age-matched normals. The left eye, which has received a penetrating keratoplasty following advanced keratoconus is discussed in section 8.9.2.

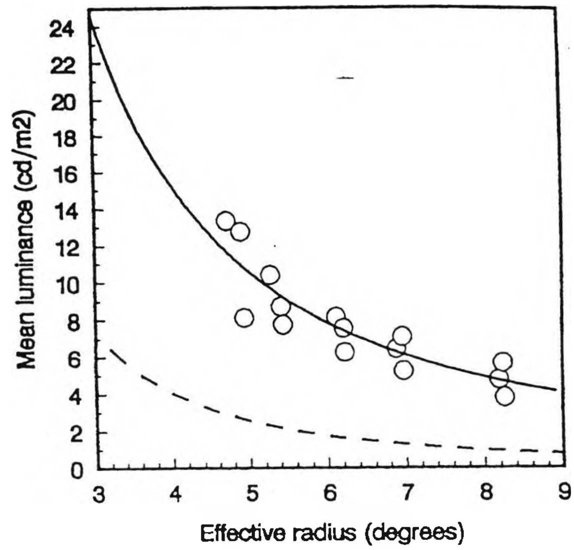
Subject MR reveals a modest (2.74) increase in scatter in the right eye and a greater (8.33) loss in the left, which is accompanied by a reduction in CS across all spatial frequencies in the left eye, with reductions at most spatial frequencies in the right eye (figure 8.11a, b, c, d). Both eyes reveal high *n* values, (2.52 and 2.42, respectively), which indicates that the light scatter has a narrow angular distribution.

The eyes of subject AD exhibit a modest increase in light scatter when compared to age-matched normals. The CSF is reduced across all spatial frequencies compared to normal subjects, which is consistent with this subject's VA (6/9 in both eyes) (figure 8.12a, b, c, d).

Figure 8.2 *Scatter profile and contrast sensitivity results for Subject NT*

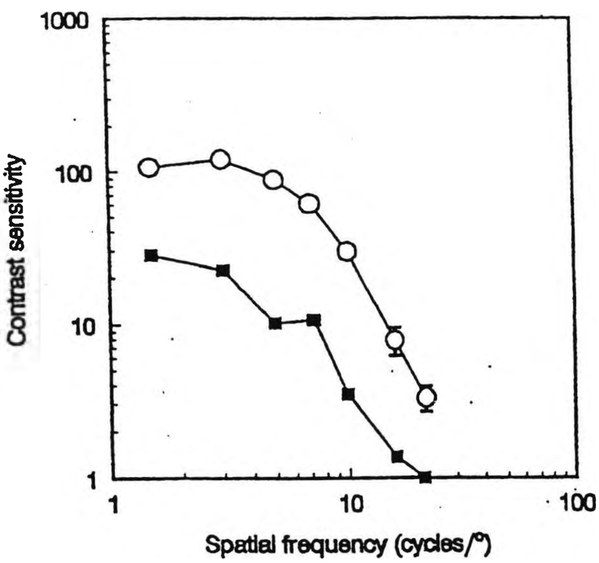


(a) Right eye scatter (O)

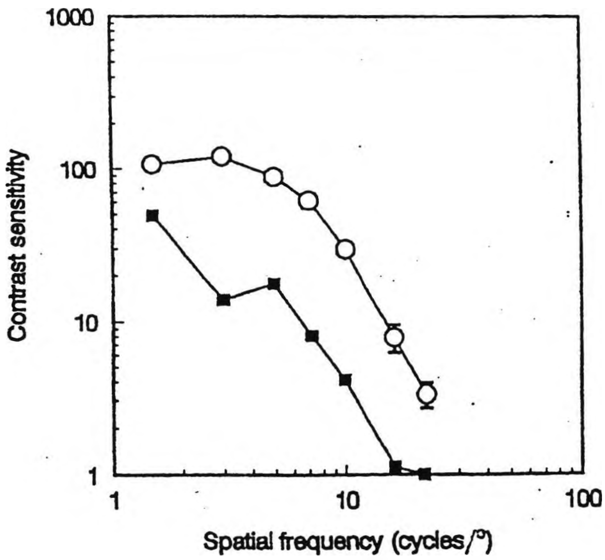


(b) Left eye scatter (O)

(- - - Age-matched normal scatter values)



(c) Right eye contrast sensitivity (■)

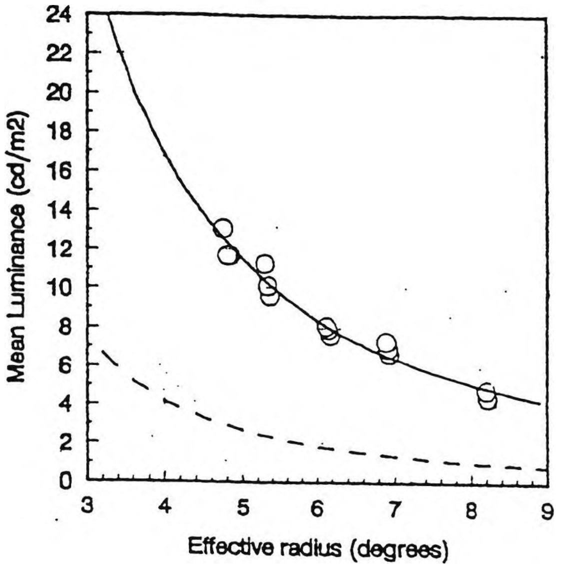


(d) Left eye contrast sensitivity (■)

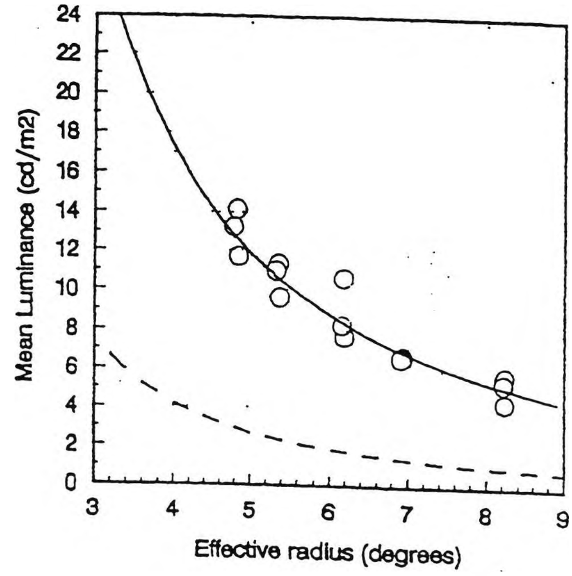
(O Age-matched normal contrast sensitivity values)

Subject NT (keratoconus), male, Asian, 46 years.		
	Right eye	Left eye
Visual acuity	6/9	6/9
Type of contact lens worn	PMMA	PMMA
Length of contact lens wear	25 years	25 years
External eye	Vogt's striae; paracentral scarring++	Vogt's striae; paracentral scarring++

Figure 8.3 *Scatter profile and contrast sensitivity results for Subject SH*

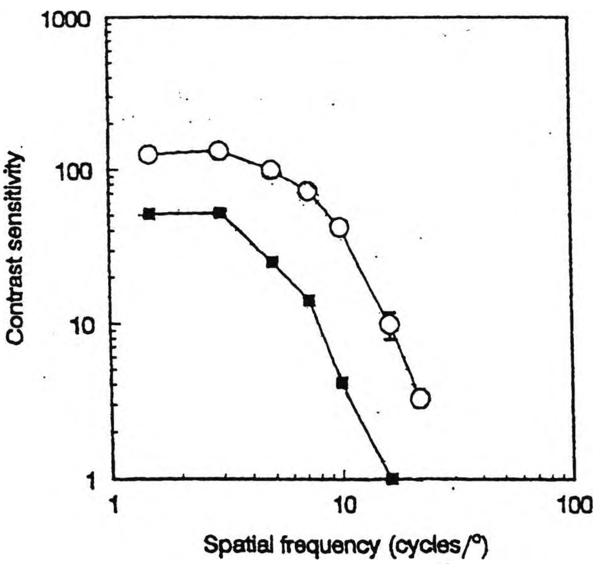


(a) Right eye scatter (O)

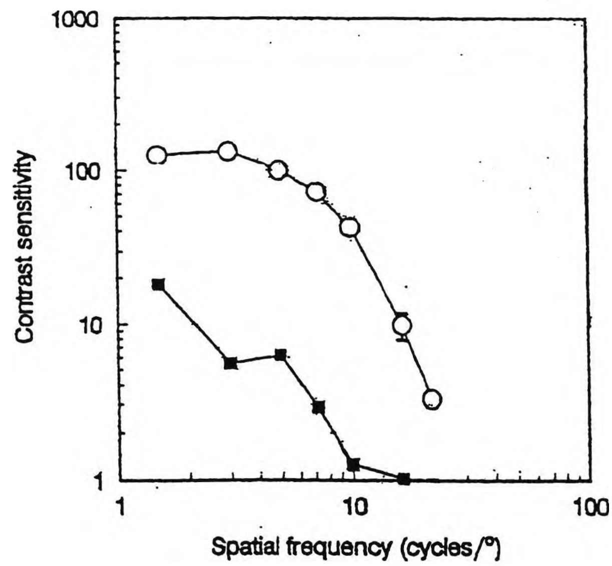


(b) Left eye scatter (O)

(- - - Age-matched normal scatter values)



(c) Right eye contrast sensitivity (■)

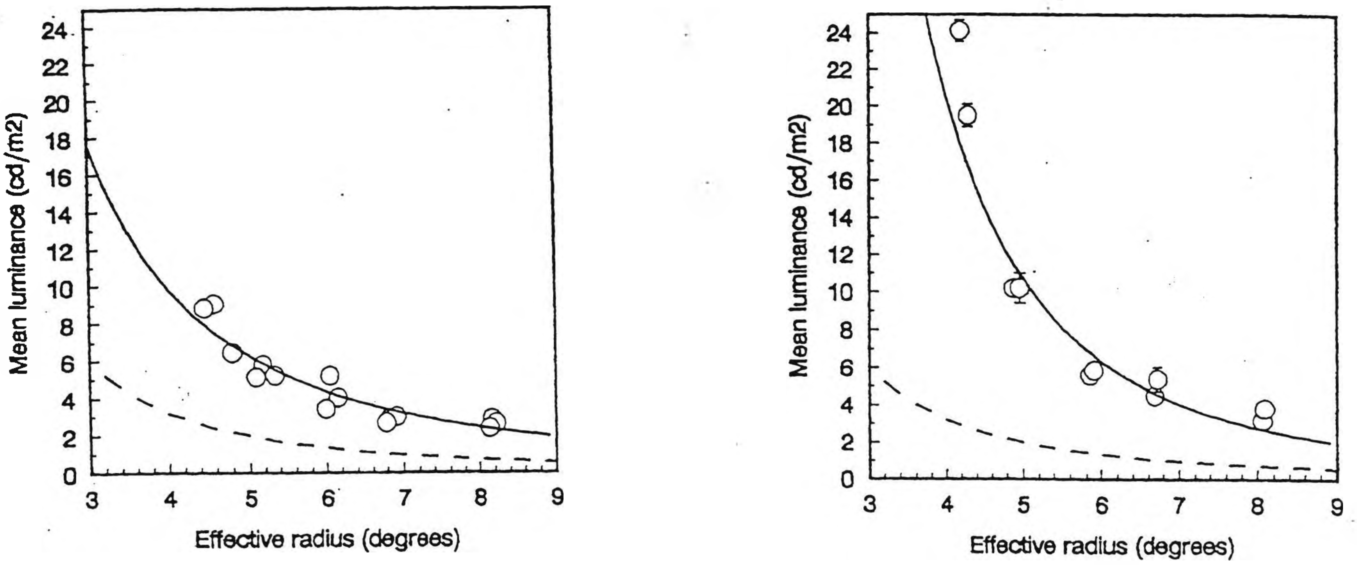


(d) Left eye contrast sensitivity (■)

(O Age-matched normal contrast sensitivity values)

Subject SH (keratoconus), female, Caucasian, 43 years.		
	Right eye	Left eye
Visual acuity	6/12-1	6/9
Type of contact lens worn	Hydrogel/RGP	Hydrogel/RGP
Length of contact lens wear	8/8 years	8/8 years
External eye	Vogt's striae; Bowing of cornea+; scarring+	Vogt's striae: Bowing of cornea++; scarring+++

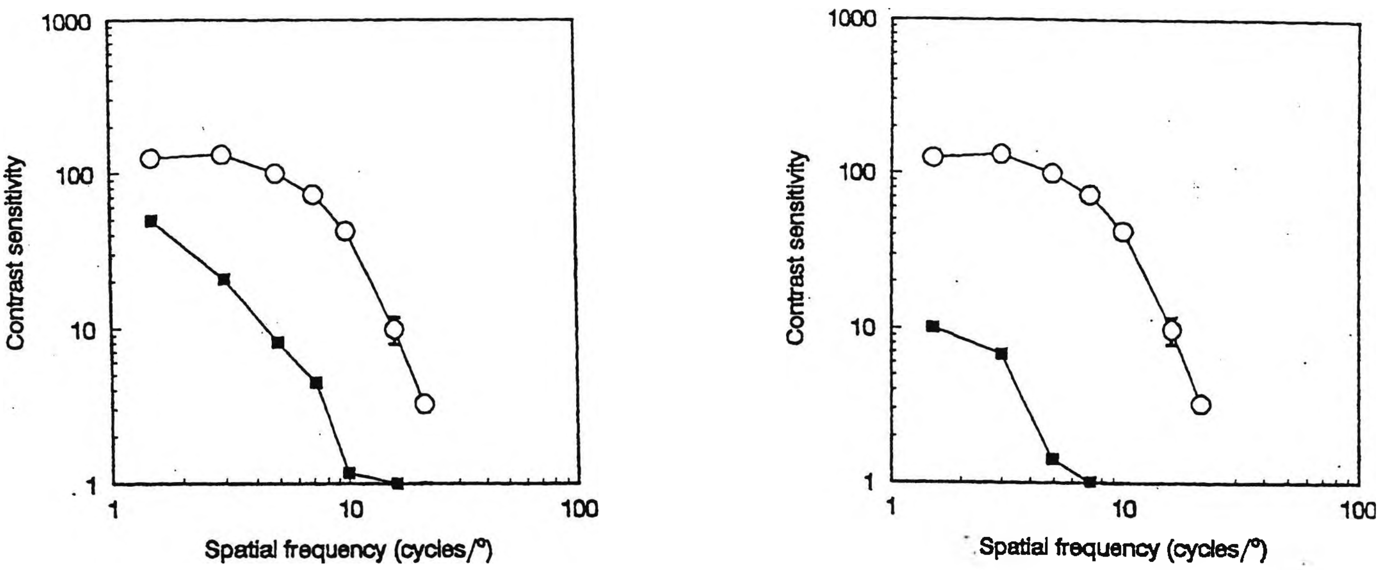
Figure 8.4 *Scatter profile and contrast sensitivity results for Subject DA*



(a) Right eye scatter (O)

(b) Left eye scatter (O)

(- - - Age-matched normal scatter values)



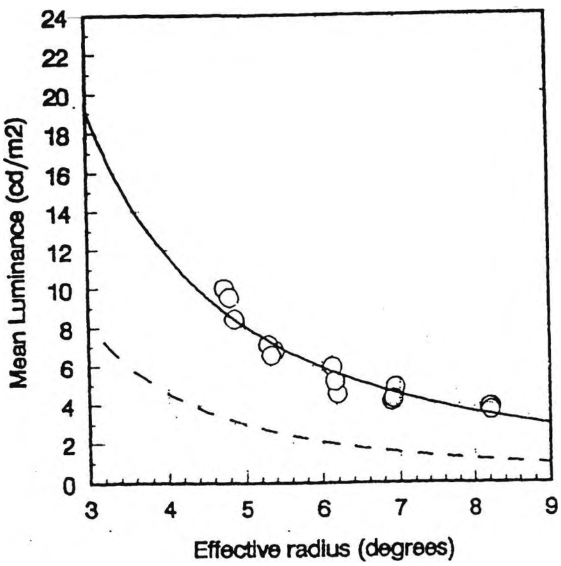
(c) Right eye contrast sensitivity (■)

(d) Left eye contrast sensitivity (■)

(O Age-matched normal contrast sensitivity values)

Subject DA (keratoconus), male, Caucasian, 19 years.		
	Right eye	Left eye
Visual acuity	6/9	6/36
Type of contact lens worn	RGP	RGP
Length of contact lens wear	5 years	5 years
External eye	Vogt's striae; Bowing of cornea+	Partial Fleischer ring; Bowing of cornea+++

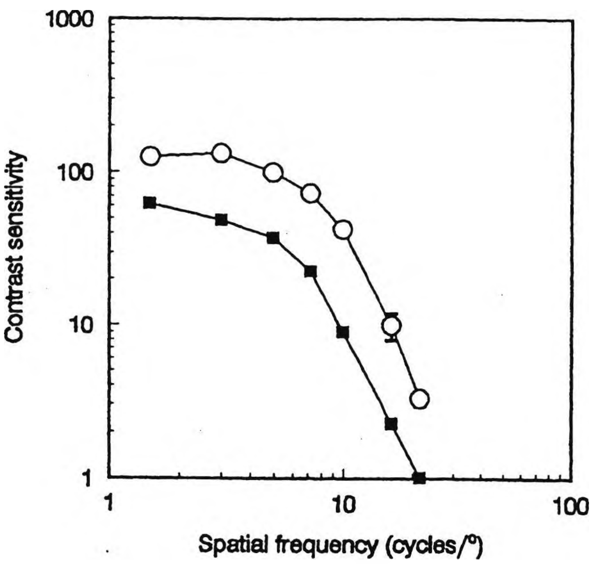
Figure 8.5 *Scatter profile and contrast sensitivity results for Subject GE*



(a) Right eye scatter (O)

(b) Left eye scatter (O)

(- - - Age-matched normal scatter values)



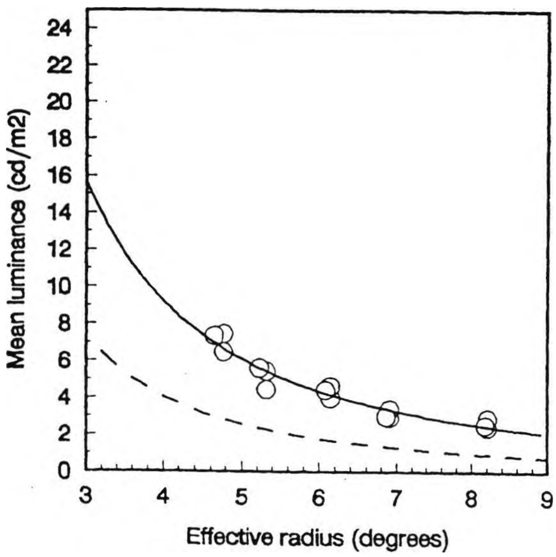
(c) Right eye contrast sensitivity (■)

(d) Left eye contrast sensitivity (■)

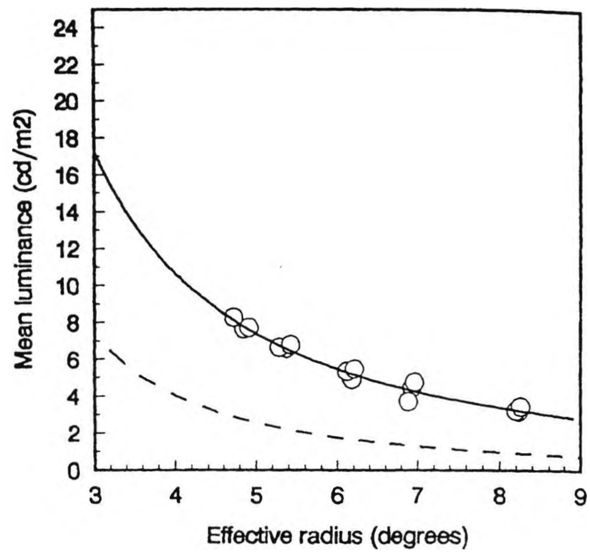
(O Age-matched normal contrast sensitivity values)

Subject GE (keratoconus), male, Caucasian, 47 years.		
	Right eye	Left eye
Visual acuity	6/9+1	-
Type of contact lens worn	PMMA/RGP	-
Length of contact lens wear	1/21 years	-
External eye	Vogt's striae; paracentral scarring+++	

Figure 8.6 *Scatter profile and contrast sensitivity results for Subject AF*

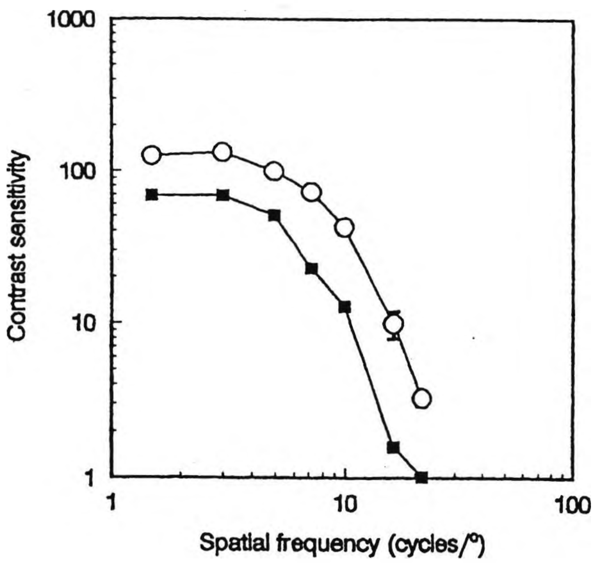


(a) Right eye scatter (O)

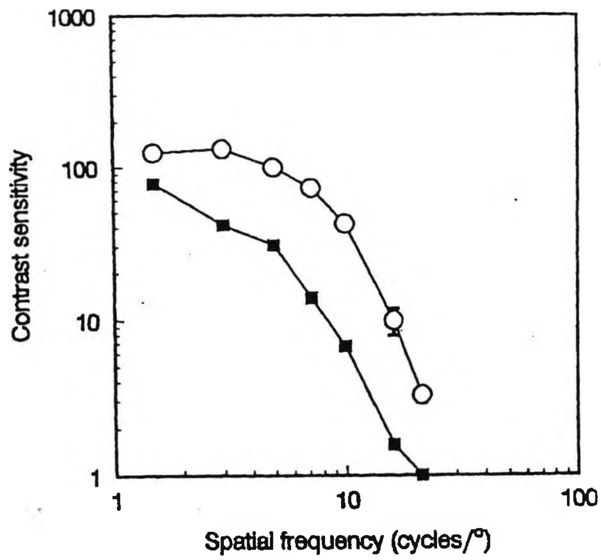


(b) Left eye scatter (O)

(- - - Age-matched normal scatter values)



(c) Right eye contrast sensitivity (■)

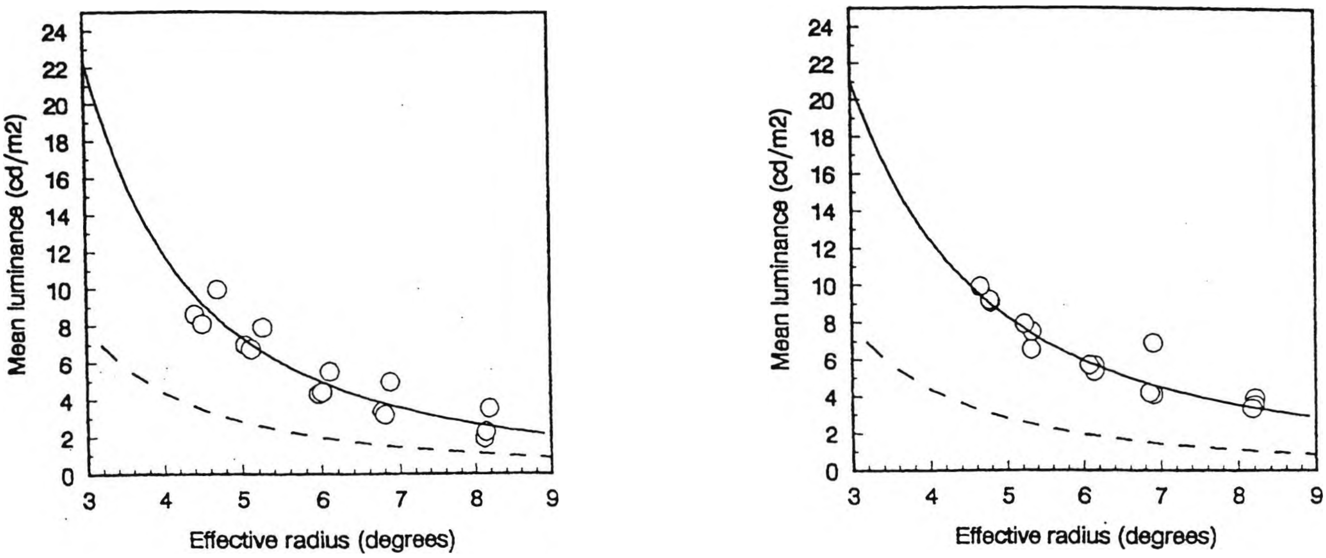


(d) Left eye contrast sensitivity (■)

(O Age-matched normal contrast sensitivity values)

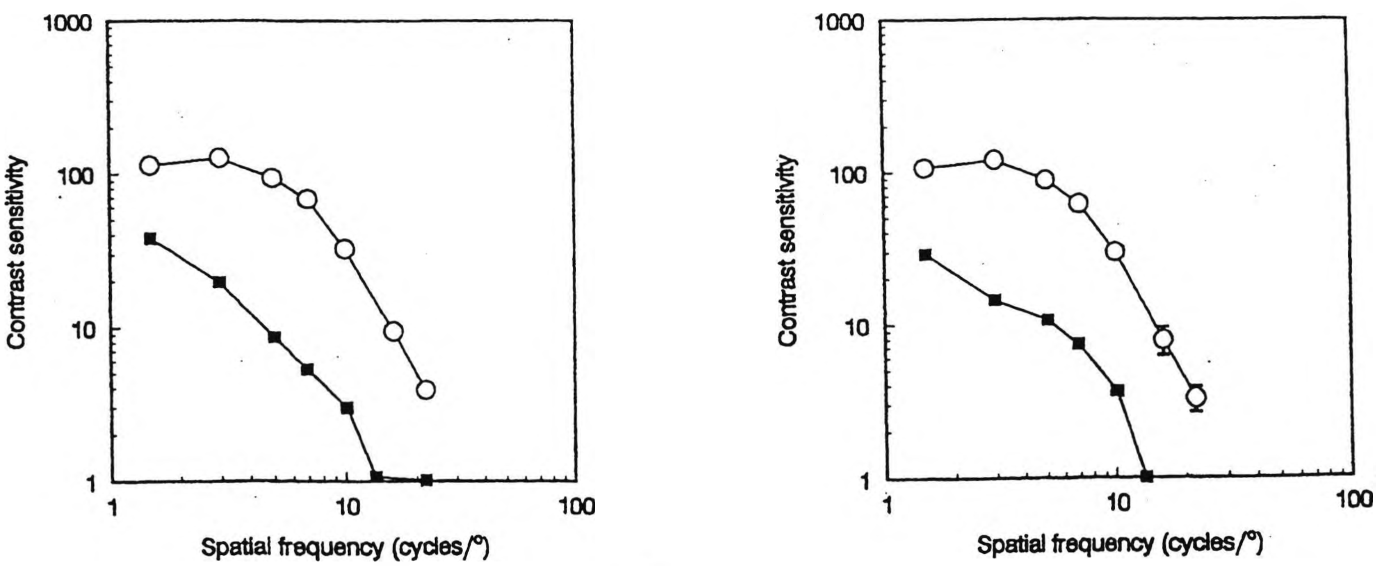
Subject AF (keratoconus, R penetrating keratoplasty), male, Caucasian, 42 years.		
	Right eye	Left eye
Visual acuity	6/9	6/9
Type of contact lens worn	RGP	RGP
Length of contact lens wear	2 years	2 years
External eye	Opaque cornea	Vogt's striae; paracentral scarring++

Figure 8.7 *Scatter profile and contrast sensitivity results for Subject BB*



(a) Right eye scatter (O) (b) Left eye scatter (O)

(- - - Age-matched normal scatter values)

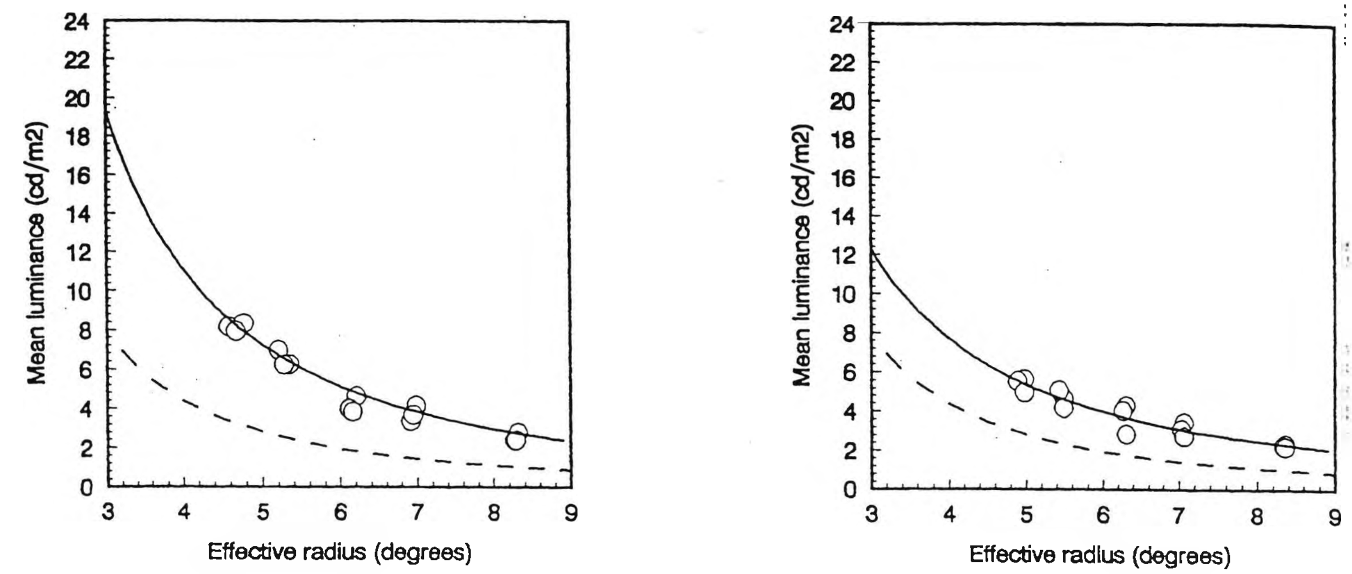


(c) Right eye contrast sensitivity (■) (d) Left eye contrast sensitivity (■)

(O Age-matched normal contrast sensitivity values)

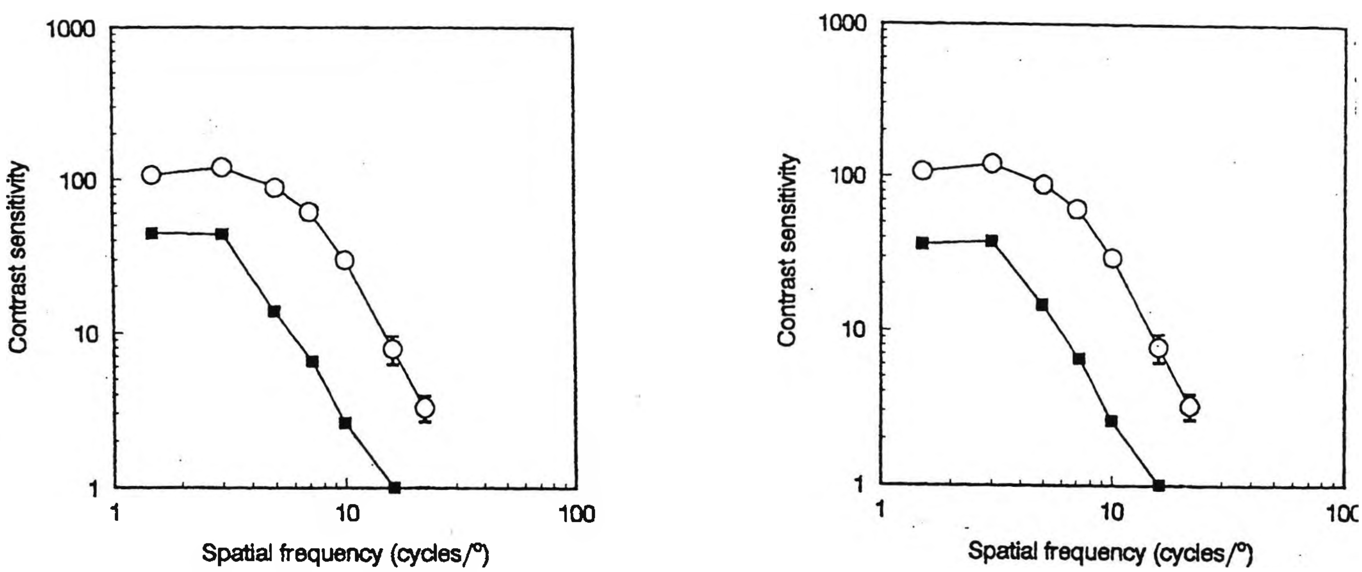
Subject BB (keratoconus), male, Asian, 45 years.		
	Right eye	Left eye
Visual acuity	6/12	6/18
Type of contact lens worn	PMMA/RGP	PMMA/RGP
Length of contact lens wear	10/10 years	10/10 years
External eye	Vogt's striae; Bowing of cornea+; central scarring++	Vogt's striae: Bowing of cornea+; central scarring++

Figure 8.8 *Scatter profile and contrast sensitivity results for Subject ML*



(a) Right eye scatter (O) (b) Left eye scatter (O)

(- - - Age-matched normal scatter values)

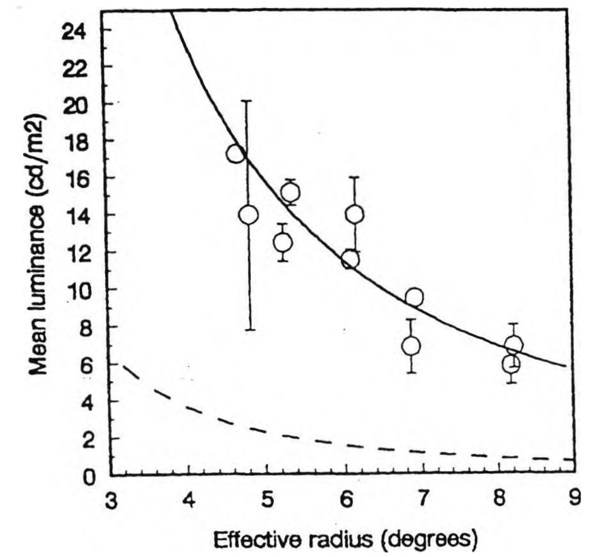


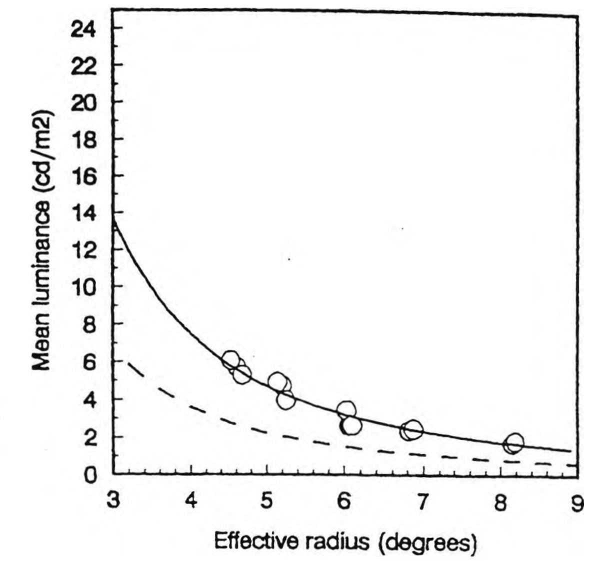
(c) Right eye contrast sensitivity (■) (d) Left eye contrast sensitivity (■)

(O Age-matched normal contrast sensitivity values)

Subject ML (keratoconus), male, Caucasian, 45 years.		
	Right eye	Left eye
Visual acuity	6/12-1	6/9
Type of contact lens worn	RGP	RGP
Length of contact lens wear	10 years	10 years
External eye	Vogt's striae; Bowing of cornea+; Central scarring+	Vogt's striae: Bowing of cornea++; Central scarring+++

Figure 8.9 *Scatter profile and contrast sensitivity results for Subject GO*

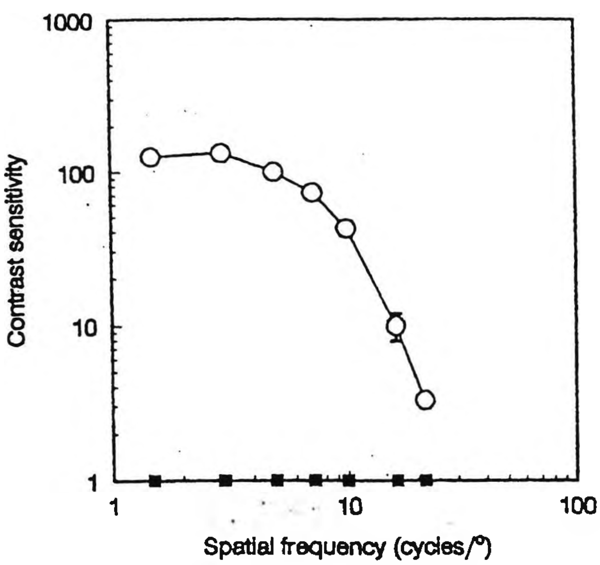


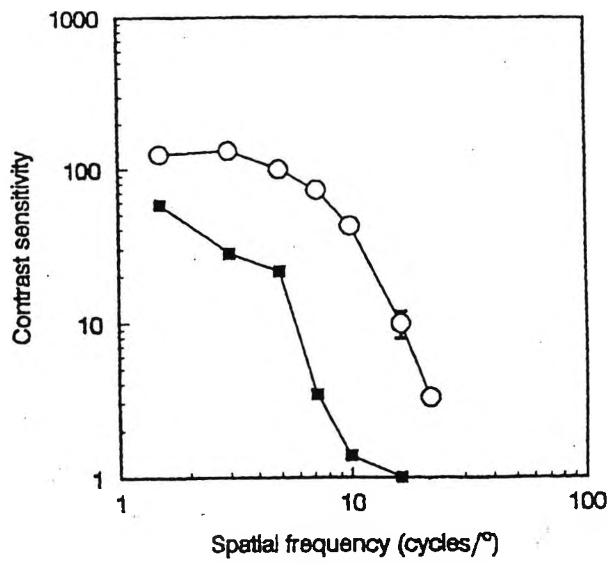


(a) Right eye scatter (O)

(b) Left eye scatter (O)

(- - - Age-matched normal scatter values)





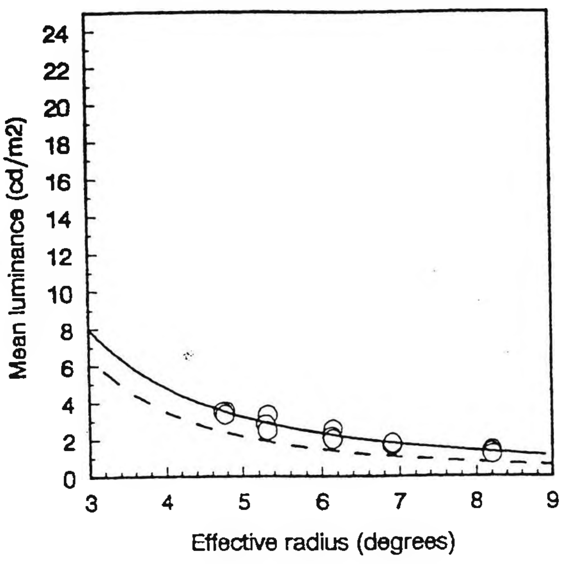
(c) Right eye contrast sensitivity (■)

(d) Left eye contrast sensitivity (■)

(O Age-matched normal contrast sensitivity values)

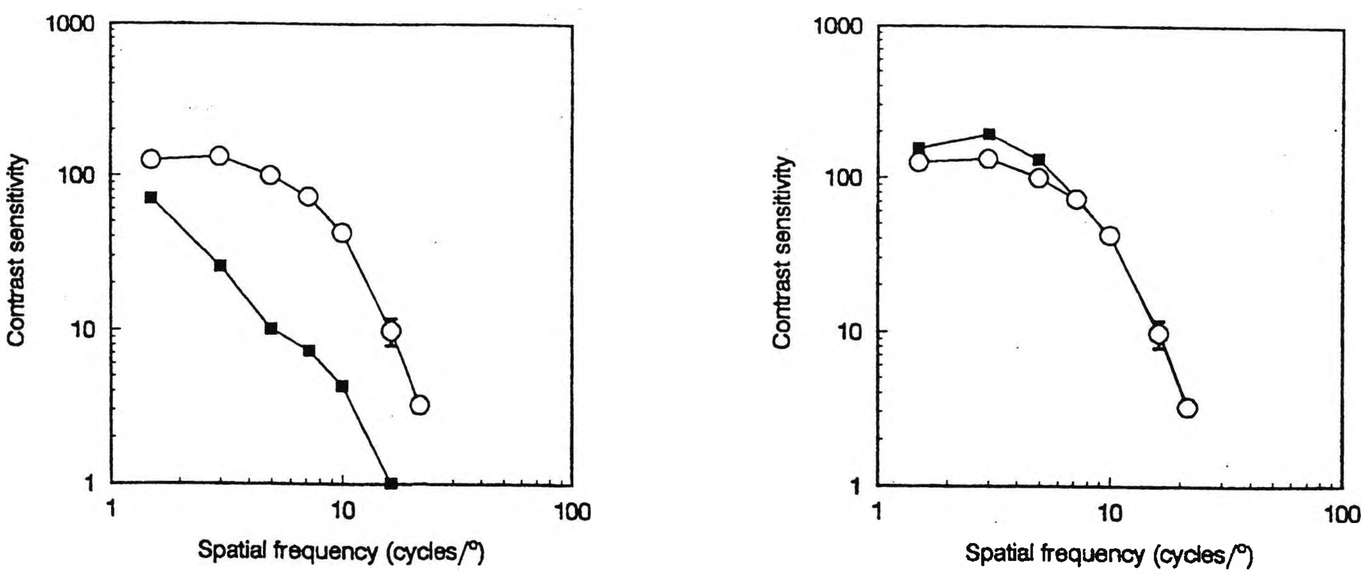
Subject GO (keratoconus, RE Excimer laser, superficial keratectomy), male, Caucasian, 33 years.		
	Right eye	Left eye
Visual acuity	0.5/60	6/18-2
Type of contact lens worn	RGP	RGP
Length of contact lens wear	5 years	5 years
External eye	Central and peripheral scarring++	Vogt's striae; paracentral scarring+

Figure 8.10 Scatter profile and contrast sensitivity results for Subject MP



(a) Right eye scatter (O) (b) Left eye scatter (O)

(- - - Age-matched normal scatter values)

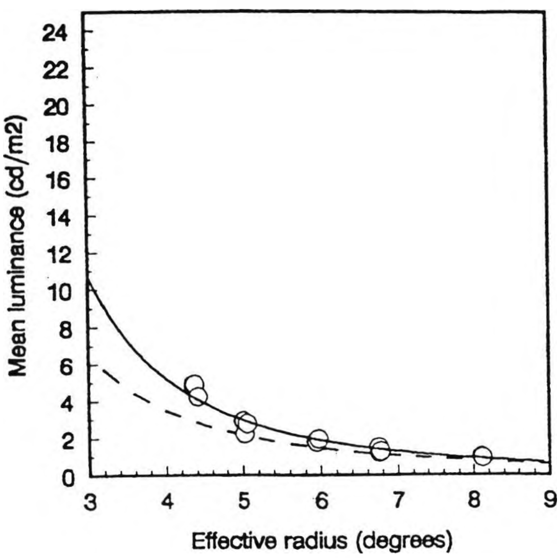


(c) Right eye contrast sensitivity (■) (d) Left eye contrast sensitivity (■)

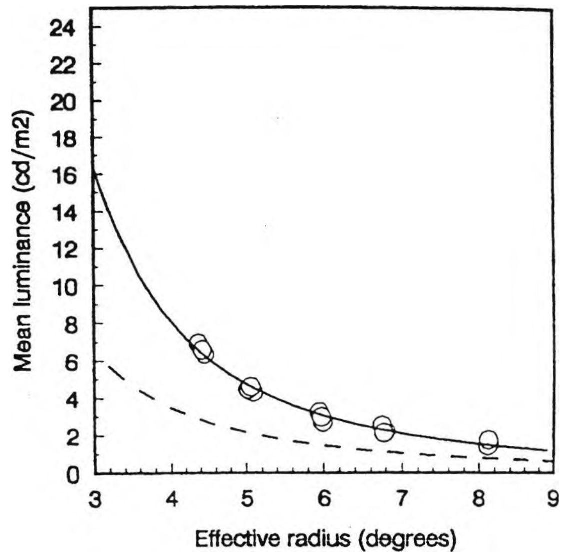
(O Age-matched normal contrast sensitivity values)

Subject MP (keratoconus, LE penetrating keratoplasty), male, Caucasian, 29 years.		
	Right eye	Left eye
Visual acuity	6/9	6/5+1
Type of contact lens worn	RGP	RGP
Length of contact lens wear	14 years	14 years
External eye	Vogt's striae; Fleischer ring; Bowing of cornea+++	Prominent sutures

Figure 8.11 *Scatter profile and contrast sensitivity results for Subject MR*

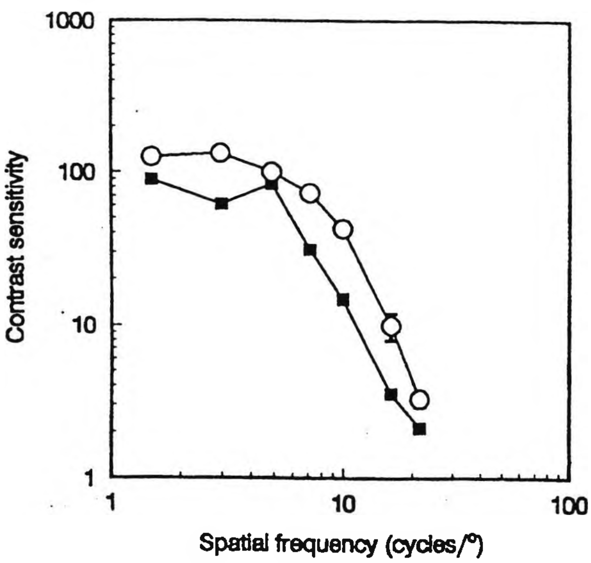


(a) Right eye scatter (O)

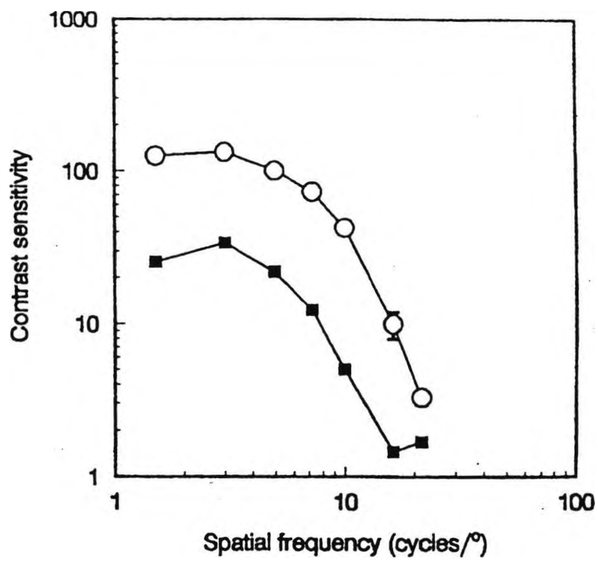


(b) Left eye scatter (O)

(- - - Age-matched normal scatter values)



(c) Right eye contrast sensitivity (■)

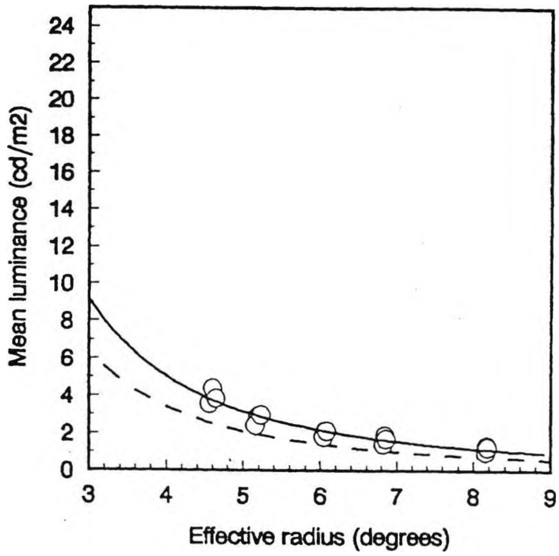


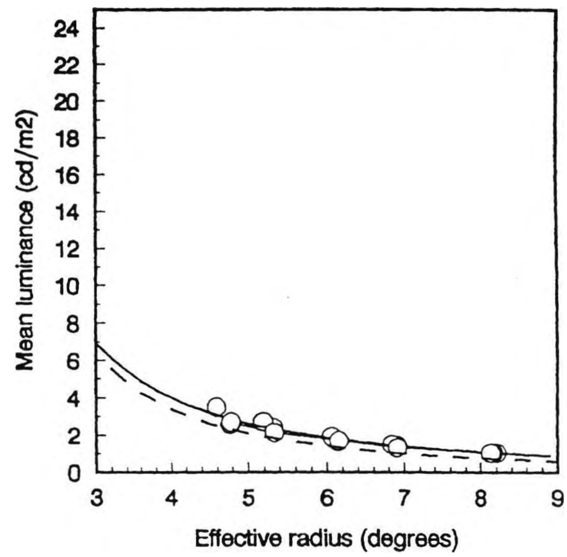
(d) Left eye contrast sensitivity (■)

(O Age-matched normal contrast sensitivity values)

Subject MR (keratoconus), male, Caucasian, 30 years.		
	Right eye	Left eye
Visual acuity	6/9-1	6/12
Type of contact lens worn	-	-
Length of contact lens wear	-	-
External eye	Vogt's striae; Bowing of cornea++	Vogt's striae; Fleischer ring at base of cone; Bowing of cornea +++

Figure 8.12 *Scatter profile and contrast sensitivity results for Subject AD*

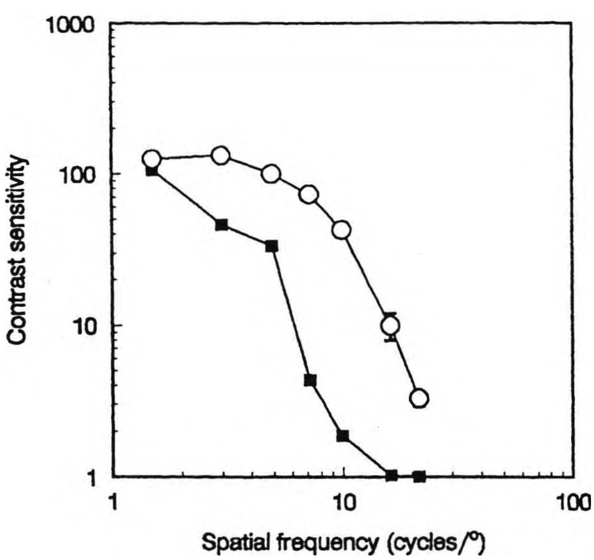


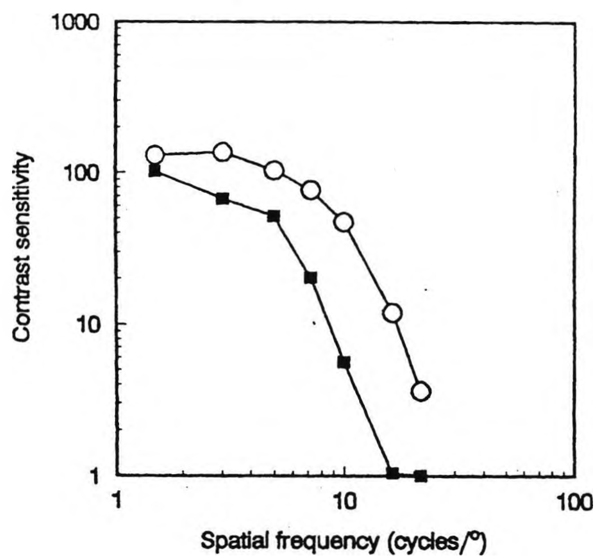


(a) Right eye scatter (O)

(b) Left eye scatter (O)

(- - - Age-matched normal scatter values)





(c) Right eye contrast sensitivity (■)

(d) Left eye contrast sensitivity (■)

(O Age-matched normal contrast sensitivity values)

Subject AD (keratoconus), male, Caucasian, 25 years.		
	Right eye	Left eye
Visual acuity	6/9	6/9
Type of contact lens worn	RGP	RGP
Length of contact lens wear	2 years	2 years
External eye	Vogt's striae; Bowing of cornea++;	Vogt's striae: Bowing of cornea++

8.9.2 Results for subjects having received penetrating keratoplasties following keratoconus

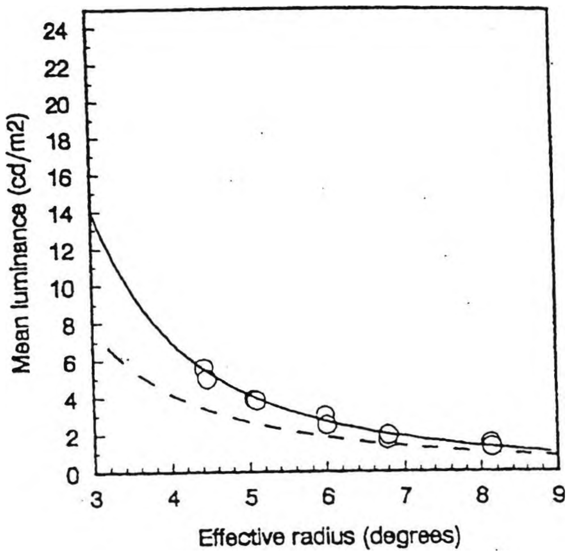
Table 8.4 - Scatter results obtained from three subjects having received penetrating keratoplasties following keratoconus.

Subject		Gender	Age (years)	Eye	*n*	*k*	*k'*	*k'-k' (age)*	s.d.
AF*	Post-op	Male	42	RE	1.84	34.40	22.17	13.90	4.63
CC	Post-op	Female	44	LE	2.35	50.18	13.45	4.76	1.33
MP	Pre-op	Male	25	LE	2.15	88.00	30.90	24.22	-
	Post-op		29	LE	1.67	11.43	10.07	3.21	1.01

** Subject reporting symptoms of glare*
Pre-op = pre-operative results
Post-op = post-operative results

The right eye of subject AF shows increases in light scatter following penetrating keratoplasty, compared to an age-matched normal, which is reflected in the loss of CS across all spatial frequencies (figure 8.6a, c). The results for subject CC reveal an increase in levels of scatter (*k'-k'(age)* = 4.76) and a reduced CSF apart from 22 cpd, compared to age-matched normals (figure 8.13b, d). The right eye was not evaluated as the subject felt that the test was too difficult to complete. This was due to the subject's low VA (3/60). Post-operatively, subject MP reveals a slight increase in light scatter compared to age-matched normals (*k'-k'(age)* = 3.21) and the CSF is within the normal range expected for the subject's age. In fact, the CSF for spatial frequencies of 1.5, 3 and 5 cpd are better than expected for the subject's age of 33 years (figure 8.14b, d). Figure 8.14a, and c show the results obtained from investigating the same eye three years previously. Although only one scatter run and a limited number of spatial frequencies were tested, it is clear that penetrating keratoplasty has resulted in a marked reduction in forward light scatter and an improvement in visual function. The pre-operative *k'* value was 30.90 compared to 10.07 post-operatively.

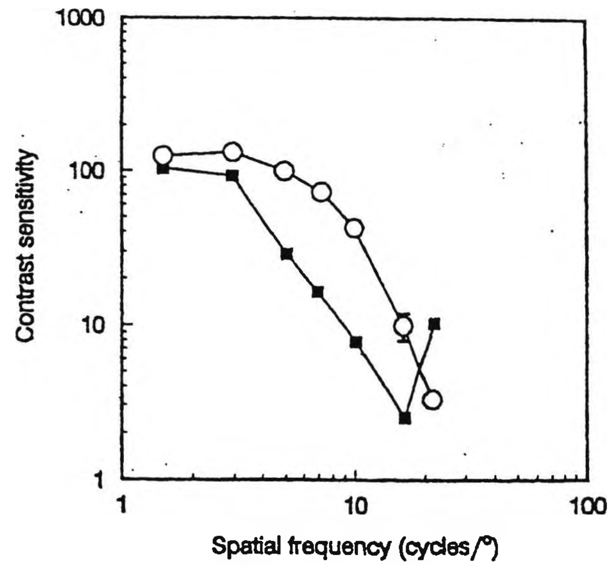
Figure 8.13 *Scatter profile and contrast sensitivity results for Subject CC*



(a) Right eye scatter (O)

(b) Left eye scatter (O)

(- - - Age-matched normal scatter values)



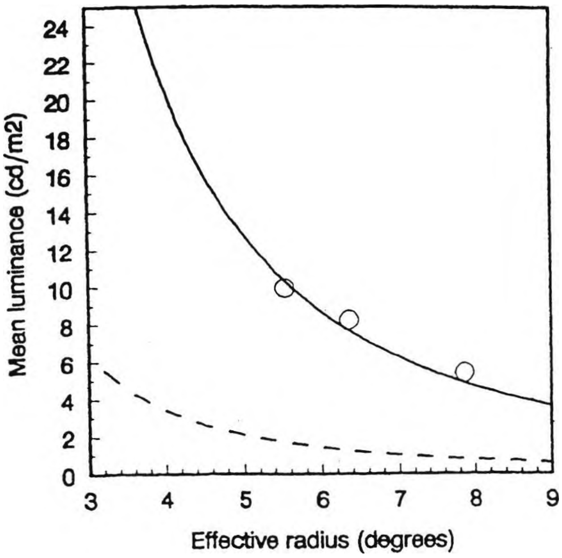
(c) Right eye contrast sensitivity (■)

(d) Left eye contrast sensitivity (■)

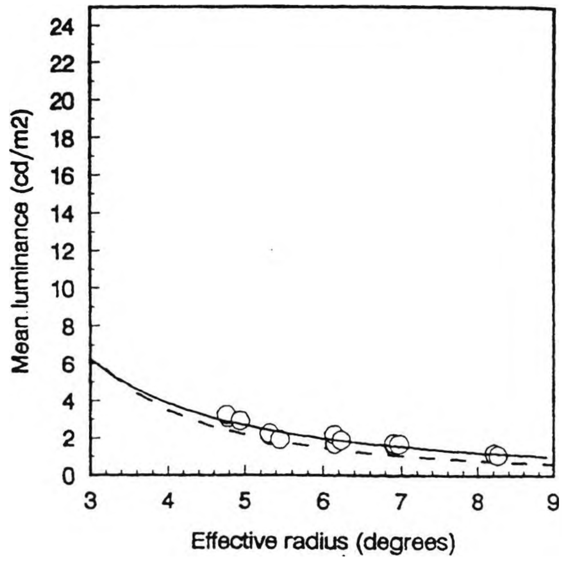
(O Age-matched normal contrast sensitivity values)

Subject CC (keratoconus, RE Excimer laser, LE penetrating keratoplasty), female, Caucasian, 44 years.		
	Right eye	Left eye
Visual acuity	3/60	6/9
Type of contact lens worn	RGP	RGP
Length of contact lens wear	20 years	20 years
External eye	Central striae; central scarring+++	Transparent cornea

Figure 8.14 *Scatter profile and contrast sensitivity results for Subject MP*

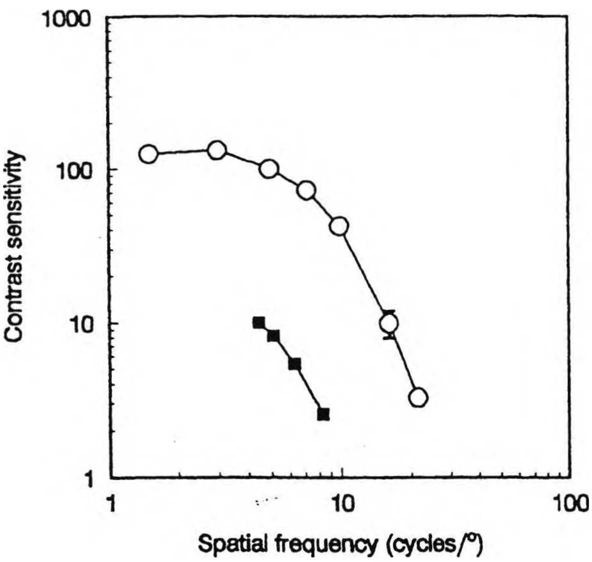


(a) Pre –op scatter (O)

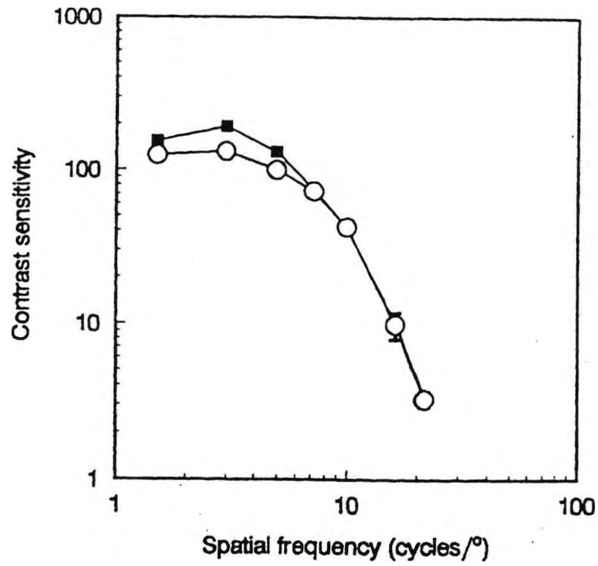


(b) Post-op scatter (O)

(- - - Age-matched normal scatter values)



(c) Pre-op contrast sensitivity (■)



(d) Post-op contrast sensitivity (■)

(O Age-matched normal contrast sensitivity values)

Subject MP (LE penetrating keratoplasty), male, Caucasian.		
	Left eye – Pre-op	Left eye – Post-op
Age	25 years	29 years
Visual acuity	6/12	6/5+1
Type of contact lens worn	RGP	RGP
Length of contact lens wear	11 years	14 years
External eye	Scarring++	Prominent sutures

Pre-op = Pre-operative

Post-op = Post-operative

8.9.3 Results for a subject receiving Excimer laser treatment and a superficial keratectomy following keratoconus

Table 8.5 - Scatter results obtained from one subject who had received Excimer laser and a superficial keratectomy following keratoconus.

Subject	Gender	Age (years)	Eye	*n*	*k*	*k'*	*k'-k' (age)*	s.d.
GO*	Male	33	RE	1.80	82.62	55.26	48.14	8.11

* *Subject reporting symptoms of glare*

The right eye of subject GO shows a large increase in light scatter (k' = 55.26) compared to age-matched normals (k' = 7.12). This is accompanied by a complete depression of the CSF. The right eye reveals a much higher level of light scatter than the left eye, despite treatment to improve visual function (figure 8.9a, c).

8.9.4 Results for a subject with blue dot cataract having received an epikeratophakia following keratoconus

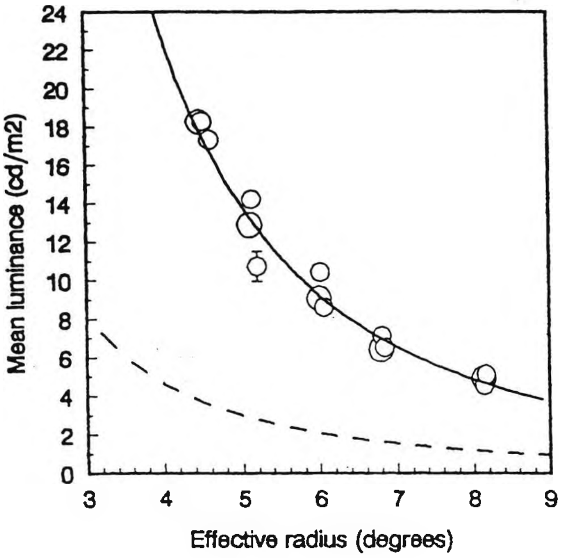
Table 8.6 - Scatter results obtained from one subject with blue dot cataract having received an epikeratophakia following keratoconus.

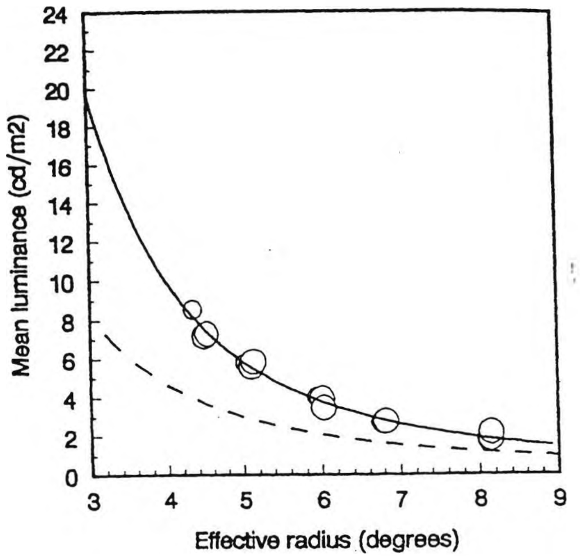
Subject	Gender	Age (years)	Eye	*n*	*k*	*k'*	*k'-k' (age)*	s.d.	Grading of keratoconus
JP*	Male	47	RE	2.23	143.69	43.84	34.35	2.26	-
			LE	2.38	40.11	18.68	9.91	0.64	2

* *Subject reporting symptoms of glare*

Subject JP was referred from Moorfields Eye Hospital following epikeratophakia for advanced keratoconus in the right eye. The subject also suffers from congenital bilateral blue dot cataract. Each eye reveals elevated levels of scatter with a narrow angular distribution (due to the low *n* values obtained) compared to age-matched normals, particularly in the right eye (43.84 compared to 9.49). The right eye CSF reveals a greater depression of sensitivity compared to the left eye (figure 8.15a, b, c, d).

Figure 8.15 *Scatter profile and contrast sensitivity results for Subject JP*

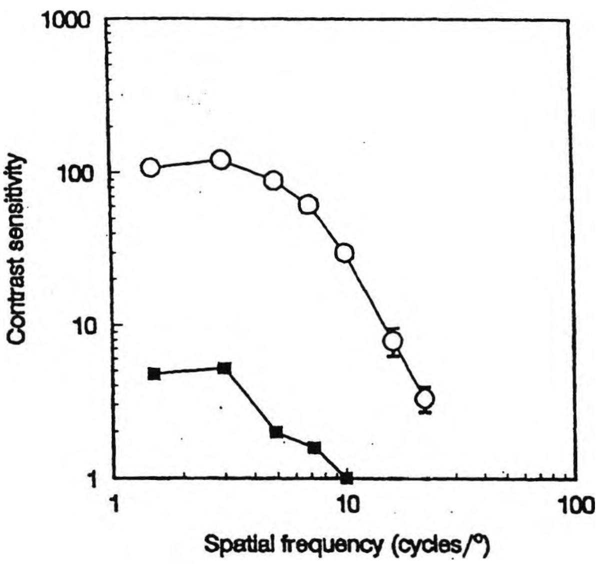


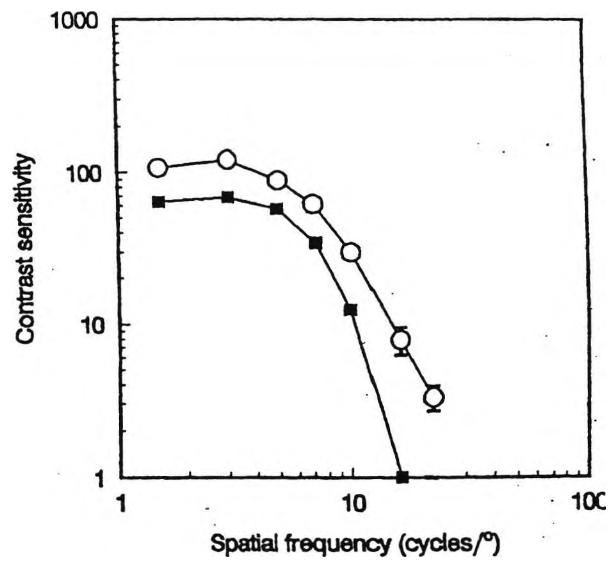


(a) Right eye scatter (O)

(b) Left eye scatter (O)

(- - - Age-matched normal scatter values)





(c) Right eye contrast sensitivity (■)

(d) Left eye contrast sensitivity (■)

(O Age-matched normal contrast sensitivity values)

Subject JP (keratoconus, RE epikeratophakia 6 years, congenital bilateral blue dot cataract), male, Caucasian, 47 years.		
	Right eye	Left eye
Visual acuity	3/60	6/9
Type of contact lens worn	RGP	RGP
Length of contact lens wear	5 years	5 years
External eye	Prominent sutures; Opaque cornea; Scarring and creasing of epithelium	Vogt's striae; Thinning centrally and inferiorly+

8.9.5 Results for subjects with other corneal abnormalities

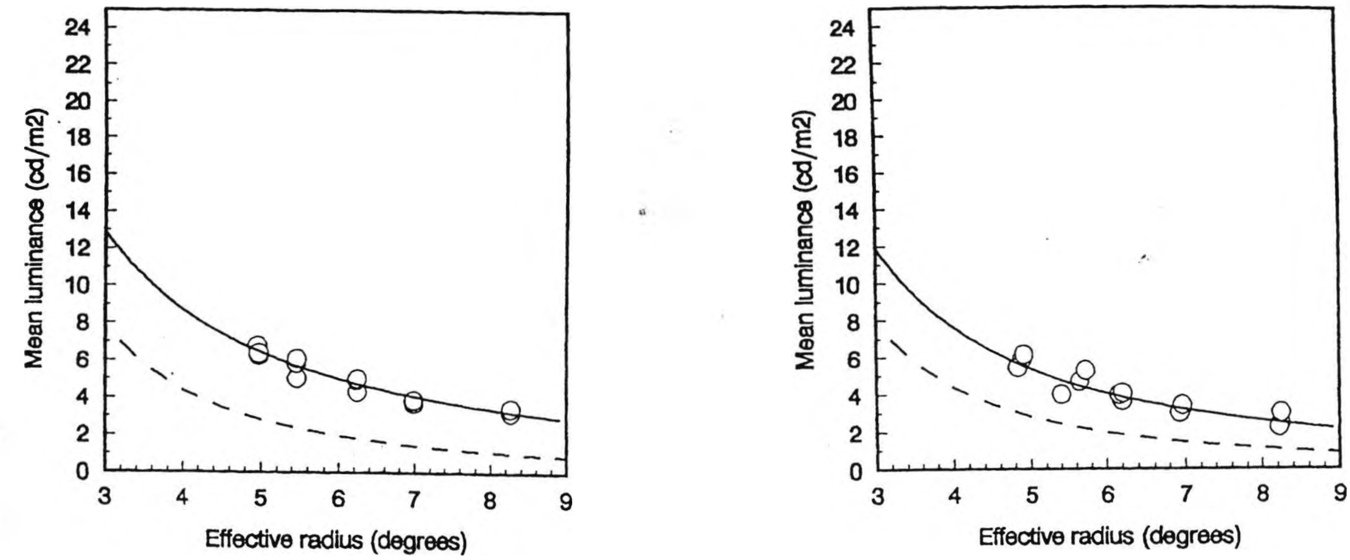
Table 8.7 - Scatter results obtained from three subjects with corneal abnormalities.

Subject	Gender	Age (years)	Eye	*n*	*k*	*k'*	*k'-k' (age)*	s.d.
AV*	Male	46	RE	1.36	16.26	38.20	29.00	7.02
			LE	1.56	18.68	21.89	12.69	3.15
JR	Female	65	RE	1.42	77.57	21.88	-2.76	1.03
			LE	1.62	40.57	27.26	2.62	5.37
ED	Female	48	RE	1.79	14.80	10.06	0.24	2.20
			LE	2.01	19.45	8.70	-1.12	0.32

Subject reporting symptoms of glare

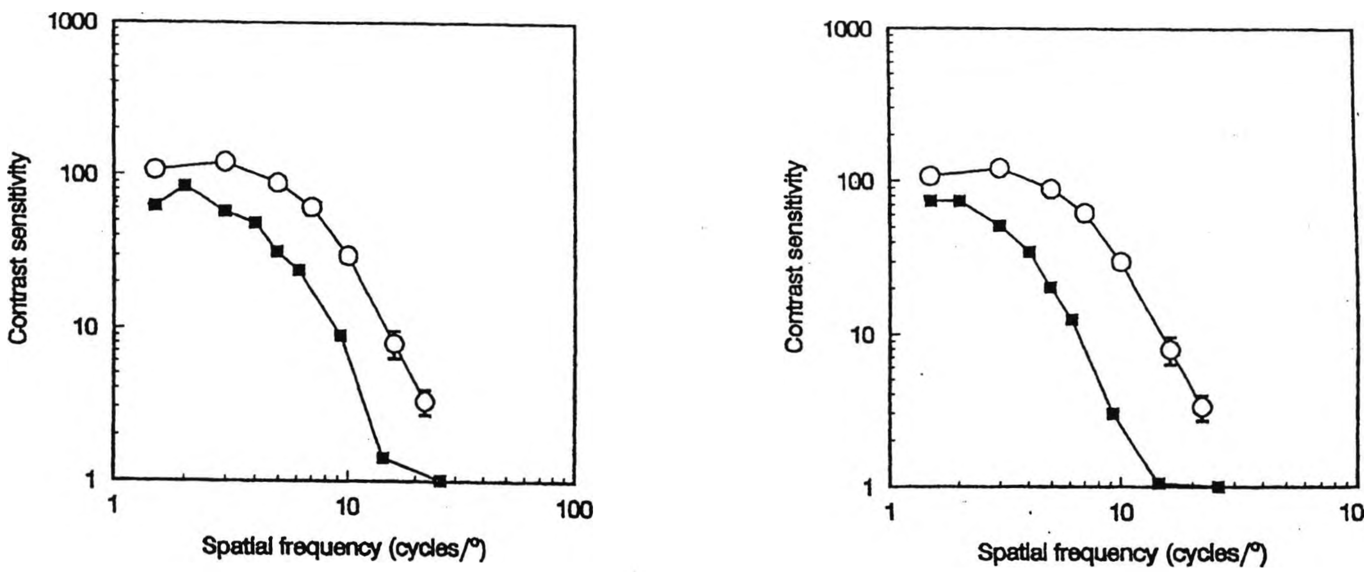
Subject AV reveals high levels of scatter in both eyes, (38.20 and 21.89) compared to age-matched normals (9.20). Figure 8.16a, b shows the angular distribution of light scatter for subject AV. Both eyes reveal low *n* values, with the right eye (1.36) showing a wider distribution than the left (1.56). The increase in light scatter is to be expected, given the bilateral stromal opacities observed. The CSF is reduced for all spatial frequencies (figure 8.16c, d). The right eye of subject JR reveals slightly less light scatter than one would expect for this subject's age, whilst the left eye reveals slightly elevated levels of light scatter compared to an age-matched normal. This is reflected in figures 8.17a, b. Again, both eyes reveal low *n* values, with the right eye (1.42) showing a wider distribution than the left (1.62). The CSF for the right eye shows a high level of sensitivity, which is in fact better than age-matched normals, apart from 1.5 cpd. However, the left eye shows slightly reduced sensitivity at all spatial frequencies apart from 7 cpd. There is a marked reduction in sensitivity at 16 and 22 cpd. Interestingly, the increase in scatter values and CS loss observed for this subject occur despite an excellent level of VA (6/4 in both eyes) (figure 8.17c, d). Subject ED did not reveal elevated levels of scatter, when compared to age-matched normals (10.06 and 8.70 compared with 9.82) (figure 8.18a, b). The CSF exceeds normal values for the right eye, but is reduced at spatial frequencies of 1.5, 3, 10 and 22 cpd in the left eye (figure 8.18c, d). External eye examination revealed evenly distributed bilateral plaque anomalies in the peripheral epithelial stroma which do not appear to greatly affect visual function. As a consequence, the patient does not complain of glare problems.

Figure 8.16 *Scatter profile and contrast sensitivity results for Subject AV*



(a) Right eye scatter (O) (b) Left eye scatter (O)

(- - - Age-matched normal scatter values)

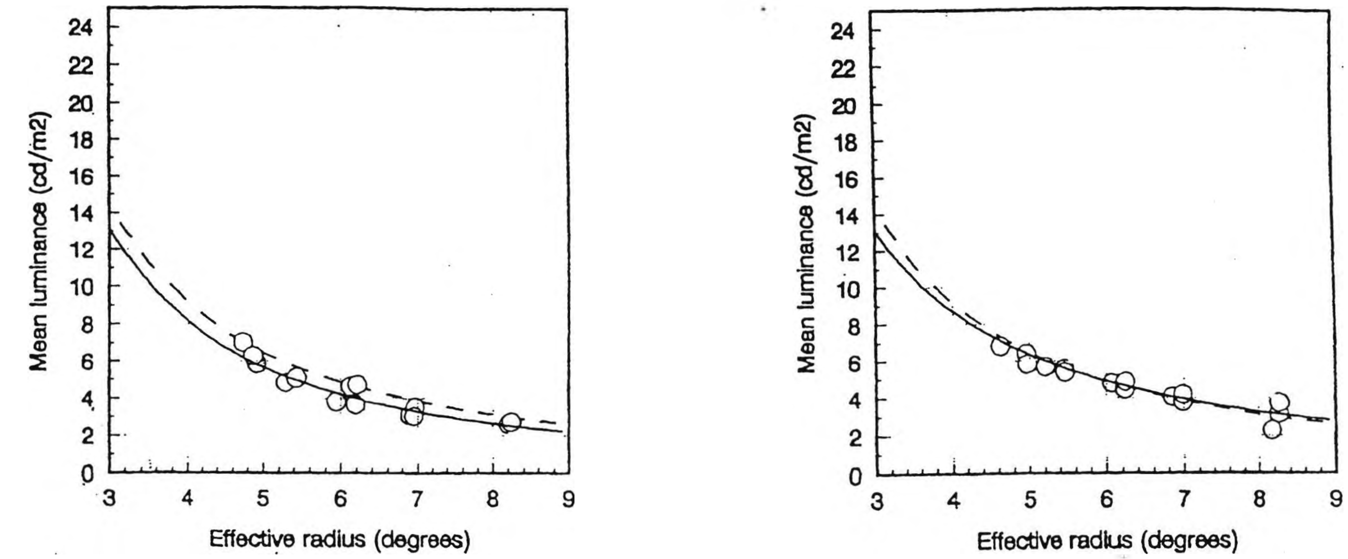


(c) Right eye contrast sensitivity (■) (d) Left eye contrast sensitivity (■)

(O Age-matched normal contrast sensitivity values)

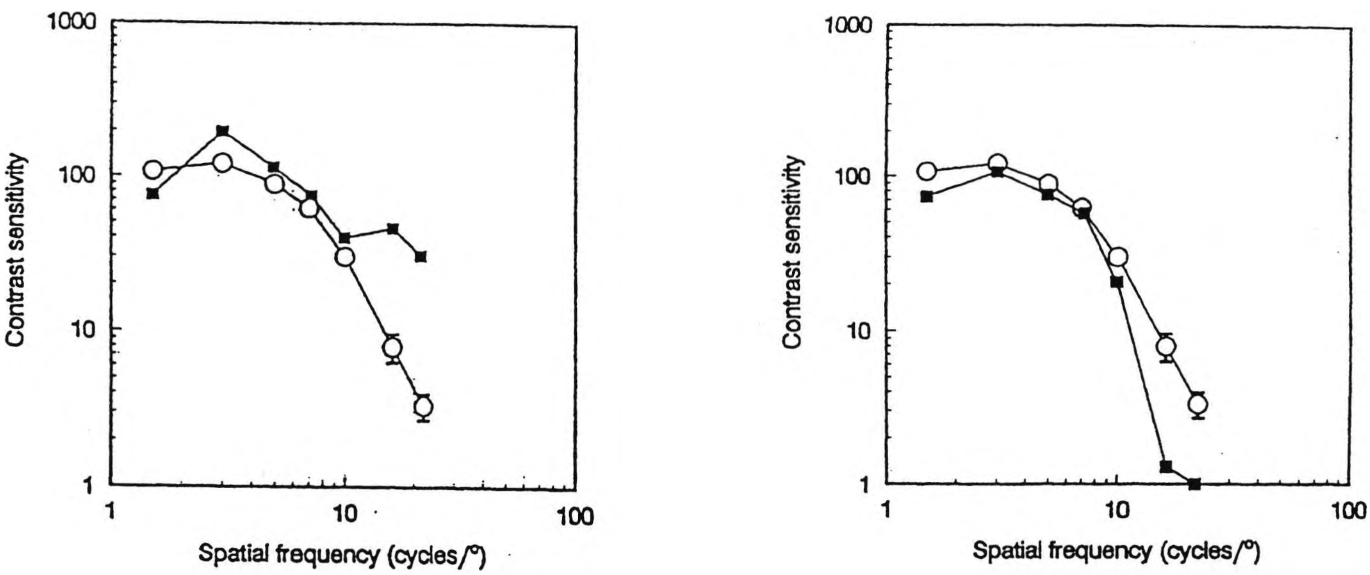
Subject AV (stromal dystrophy 5 years), male, Caucasian, 46 years.		
	Right eye	Left eye
Visual acuity	6/6-3	6/9
External eye	Stromal opacities++	Stromal opacities++

Figure 8.17 *Scatter profile and contrast sensitivity results for Subject JR*



(a) Right eye scatter (O) (b) Left eye scatter (O)

(- - - Age-matched normal scatter values)

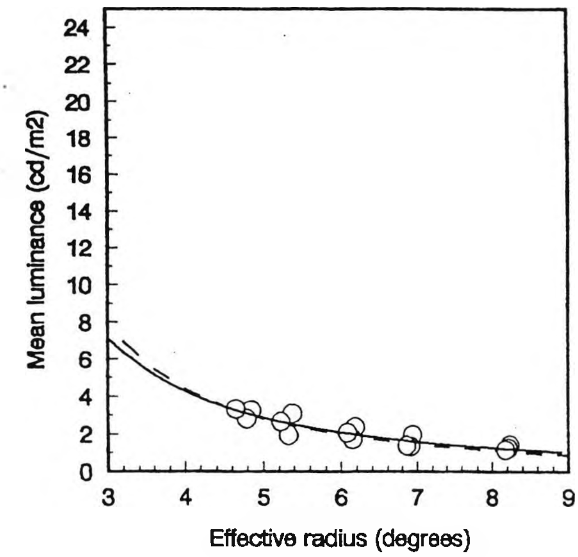


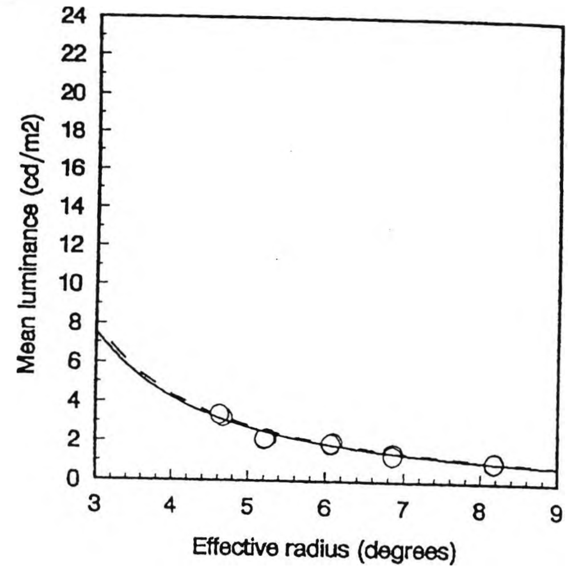
(c) Right eye contrast sensitivity (■) (d) Left eye contrast sensitivity (■)

(O Age-matched normal contrast sensitivity values)

Subject JR (corneal guttering 5 years), female, Caucasian, 65 years.		
	Right eye	Left eye
Visual acuity	6/4	6/4
External eye	Inferior peripheral corneal guttering+	Inferior peripheral corneal guttering+

Figure 8.18 *Scatter profile and contrast sensitivity results for Subject ED*

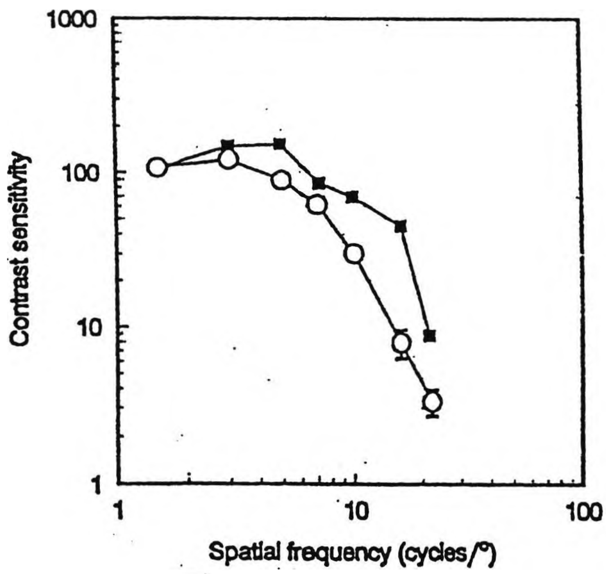


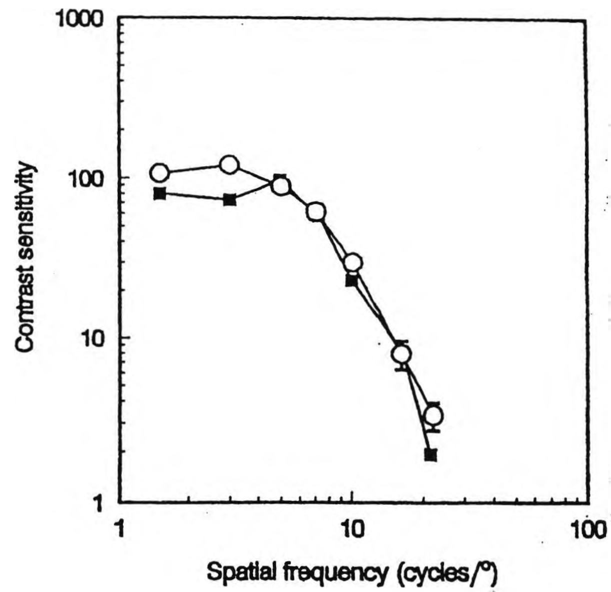


(a) Right eye scatter (O)

(b) Left eye scatter (O)

(- - - Age-matched normal scatter values)





(c) Right eye contrast sensitivity (■)

(d) Left eye contrast sensitivity (■)

(O Age-matched normal contrast sensitivity values)

Subject ED (epithelial dystrophy), female, Caucasian, 48 years.		
	Right eye	Left eye
Visual acuity	6/6-3	6/9
External eye	Plaque anomalies	Plaque anomalies

8.10 Discussion of Chapter 8

8.10.1 Discussion of subjects with keratoconus

8.10.1.1 Measurements of forward light scatter

All subjects with keratoconus exhibited high degrees of intraocular light scatter, with scatter values elevated above the values of k' found in age-matched normals. The increase in scatter varied between subjects, as they had varying degrees of keratoconus. The severity of the keratoconus tested ranged from moderate changes (Grade 2) to advanced keratoconus (Grade 3). Seven eyes were graded as Grade 2 and had a mean k' of 17.92 (range 8.81 to 41.03). Eleven eyes were classified as Grade 3 and had a mean k' of 30.35 (range 11.03 to 54.68). Although the mean increase in k' was greater in the Grade 3 keratoconic subjects compared with Grade 2, there was considerable overlap between the two groups. Statistical analysis did not reveal a significant difference between the k' values at the 5% level (two sample t-test $p = 0.06$, $t = -2.02$). n was seen to vary greatly between individuals with keratoconus (as measured by the P_SCAN 100 scatter apparatus) which confirms that assuming a constant value of 2 for n is inappropriate. All keratoconic subjects examined complained of glare, which is consistent with the finding of increased light scatter in these subjects. The findings of this study are in contrast to Edrington et al (1999), who reported that patient-reported symptoms of glare correlate only with corneal scarring. However, this study only investigated measures of backscatter. Five of the patients examined in the present study did not present with corneal scarring, yet still reported symptoms of glare.

The principal cause of the increase in light scatter in keratoconic subjects is likely to be the stromal thinning and conical deformity of the cornea. These corneal changes, combined with the fragmentation and scarring of Bowman's layer with clusters of activated keratocytes, have been shown to significantly affect VA (Probst 1996). It should be noted that most of the keratoconics studied (with the exception of subject MR) wore either PMMA or RGP lenses in order to maintain visual function. Therefore, it is possible that contact lens wear may have contributed to the increase in k' in these keratoconic subjects. Indeed, Davis et al (1993) reported spontaneous development of striae after inserting RGP contact lenses on six patients suspected of having early keratoconus. Subsequently, Sturbaum (1996) claimed that the primary cause of endothelial polymegethism and pleomorphism found in keratoconics was the wearing of contact lenses. Whilst some reports suggest that rigid lenses induce keratoconus, the wearing of contact lenses is not thought to influence the progression of the disease (Woodward 1991). Nevertheless, it is impossible to dissociate the effect of contact lens wear and the effect of keratoconus on the values of k' obtained in the present study. However, the effects of increased intraocular light scatter will be real, whatever the cause.

8.10.1.2 Measurements of contrast sensitivity

A CS loss over all spatial frequencies was observed in keratoconic subjects, even in those with relatively good VA. This finding is in agreement with other studies (Hess and Carney 1979; Carney 1982a, b; Carney and Lembach 1991). Hess and Carney (1979) suggested that more advanced keratoconic cases may be strongly associated with the presence of a low frequency abnormality and that it is the degree of opacification which determines the spatial frequency of the loss. The present results do not fully support this finding, as subjects with moderate keratoconus (Grade 2) and no corneal opacities also revealed loss at all spatial frequencies. Nevertheless, those subjects with greater amounts of light scatter indeed showed a greater reduction in CS at low spatial frequencies, than those subjects exhibiting comparatively less scatter. The results do not concur with the findings of Mannis et al (1984) and Zadnik et al (1987) who reported CS loss restricted to high and intermediate spatial frequencies in eighteen patients suffering from keratoconus.

Histologically, in keratoconus reaggregation of collagen fibrils occurs in Bowman's layer, and there is complete disruption of the orientation of the stromal collagen fibres (Daxer and Fratzl 1997; Kato et al 1997). Therefore, it is not unreasonable to assume that these changes will contribute to a decline in the CSF, despite the absence of corneal scarring.

8.10.2 Discussion of subjects receiving penetrating keratoplasties following keratoconus

8.10.2.1 Measurements of forward light scatter

Following penetrating keratoplasty due to keratoconus, subjects AF, MP and CC revealed varying increases in forward light scatter, compared to age-matched normals. The highest post-operative values of light scatter were recorded for subject AF, who also complained of symptoms of glare. k' was approximately 50% greater in the left eye of subject AF, which had received surgical treatment, compared to the fellow eye with advanced keratoconus (figure 8.5a, b). Subjects MP and CC did not complain of glare problems, and k' values were modestly increased, compared to age-matched normals. Subjects such as these, who are selected for penetrating keratoplasty, often experience a severe reduction in visual function prior to surgery, and therefore are less likely to complain of symptoms of scattered light after surgery. Although increased k' values were obtained from this group of subjects, the scatter values were less than the majority of keratoconic subjects (with the exception of subject AF). The improvement in visual function following penetrating keratoplasty is clearly demonstrated by the pre and post-operative results obtained from the left eye of subject MP. Even though this subject had slightly raised levels of light scatter, the vast improvement in CS and the decrease in scatter values demonstrates the visual benefits of surgical intervention.

8.10.2.2 Measurements of contrast sensitivity

Mannis et al (1987) reported that although optically successful keratoplasty in patients with bilateral corneal disease tended to improve CS in the operated eye, CS curves were abnormal compared with those of normal subjects (except at 0.5 cpd, a spatial frequency not tested in the current study). The reduced CS found at all spatial frequencies for CC and AF (apart from 22 cpd for CC) supports Mannis' finding. Subject CC had been grafted 8 years previously, but also had to wear a contact lens to improve visual function. Contact lens wear in an eye with penetrating keratoplasty may be a contributory factor in reducing the CSF found at all but 22 cpd. Contact lenses may cause a corneal graft to become opaque over a period of lens wear following a penetrating keratoplasty (Stallard 1973). Although the graft appeared clear on slit lamp examination, it is possible that subclinical cellular irregularities had occurred. Subject AF had a similar CSF following penetrating keratoplasty, compared to the fellow eye with Grade 3 keratoconus. This is to be expected as the right eye still retained relatively high levels of scattered light. Mild irregularities in graft contour may be the cause of CS losses in such patents (Wicker et al 1992).

The left eye of subject MP, which had received a penetrating keratoplasty, did not reveal a reduced CSF and was, in fact, better than expected for the subject's age at spatial frequencies of 1.5, 3 and 5 cpd. Even though only a limited range of spatial frequencies were tested pre-operatively, the CS is markedly reduced compared to normal and post-operatively. The marked improvement in the CSF for the post-operative eye demonstrates the increase in visual function that can be achieved after surgery (the subject having received surgery 3 years previously).

8.10.3 Discussion of a subject receiving Excimer laser and a superficial keratectomy following keratoconus

8.10.3.1 Measurements of forward light scatter

Testing the right eye of subject GO revealed high levels of scatter (55.26) compared to both age-matched normals (7.34) and also compared to the eye with untreated keratoconus (15.09). VA in the right eye improved to 6/60 with a pinhole and with a contact lens but unfortunately, the subject found the contact lens too uncomfortable to wear for the duration of testing. As a consequence, only half the experiments could be completed and although the *k'* is high, the standard errors show that the results should be treated with caution. Unsurprisingly, the subject complained of symptoms of glare, which is to be expected following the cellular disruption associated with a superficial keratectomy. The eye had been operated on four months previously.

8.10.3.2 Measurements of contrast sensitivity

Many studies have reported CS losses following surgical intervention for keratoconus (Carney and Kelley 1991; Carney and Lembach 1991; Khong et al 1993). Results from subject GO who had received a superficial keratectomy in addition to Excimer laser are consistent with the findings of previous studies in showing a much more severe CS loss than keratoconic subjects. Measurements of CS in the right eye revealed a complete depression of the CSF, as no CS gratings were visible.

8.10.4 Discussion of one subject with blue dot cataract who had received an epikeratophakia following keratoconus

8.10.4.1 Measurements of forward light scatter

Subject JP revealed elevated light scatter in each eye. The right eye had received an epikeratophakia due to keratoconus, which produced elevated *k'* values (43.84), compared to age-matched normals (9.37). Symptoms of post-operative glare following a similar procedure (epikeratoplasty) have been reported by a number of studies (e.g. Hovding and Bertelsen 1992). The fellow eye suffered from a moderate level of keratoconus which resulted in increased scatter values compared to age-matched normals, however, the value of k' was less than that observed in the right eye. The most obvious cause of the increase in light scatter was the creasing and scarring of the epithelium as a result of the epikeratophakia. The subject also suffered from blue dot cataract, which may also contribute to the elevated scatter.

8.10.4.2 Measurements of contrast sensitivity

The CSF was depressed in the right eye across all spatial frequencies, a finding that was consistent with high levels of light scatter and poor VA. Several studies have shown that CS is reduced following epikeratoplasty (Carney and Kelley 1991; Carney and Lembach 1991). Although JP's left eye had a much higher level of acuity, k' was still twice the normal age-matched value and was accompanied by a reduction in CS at all spatial frequencies (especially 22 cpd). It is of no surprise that this patient complained of glare as a result of increased forward light scatter.

8.10.5 Discussion of subjects with other corneal abnormalities

8.10.5.1 Measurements of forward light scatter

Subjects with corneal abnormalities exhibited extensive variation in the observed level of intraocular scattered light. Subject AV revealed the greatest level of light scatter in this group of subjects ($k' = 38.20$) (table 8.7, figure 8.16). This was to be expected, as the subject suffered from extensive bilateral corneal guttatae, which resulted in subjective visual problems. Subject JR suffered from peripheral corneal guttering which resulted in an increase in light scatter in the left eye, compared to age-matched normals. The scatter results of the right eye did not reveal a similar increase in light scatter. Slit lamp examination of subject ED revealed a slight epithelial dystrophy, which appeared to have little affect on the measures of light scatter. This was consistent with the lack of subjective visual complaints.

It is inevitable that certain changes in the cornea, perhaps due to oedema, the deposition of corneal plaques or the formation of guttatae, will result in increased straylight. In the small number of eyes studied, the extent of the opacification or abnormality in the cornea visible by slit lamp biomicroscopy was consistent with the amount of scattered light. The present study reaffirms Hess and Carney's (1979) suggestion that the nature of visual loss needs to be individually assessed for the diverse types of visual disturbance that result from corneal abnormalities.

8.10.5.2 Measurements of contrast sensitivity

Subject AV revealed a reduced CS function for all spatial frequencies tested. Subject JR only revealed loss at 1.5 cpd in the right eye whilst the left eye revealed a depression of CS at mainly 10, 16 and 22 cpd. Subject ED revealed a normal CSF in the right eye but a slightly reduced CSF at all spatial frequencies in the left eye, apart from 3, 5 and 16 cpd. It can be concluded that each subject in this group suffered a different type of CS loss. That said, the results of subject JR do agree with the findings of Hess and Carney (1979) who showed a CS loss at high to medium frequencies in patients with corneal disease. However, comparison is difficult as both studies investigated only a small number of subjects.

8.11 Conclusions

Keratoconics (prior to and following surgery) and subjects with other corneal abnormalities experience increased intraocular light scatter, compared with age-matched normals. Each keratoconic demonstrated increased levels of intraocular light scatter, which were associated with symptoms of glare and also a reduction in the CSF at all spatial frequencies. The level of light scatter observed in this group of patients was not related to the backscatter grading of the condition (two sample t-test $p = 0.06$, $t = -2.02$). Following penetrating keratoplasty, each subject revealed increased levels of forward light scatter, compared to age-matched normals. However, two out of three subjects revealed reduced levels of light scatter compared to the majority of keratoconics. All subjects following penetrating keratoplasty revealed some form of CS loss. Two subjects who had undergone various other types of surgical management following keratoconus revealed high levels of light scatter. The raised scatter values were accompanied by severe CS losses at all spatial frequencies. Subjects with other corneal abnormalities exhibited wide inter-subject variability in the amounts of light scatter and CS loss, which was due to the diverse nature of the conditions examined. However, it is clear that extensive corneal involvement produced elevated levels of light scatter.

Direct measures of forward light scatter in subjects with corneal abnormalities (including keratoconus prior to and following surgery) have, on the whole, revealed increased levels of light scatter compared to normal age-matched subjects. The finding that patients with such corneal abnormalities experience high levels of light scatter may account for some or all of the poor visual function experienced by such subjects. In fact, in order to improve visual function degraded by light scatter, certain keratoconic subjects examined in this study subsequently received early surgical intervention as a direct result of the findings of this study. Therefore, this method of directly assessing intraocular light scatter has provided the clinician with an improved appreciation of a keratoconic's visual experience and the likely effects of the increased light scatter on visual performance as measured by CS. This demonstrates the clinical value of testing forward light scatter using the P_SCAN 100 scatter apparatus. The findings of this chapter, together with those from Chapter 5, facilitate comparison of the magnitude of the effects on scatter and CS of long-term contact lens wear, normals and those with corneal abnormalities.

CHAPTER 9

The light scattering characteristics of the contact lens-wearing eye

9.1 Introduction

Contact lenses are an intimate form of vision correction that have been fitted for the past 100 years. Since their advent, contact lenses have passed through the ages of glass, polymethylmethacrylate (PMMA), hydrogel, rigid gas permeable (RGP) and silicone elastomer lenses. These developments have led to improvements in physiological compatibility of materials, however, despite much recent research on the physiological impact of lenses on the eye, the consequence of long-term contact lens wear has received only limited attention.

The ability to detect and quantify subtle corneal responses resulting from contact lens wear is a highly desirable clinical goal. Numerous physiological changes can manifest (e.g. corneal oedema), not only during the adaptation stage but also after many years of lens wear (Mandell et al 1970). The most widely used clinical procedure to detect physiological changes resulting from contact lens wear is slitlamp biomicroscopy. Slitlamp examination allows a subjective assessment of the light scattered back from the cornea. Although a number of subjective scoring systems of the amount of visible corneal oedema have been proposed, truly objective quantitative evaluation is limited. In addition, slitlamp biomicroscopy provides little useful information regarding the patient's visual function, as it is known that backward scattered light (as seen using a biomicroscope) does not equal forward scattered light (Allen and Vos 1967). The most widely used method of testing visual function in contact lens wearers is Snellen VA, but the disadvantages of this method are numerous, as discussed in section 1.3.2.1.1.

Knowledge of the light scattering characteristics of a variety of subject groups, namely, normal subjects of different ages, and those with anterior segment eye conditions, facilitates the primary aim of this research which is to investigate the light scattering characteristics of the contact lens-wearing eye, using a novel technique. Although contact lenses have been in use for approximately 40 years, little research has been conducted into the effects of such long-term lens wear. Given the number of physiological responses that occur during contact lens wear, it is not unreasonable to hypothesise that such changes manifest as increased intraocular light scatter. Therefore, the author wished to establish whether long-term contact lens wear causes increased levels of light scatter when compared to age-matched controls. Furthermore, the author wished to determine whether long-term contact lens wear results in altered visual performance. Therefore, CS was also employed to examine the effects of long-term contact lens wear on the CSF.

9.2 Physiological changes in response to contact lens wear

The cornea requires nutrients, principally in the form of glucose, amino acids and oxygen, to perform its normal metabolic functions (section 6.2). The cornea's avascular structure means that the main sources of nutrients are the aqueous humor and the atmosphere via the tears. The latter provides oxygen, and the former principally glucose and amino acids (Maurice and Watson 1965; Maurice 1967). If the oxygen supply is deficient, the cornea is unable maintain aerobic glycolysis. As a result, glycogen stores within the cornea become depleted, and lactic acid accumulates in the corneal tissue. Other metabolic changes affect levels of succinic (Hill et al 1974) and lactate dehydrogenase (King et al 1971) and other enzyme systems (Thoft and Friend 1975). In turn, this leads to the development of epithelial and stromal oedema due to the additional osmotic burden on these tissues (Klyce and McCarey 1986). Therefore, corneal transparency is closely connected with the availability of oxygen (Fatt and Beiber 1982).

Over fifty years ago, Smelser and co-workers demonstrated that oxygen deprivation as a result of PMMA contact lens wear produced distinct structural and optical changes in the cornea (Smelser and Ozanics 1953; Smelser and Shen 1955). Hypoxia of the cornea is one of the principal causes of contact lens wear complications. Oxygen consumption of the individual layers has been reported as 3.83 $\mu l/hr/cm^2$ for the epithelium, 3.68 $\mu l/hr/cm^2$ for the stroma, 2.03 $\mu l/hr/cm^2$ for the endothelium and 9.54 $\mu l/hr/cm^2$ for the whole cornea (Freeman 1972). Maintenance of a satisfactory oxygen supply is dependent on oxygen levels in the tears, at the aqueous surface from the aqueous fluid itself, and also on the permeability of the tissue to the transfer of oxygen. The oxygen tension profile of the cornea is clearly affected by the presence of a contact lens. In general, this significantly reduces the oxygen tension level to an extent that depends on characteristics of the contact lens material itself. These characteristics include oxygen transmissibility of the material and whether the lens is made from a relatively immobile hydrogel, or instead from a hard lens that moves on the cornea thus allowing some tear exchange (20% of the tear volume may be exchanged during each blink). RGP lenses allow oxygen to pass through the lens and, together with the tear exchange beneath the lens, induce less corneal oedema than hydrogel lenses of comparable Dk/t. In contrast, well fitted hydrogel lenses allow an exchange of only 1% per blink. As these lenses cover the whole cornea, little oxygen passes through to the cornea directly and material transmission is thus important.

9.3 Short-term corneal changes in response to hypoxia caused by contact lens wear

It is generally agreed that corneal oedema occurs during early adaptation to all types of contact lenses (Mandell et al 1970; Schauer et al 1973). This is primarily caused by oxygen deprivation of the cornea but may also be due to changes in tear osmolarity. Although the clinical appearance and location of oedema may differ depending on the type of lens worn, the basic mechanisms causing the physiological response remain the same.

9.3.1 Epithelial oedema

Corneal oedema is obvious in hard lens wearers using the slit-lamp, because there is a clear separation between oedematous central and non-oedematous peripheral epithelium (Korb and Exford 1968). In contrast, oedema from hydrogel lens wear is more difficult to observe because it is diffuse across the whole epithelium. Increased epithelial light scatter as a consequence of oedema will result in patients complaining of hazy vision following lens removal. In addition, superficial punctate keratitis (SPK) may be visible as a consequence of epithelial oedema, especially after many hours of lens wear (regardless of lens type). Water moves into the epithelium through the surface breaks and contributes to light scatter. However, patients may experience hazy vision due to oedema (termed Sattler's veil (Finkelstein 1952; Kwon et al 1972)) without signs of SPK.

Finkelstein (1952) was among the first to recognise that Sattler's veil was an epithelial diffraction phenomenon as a result of contact lens wear (section 6.4.1). Finkelstein (1952) measured the half-arc of the halo seen by contact lens users and concluded that halos arose from the basal cell layer. Subsequent work by Lambert and Klyce (1981) used an in vitro model of Sattler's veil to test the basis of halo formation in rabbits. After hypoxia of the epithelial surface, results showed that light scattering sites formed between epithelial cells. The sides of the polygonal meshwork of scattered light were more or less randomly orientated. As a result, the diffraction pattern produced a circle, forming diffuse halos observed around a point source of light. It was suggested that these scattering sites resulted from a differential refractive index (RI) between the basal cell cytoplasm and the extracellular space, which then acted as a large meshwork or diffraction grating. Theoretically, an associated cell swelling and separation would be predicted, however, a consistent change in epithelial thickness was not demonstrable, even using the highly sensitive automatic specular microscope. Similar observations have been reported by numerous other workers (e.g. Wilson and Fatt (1980) section 6.3.2). The most likely explanation for the diffraction phenomenon is that hypoxia, by stimulating lactate production, leads to an increase in lactate concentration between basal cells. Being osmotically active, lactate draws water out of the cells, so increasing the extracellular space between them. Because this space has very little protein relative to the cells, it has a lower RI and light will scatter at the interface. In fact, in vitro experiments suggest that lactate production by the cornea doubles under conditions of hypoxia (Riley 1969). Lambert and Klyce (1981) concluded that hypoxic changes in the refractive properties of the epithelium produce a pattern of backscattered light from the extracellular space. This has been identified as being the source of the halo in Sattler's veil.

9.3.2 Stromal oedema in contact lens wear

Stromal oedema usually accompanies the epithelial oedema that occurs as a result of corneal hypoxia due to contact lens wear. The extent of swelling is inversely related to the Dk/L of the contact lens material or the oxygen tension of the tears (O'Neal et al 1984). Stromal oedema will be the consequence of breaks in the epithelial or endothelial barriers, when there is a reduction in the endothelial pump, and/or when there is increase in osmotic activity of the stromal component. Klyce and co-workers demonstrated that corneal swelling can be predicted based on the osmotic activity of the lactate that is accumulated in the stroma during hypoxia (Klyce and Russell 1979; Klyce 1981). The results of other similar studies (e.g. Rohde and Huff 1986) support the proposed 'lactate osmotic hypothesis' for hypoxic stromal swelling. The consequence of stromal oedema has been discussed in section 6.4.2.

9.3.3 Endothelial blebs and corneal pH

Zantos and Holden (1977) noted that small black spots were formed on the endothelial surface within 20 minutes of inserting a contact lens. The black spots reached a maximum in number and relative area approximately 30 minutes after insertion. These spots, termed 'blebs' (section 6.4.3) were found to occur under three conditions: (i) with contact lens wear, (ii) with nitrogen gas application through a goggle and (iii) by passing a CO_2 / O_2 / N (1:2:7) gas mixture over the eye (Holden et al 1984). The latter condition did not lead to stromal swelling as there was no hypoxia, however, the increased CO_2 concentration reduced the corneal pH. Therefore, the appearance of endothelial blebs was caused by stromal acidosis.

Later, Bonanno and Polse (1987) measured the reduction of stromal pH in subjects during (i) hypoxia and (ii) during lens wear. It was demonstrated that the drop in stromal pH during lens wear was caused by hypoxic acidosis and accumulation of CO_2 in the cornea as a result of contact lens wear. Holden et al (1987) confirmed that CO_2 can accumulate during lens wear and that the CO_2 transmissibility of contact lenses is similar to the oxygen transmissibility (Ang and Efron 1990). The clinical impact of corneal acidosis due to contact lens wear is not fully understood but the changes are generally accepted as being detrimental to ocular health (Tomlinson 1992).

9.4 Long-term corneal changes in response to hypoxia caused by contact lens wear

Chronic hypoxia, as experienced during long-term contact lens wear, may have morphological and functional consequences on all corneal structures. The level of hypoxia experienced by a patient over a number of years may produce a number of clinical signs (table 9.1).

Table 9.1 - The corneal sequelae of contact lens-induced relative anoxia (Tomlinson 1992).

Structure	Short-term change	Long-term change
Epithelium	Erosions	Microcysts
	Oedema	Bullae
	Ulceration	Vacuoles
	Warpage	Thinning
		Vascularisation
		Reduced oxygen consumption
		Increased fragility
		Reduced sensitivity
		Reduced cell mitosis
Stroma	Oedema	Thinning
	Striae	Infiltrates
		Vascularisation
Endothelium	Bleb	Polymegethism
	Folds	Bedewing
		Guttatae

The formation of deep stromal opacities have also been observed in response to long-term contact lens wear (Pinckers et al 1987). Remeijer et al (1990) investigated 32 patients following long-term PMMA or hydrogel contact lens wear (up to 19 years) and observed deep 'whitish' opacities directly adjacent to Descemet's membrane in the central part of the cornea. The lesions were most often found in association with hydrogel lens wear (90.6%) after prolonged use (8.8 years) but were also observed in PMMA contact lens wearers (9.4%), although this did not occur until after more prolonged use (18.5 years). The lesions diminished in all patients after discontinuation of contact lens wear or replacement with RGP lenses. It was suggested that lesions were either caused by an allergic reaction to thiomersal (contained in certain contact lens cleaning fluids) or were due to chronic hypoxia of the corneal stroma and endothelium.

Polse et al (1990) proposed a parameter termed 'hypoxic dose', that takes into account the level of hypoxia and the duration of oxygen reduction. The authors investigated endothelial polymegethism, endothelial cell density and CT in extended contact lens and PMMA wearers and found that hypoxic exposure was dose-dependent (i.e. the greater the length of hypoxia, the greater the corneal alterations in response to lens wear). The hypoxic exposure resulted in altered endothelial morphology which reduced corneal function. Individuals who had a significant hypoxic dose had poorer corneal hydration control, as measured in a corneal stress test, compared to non-lens wearers although no clinical signs of hypoxia were evident (Polse et al 1990). Therefore, subclinical morphological and functional corneal alterations may occur in response to long-term contact lens wear without clinical signs of hypoxia being observed.

As the present study attempts to compare the long-term effects of different types of lenses (i.e. PMMA, hydrogel and RGP), the following introduction to the effects of lens wear has been divided according to the type of contact lens.

9.4.1 The effect of long-term hard contact lens wear

More than 200 publications have discussed gross ocular changes produced by PMMA lenses. Ocular changes include irregular and regular astigmatism, prolonged spectacle blur, oedema (with or without associated wrinkles or folds in Descemet's membrane), epithelial abrasions, stromal infiltrates, vascularisation of the cornea, decreased corneal and eyelid sensitivity, alterations in blink rate, tarsal follicular and/or papillary formation, and altered tear chemistry.

PMMA contact lenses have been in use for over 60 years but have gradually been replaced in popularity by hydrogel and RGP contact lenses. Subjects who continue to wear PMMA lenses are by way of selection contented with their refractive correction, and the comfort and convenience of their contact lenses. Consequently, PMMA lenses are still worn by certain patients, despite the apparent disadvantages of their use.

9.4.1.1 Endothelial response to long-term hard lens wear

Schoessler and Woloschak (1981) photographed with a Nikon endothelial camera the endothelium of 10 contact lens-wearing patients who had worn PMMA lenses for five years or more. Results from the veteran lens wearers revealed fewer typical hexagonal cells and extensive polymegethism, compared to age-matched controls. The preponderance of pleomorphic cells found in PMMA wearers (especially in the 20-30 year old age group), suggested that the cells had been altered during the course of contact lens wear. It was proposed that the altered morphology of endothelial cells may represent altered cell function, which may increase the likelihood of corneal problems in later years, especially following corneal surgery.

Other studies have confirmed the findings of Schoessler and Woloschak (1981). Caldwell et al (1982), using small field specular microscopy, reported a statistically significant endothelial cell loss associated with PMMA contact lenses which correlated with the duration of lens wear. Thirty-two subjects were investigated and the duration of wear distribution ranged from 10 to 27 years. Prolonged hard lens wear reduced endothelial cell count by as much as 10% over several decades, although the data are potentially flawed due to the lack of an adequate control group. In a subsequent study, Caillaud and Cochet (1983) examined 52 non lens-wearing eyes and 90 eyes of regular contact lens wearers with a Heyer Schulte specular microscope. The regular wearers had worn either HEMA or PMMA lenses (or a combination of both) for periods ranging from 2 to 25 years. The study reported that endothelial cell density reduced with age without being dramatically altered by contact lens wear. In contrast, pleomorphism of endothelial cells was significantly increased in contact lens wearers, compared with control cases. The duration of lens wear (in years) was stated as a factor which increases pleomorphism in patients who otherwise tolerate their lenses well.

Hirst et al (1984), using specular photomicrographs, investigated 22 apparently successful hard contact lenses and 22 controls matched for age, race, gender and refractive error. The study reported that PMMA contact lens wear correlated with increased pleomorphism and morphological changes which included deep stromal striae, intra- and extracellular "blackout" areas and clustering of extremely small and large cells. Subsequently, MacRae et al (1986) investigated 24 eyes of 12 patients who had worn PMMA contact lenses for more than 10 years and also 15 former users of PMMA lenses. Subjects were evaluated by specular microscopy and morphometric analysis of the endothelium. The corneal endothelium of PMMA hard contact lens wearers revealed polymegethism, pleomorphism and a greater deviation from a regular hexagonal pattern. Such findings were absent in non-wearers. Cell density was reported to be within the predicted limits for age-matched controls. A greater morphometric change was evident when subjects were examined after five hours of lens wear compared to baseline measurements taken in the morning. In addition, the PMMA wearers exhibited more profound non-reversible endothelial changes than observed in hydrogel lens wearers, which correlated with greater duration of wear. These endothelial changes were found to be non-reversible. Although there was no significant loss of cell count in this group of PMMA wearers compared to controls, it was suggested that polymegethism and pleomorphism are the first stages of a tendency for the endothelium to lose cells more rapidly.

Endothelial polymegethism and pleomorphism as a result of PMMA lens wear has also been observed by Schoessler (1991) and was recently confirmed by Setala et al (1998) who investigated 44 eyes wearing PMMA lenses for at least 10 years. The study reported extensive pleomorphism and polymegethism compared to non lens-wearing subjects and also reported a decrease in endothelial cell density.

The aetiologies of polymegethism and reduced endothelial function in response to long-term PMMA lens wear are unknown. It has been suggested that these changes are due to chronic hypoxia at the endothelium. However, reports indicating a reduction of oxygen levels at the endothelium have been equivocal (Kwon et al 1972; Barr and Schoessler 1980). Polymegethism could be caused by chronic reductions in corneal pH as it has been demonstrated that both stromal (Bonnano and Polse 1987) and aqueous humor pH (Thomas et al 1990) become reduced during contact lens wear. The mechanism by which pH could alter endothelial cell morphology remains unclear.

9.4.1.2 The effect of hard lens wear on corneal sensitivity

Hamano (1960) measured corneal sensitivity (Haag Streit pachometer 900) in 91 subjects wearing hard contact lenses. Certain subjects had worn lenses for no more than one year and others up to 22 years. Corneal touch threshold (CTT) was shown to be significantly elevated in subjects wearing lenses for between five and seven years. CTT then became reduced to a level slightly above the control group. Gould and Inglima (1964) observed little change in CTT compared to normal subjects after ten week's wear and one year. Unfortunately, no reference was made to the number of hours the patients had worn the lenses on the day of measurement. This information is critical because measurements made in the morning before lenses are inserted would indeed show no change in CTT due to the fact that there is usually complete overnight recovery of CTT during the first years of lens wear (Millodot 1991). Morganroth and Richman (1969) assigned subjects to two groups, one with new lens wearers (less than three months) and one with long-term lens wearers (between five to nine years). Although groups showed CTT higher than control subjects, the group wearing the lenses for the longer time had a CTT twice that of those who were new to lens wear.

Millodot (1976) took CTT measurements from a group of nine non lens-wearing subjects who were then fitted with hard lenses. Measurements were repeated two years later and the author reported a small difference in CTT compared to baseline measurements. Certain subjects showed an improvement in CTT, whilst others showed a degradation of sensitivity following two years of lens wear. Later, the same author carried out an investigation of patients wearing PMMA lenses for up to 22 years (Millodot 1978). Data obtained in the morning before lens insertion demonstrated that overnight CTT recovery was more or less complete in subjects who had worn lenses for up to two to three years. After five years of wear, there was a significant increase in CTT in the morning, indicating that overnight recovery had not fully completed. CTT was also found to increase as the duration of lens wear lengthened (figure 9.1).

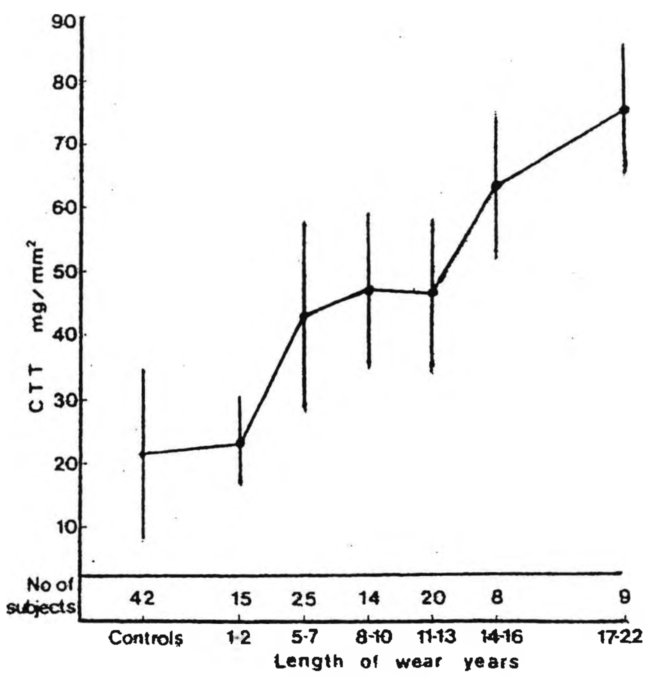


Figure 9.1 - CTT as a function of length of wear of hard contact lenses. Controls indicate non-contact lens wearers (Millodot 1978).

Sanaty and Temel (1998) reported similar conclusions in their investigation of 20 subjects who had worn PMMA lenses for up to 20 years. The reduction of corneal sensitivity was found to be most prominent centrally and was related with the duration of PMMA contact lens use.

9.4.1.3 Summary

PMMA lenses stimulate a number of corneal changes principally due to reduced oxygen levels at the corneal surface. Most investigations into the long-term use of PMMA lenses have reported:

- Endothelial polymegethism and pleomorphism (Schoessler and Woloschak 1981; Caldwell 1982; Hirst et al 1984; MacRae et al 1986; Schoessler 1991; Setala et al 1998)
- Decreased corneal sensitivity (Hamano 1960; Morgonroth and Richman 1969; Millodot 1976, 1978; Sanaty and Temel 1998).

9.4.2 Effect of long-term hydrogel contact lens wear

Most hydrogel contact lenses transmit a limited quantity of oxygen to the cornea, but this alone is not sufficient to prevent corneal oedema (Fatt and St Helen 1971). Therefore, hydrogel lenses should be fitted so that the tear pump, provided by blinking, is sufficient to circulate oxygen beneath the lens and thus prevent corneal oedema. A number of investigators have shown that the oxygen level required to prevent corneal oedema is not achieved with the hydrogel lenses in common use (Bailey and Carney 1973; Mandell 1971; Polse et al 1975). For any given hydrogel material the oxygen passing through the contact lens is inversely proportional to its thickness, therefore, developments in lens design aim to produce as thin lenses as possible (Fatt 1978). Although attempts have been made to increase the amount of oxygen received by the cornea, hydrogel lenses are still thought to produce a certain amount of corneal oedema.

9.4.2.1 The effect of hydrogel lens wear on corneal thickness

In the most extensive study to date into the effects of long-term hydrogel lens wear on corneal physiology, Holden et al (1985) investigated 27 patients who had worn a high water content hydrogel lens in only one eye on an extended wear basis for an average of 62

(± 29) months. The other eye which was either emmetropic or amblyopic, acted as the control. Epithelial examination revealed a reduction in oxygen consumption in response to hydrogel contact lens wear, which led to epithelial thinning. Epithelial cysts were also observed in the lens-wearing eye of most subjects. The results of the study suggested that the observed changes were due to chronic hypoxia, which led to impaired aerobic metabolic activity in the epithelium, hindering normal epithelial growth and resulting in epithelial thinning. Holden et al (1985, 1988) also examined the corneal stroma and reported that the lens-wearing eye experienced stromal thinning. Immediately on removal of the lens, stromal thickness was 2.5% greater in the lens-wearing eye relative to the control eye, but decreased following lens removal, eventually becoming thinner than the control eye by day 2. Stromal thickness in the eye that had been wearing the lens continued to decrease until day 7 and remained constant thereafter, being 2.3% thinner than the control eye. This difference was statistically significant on day 7. The precise mechanism of stromal thinning in response to hydrogel lens wear is unclear but it is thought that the cornea experiences chronic oedema during extended lens wear (Lebow and Pishka 1980; Schoessler and Barr 1980; Holden et al 1983) leading to morphological changes in stromal keratocytes (Kanai and Kaufman 1973). Since the bulk of the collagen, glycoproteins and proteoglycans are synthesised by keratocytes in the adult cornea (Hart 1982), it is possible that chronic lens-induced oedema interferes with the synthesis of stromal tissue, resulting in gradual stromal thinning. Alternatively, the chronic oedema associated with extended lens wear may lead to dissolution of stromal tissue due to the action of lactic acid, which accumulates in the stroma under hypoxic conditions in the stromal mucopolysaccharide ground substance (Klyce 1981). Stromal thinning was not associated with a change in VA, nor was there any evidence of stromal scarring or other anomalies on biomicroscopic examination. Patients were followed for 33 days after cessation of contact lens wear, by which time the epithelial microcysts had all but disappeared. There was a slight reduction in polymegethism, but no recovery in CT was detected. The study concluded that the clinical significance of stromal thinning was unclear. Although Holden (1985, 1988) concentrated on extended hydrogel lens wearers, it is probable that corneal thinning also occurs in long-term daily contact lens wear, although no studies to date have confirmed this.

9.4.2.2 Endothelial response to long-term hydrogel lens wear

The pleomorphism and polymegethism reported in response to PMMA contact lens wear is also thought to occur following long-term hydrogel contact lens wear. MacRae et al (1986) investigated 20 users of daily wear contact lenses who had worn lenses for an average of 6.3 years. The study reported that daily wear soft contact lenses caused endothelial polymegethism and pleomorphism similar to that caused by PMMA lenses. This finding was later confirmed by Schoessler (1991) who demonstrated that endothelial cells are affected by hydrogel contact lens wear in a similar manner to PMMA lens wear, thus implicating a reduced oxygen supply as being causative.

9.4.2.3 Corneal sensitivity in long-term hydrogel lens wear

There has been little research undertaken to elucidate the changes in corneal sensitivity that occur in response to long-term hydrogel lens wear. Among the research reported, Larke and Hirji (1979) monitored subjects wearing Sauflon 85 lenses and Millodot (1984) monitored subjects wearing X-Ten lenses (both high water content extended wear lenses). In both studies, corneal sensitivity diminished progressively with the number of weeks of lens wear. The maximum increase in CTT was shown with the X-Ten lens, which showed a 50% increase by the 13th week. These data show that even lenses with high oxygen transmissibility cause some loss of corneal sensitivity.

9.4.2.4 Summary

The wearing of hydrogel contact lenses appears to produce similar corneal changes to those produced by PMMA lenses:

- Endothelial cell pleomorphism and polymegethism (MacRae et al 1986; Schoessler 1991)
- Decreased corneal sensitivity (Millodot 1984).

Furthermore, epithelial and stromal thinning in response to extended hydrogel lens wear has been reported by Holden (1985, 1988), indicating that long-term wear of hydrogel contact lenses may significantly alter the synthesis of corneal tissue.

9.4.3 Effect of long-term RGP lens wear

Much research has concentrated on PMMA lens wear as the corneal consequences to an impermeable oxygen barrier are many. In contrast, RGP lenses have received little attention due to the fact that they are permeable to oxygen and are therefore thought to address the problems encountered with PMMA lens wear. In addition, rigid lenses show a significant amount of movement during blinking which creates a secondary route for atmospheric oxygen to reach the cornea. This secondary route can supply between 30 to 100% of the oxygen necessary for maintenance of a normal corneal metabolism (Mandell and Farrell 1980).

9.4.3.1 Endothelial response to RGP lens wear

Nieuwendaal et al (1994) examined corneal hydration control (by a corneal stress test) and endothelial morphological changes due to long-term low Dk RGP contact lens wear in 21 subjects. There was a significant increase in polymegethism and pleomorphism in the group wearing contact lenses compared with the control group and a significant relationship was found between morphological parameters and induced swelling, indicating that induced swelling decreased as the morphologic alterations increased. The study concluded that increased endothelial polymegethism and pleomorphism may be accompanied by a decreased corneal hydration control in people who wear contact lenses.

9.4.3.2 The effect of RGP lens wear on corneal sensitivity

RGP lenses are also thought to cause a certain degree of corneal sensitivity loss. Results for several types of RGP lenses show that the greater the Dk, the smaller the loss of corneal sensitivity. Douthwaite and Connelly (1986) fitted a RGP lens and a PMMA lens to each eye of the same subject. Of the two, the PMMA lens induced the greatest loss of corneal sensitivity. Lydon (1986) compared three types of rigid contact lenses and drew a similar conclusion, namely, that changes in corneal sensitivity were directly related to epithelial oxygen levels.

Bergenske and Polse (1988) showed that patients refitted with RGP lenses, having previously worn PMMA lenses, regained lens awareness. Indeed, in most patients, corneal sensitivity had returned to almost normal levels six months after refitting.

9.4.3.3 Summary

There has been little research concentrating on the effect of long-term RGP lens wear. From the studies conducted to date, low Dk RGP lenses cause similar hypoxic changes to PMMA and hydrogel lenses, that is:

- Endothelial cell pleomorphism and polymegethism (Nieuwedaal et al 1994)
- Decreased corneal sensitivity (Douthwaite and Connelly 1986; Lydon 1986).

With regards to high Dk RGP lenses, it appears that the greater the Dk of the RGP lens, the smaller the loss of corneal sensitivity. The effect of high Dk RGP lenses on endothelial cell morphology has not yet been studied.

9.5 Effect of contact lens wear on visual performance

The plethora of changes that occur during long-term contact lens wear may have a significant impact on visual performance. Common complaints of contact lens wear include photophobia and poor vision, despite good high contrast VA. Corneal oedema (Westheimer 1961; Miller et al 1967; Hess and Garner 1977), contact lens deposits (McClure et al 1977; Gellatly et al 1988), spherical aberration (Westheimer 1961) and poor lens centration each contribute to a subject's reduced visual performance with prolonged lens wear. Other phenomena that may specifically affect visual performance in PMMA or RGP lens wearers include dazzle from the lens edge, the entrance of unrefracted light into the eye and multiple reflections from the lens surface.

The most common subjective complaint of contact lens wearers is that their vision is worse when wearing lenses compared to that with spectacles. This has led to attempts to define the causative factors. Many of the studies have concentrated on the quality of vision with hydrogel lenses. Several techniques have been employed in these investigations, including Variable Contrast Acuity Charts (VCAC), CS devices, and measurements of forward light scatter.

9.5.1 Effect of contact lens wear on measures of visual acuity

Several factors may be responsible for the reduced VA experienced with different types of contact lenses. Hydrogel lens wearers may experience such difficulties as a result of uncorrected refractive cylinder, strain induced with lathe-cut lenses during the manufacturing process (Mandell and Kong 1988) and hydrogel lens induced flexure (Gundel et al 1988). Reduced vision in RGP wearers is commonly the result of lens-induced flexure (Herman 1983), warpage (Henry et al 1987; Henry et al 1990) and/or poor surface wettability (Grohe and Caroline 1989).

Millodot (1969) investigated the variation in VA experienced in response to contact lens wear. VA was measured at various luminances in four myopic contact lens-wearing subjects who had worn PMMA lenses for one year. Contact lenses generally provided better acuity at high luminances, but acuity was significantly improved with spectacles as the luminance was reduced. This finding was attributed to the spherical aberration produced by the contact lens on the eye (Ivanoff 1956; Jenkins 1963; Bonnet 1964; Elnasher and Larke 1986). Such spherical aberration was first studied by Westheimer (1961). When the eye is fitted with a contact lens, the first corneal refractive surface is replaced by that of the contact lens. The anterior surface of a contact lens is spherical with a curvature which is high relative to its aperture. As such, it produces significant spherical aberration.

Woo and Sivak (1976) concluded that there was actually little difference in the in vivo value of the eye's spherical aberration when wearing hard or hydrogel lenses. Bailey (1971) also came to the same conclusion for hard lenses. The experimentally determined values of spherical aberration for the eye are substantially better than those calculated from theoretical considerations (Jenkins 1963). This phenomenon was explained by Bonnet (1964) who reported that the corneal spherical aberration was of opposite sign to that of the crystalline lens. Therefore, the combination of the crystalline lens and cornea reduce the amount of spherical aberration in the eye.

The flexible nature of hydrogel contact lenses permits the aspheric nature of the cornea to resume its role in reducing spherical aberration. Therefore, it is logical to predict that spherical aberration should be less with hydrogel lenses than with hard lenses. Therefore, if spherical aberration causes a reduction in CS it should be more pronounced with hard lenses compared with hydrogel lenses. However, Wechsler (1978), who conducted a study of VA with spectacles, hard lenses and hydrogel lenses, suggested that spherical aberration was in fact an important factor in reducing VA in both hard and hydrogel lenses. Seventy five hydrophilic lens wearers (B&L soflens) and 75 PMMA hard lens wearers were investigated. In cases of uncorrected refractive error an over refraction was used. None of the subjects in the study had worn contact lenses during the year prior to the pre-fitting examination. Among traditional hard lens-wearing eyes, there was a small decrease in acuity when comparing best corrected spectacle acuity with the VA achieved with contact lenses. When the hydrogel contact lenses were applied, there was an appreciable decrease in VA. Even with the addition of a spherocylindrical over refraction, the acuities did not reach the same level as the acuity with spectacles alone. The study reported that 25% of contact lens wearers (hard and hydrogel) exhibited a decrease in measured VA, even with the refractive error completely corrected, suggesting that spherical aberration was a possible cause of reduced VA in both types of lens wear. Lens surface deposits were also partly responsible for the results obtained.

9.5.1.1 Effect of deposits on measures of visual acuity

Poor surface wettability may be due to lens deposits, which occur in all types of contact lenses. It is estimated that between 50 and 70% of regularly worn hydrophilic lenses have some form of deposit adhering to them (Randeri 1974; Randeri and Glicksir 1975). In fact recent studies indicate that these deposits appear on hydrogel lenses after as little as one minute of wear and that both the amount and type of deposits increase the longer the lenses are worn (Leahy et al 1990; Lin et al 1991). Rigid lenses are also prone to deposition but this seems to be less of a problem than with hydrophilic lenses (Fowler et al 1984; Fowler et al 1987; Walker 1988). The deposits occurring on rigid lenses are similar to those found on hydrophilic lenses, although the relative proportions may differ (Fowler et al 1984; Fowler et al 1987). The components of these deposits are derived primarily from the tear film and their effect is to disrupt the tear film itself (Leahy et al 1990), decreasing lens comfort and increasing wearer dissatisfaction (Roth 1978).

Clearly, contact lens deposits may have a detrimental effect on VA. McClure et al (1977) demonstrated that a drop in VA occurred over a period of six months following daily wear of an RGP contact lens and proposed that the increase in protein deposition and the reduction in VA observed with wearing time were related. Gellatly et al (1988) subsequently supported these findings and demonstrated that high contrast VA declines with increasing lens deposition and with the length of time a lens is worn.

9.5.2 Effect of contact lens wear on Variable Contrast Acuity

The use of low contrast letters is a valuable tool in the evaluation of the contact lens-wearing population, as diffusive blur caused by protein deposition may not significantly affect measures of high contrast acuity. In fact, Regan and Neima (1983) reported that diffusive blur caused a larger drop in low contrast VA than refractive blur (Ho and Bilton 1986; Guillon and Sayer 1988). This finding was disputed by Gellatly et al (1988) who reported that low contrast letter charts only scored consistently one letter lower than high contrast letter charts, and hence added no additional information. However, the extent of lens deposit that was measured in this study may not have been sufficient to induce enough diffusive blur.

Other studies using VCACs have shown that certain lathe cut daily wear hydrogel lenses outperform spin cast lenses when tested on the same patients. Similarly, Acuvue disposable lenses produced by cast moulding directly in their final form outperform spun cast (Guillon and Schock 1991) and lathe cut lenses (Guillon et al 1993). Worsening lens wettability with wear has been shown to be associated with visual losses as measured using VCACs (Doane et al 1990; Guillon et al 1991).

9.5.3 Effect of contact lens wear on the contrast sensitivity function

9.5.3.1 Hydrogel lenses

9.5.3.1.1 Studies investigating newly dispensed hydrogel lenses

An early study by Applegate and Massof (1975) found a decreased sensitivity to intermediate spatial frequencies (2 - 4 cpd) in three non-adapted subjects wearing early series Bausch and Lomb hydrogel lenses compared with spectacles. However, the subjects tested manifested a residual error when wearing lenses, and when this residual error was corrected, there was no change in the CSF. Subjects wore the lenses at least two hours prior to testing.

Bernstein and Broderick (1981) tested the CSF of nine non-contact lens-wearing subjects wearing a B & L lens (Series B3, B4, N) in one eye and a spectacle correction in the other, at two hourly intervals over an 18 hour period. No difference in CSF between spectacle and contact lens correction could be found. In contrast, Mitra and Lamberts (1981) reported a decrease in CSF at all spatial frequencies in 12 non-contact lens-wearing subjects following fitting with the B&L Soflens (Series B3, U3). Measurements were taken 30 to 60 minutes following contact lens fitting and then repeated approximately two weeks later. The decrease was attributed to several possible factors, including optical aberrations from the contact lens and subclinical corneal oedema. Uncorrected residual error was not cited as a cause of CS loss, as 11 out of 12 subjects with no residual astigmatism still exhibited significant CS loss. It was hypothesised that the decrease in the CSF with time was the result of deposit formation.

Grey (1986) reported a gradual loss of CS during the first hour of hydrogel lens wear. Eighteen non-contact lens wearers were recruited, each of whom had 6/6 acuity and less than 0.25 DC of astigmatism. Subjects were each fitted with the B & L Soflens. Six were fitted with B3 series lenses (centre thickness 0.12 mm), 6 with U3 lenses (centre thickness 0.07 mm) and 6 with the O3 series (centre thickness 0.03 mm). Pachometry measurements were also taken (using a Haag-Streit slitlamp). The author reported a significant drop in CS at all spatial frequencies tested (0.75, 2, 6 and 16 cpd) which was attributable to corneal adaptation to the contact lens following one hour of lens wear. The loss in CS increased in severity with increased hydrogel lens centre thickness. All spatial frequencies were affected, to differing degrees, and no clear pattern was evident with regard to spatial frequency. The subjects had little residual refractive error and so this could not be cited as a cause of the reduced CSF. Local environmental changes were considered as the most likely cause of the CS reduction. Ford (1974), in a comprehensive investigation into hydrogel lens parameters, concluded that there were a large number of potential causes of contact lens changes (e.g. pH, tonicity, temperature, volume of tear production, degree of hydration) which summate to modify the lens radius, diameter, and/or thickness to give a significant error of power when the lens was settled on the eye. In fact, the subjects investigated by Grey (1986) maintained a high level of VA throughout the experiment, suggesting that power error could not be the cause of the reduced CSF observed in hydrogel lens wearers. In addition, the CS loss was found to remain following removal of the lens, indicating that changes in the cornea, rather than changes in the hydrogel lens itself, were the cause of the CS loss. In fact, the reduction in CS paralleled the increase in corneal oedema as the greatest change in CT caused the greatest change in CS. The study concluded that the reduction in CS, when wearing hydrogel lenses, was due to corneal oedema.

Other studies have shown that uncorrected refractive astigmatism, even in small amounts, will result in a decrease in CSF, especially at higher spatial frequencies (Gundel et al 1988). Gundel et al (1988) investigated the effect of mild residual astigmatism on the CSF. Seven astigmatic myopes (cylinder correction less than 1.00 DC) and eight spherical myopes were investigated. All subjects had worn lenses for three to nine years and were ophthalmologically normal. The study concluded that all but the highest spatial frequencies tested were affected by residual astigmatism and that this decrease was not solely from the hydrogel lenses (spherical contact lens wearers revealed no loss of CS) or from the absence of cylinder correction (a spherical equivalent in spectacle form did not lead to as much loss in CSF). Hydrogel lens-induced flexure was implicated as a possible cause of a reduced CSF (Gundel et al 1988).

Improvements in experimental technique and more rigorous statistical analysis have led to the consensus view that hydrogel lenses do not significantly impact on CS (Teitelbaum et al 1985; Tomlinson and Mann 1985; Nowozyckyj et al 1988). It is now thought that poor controls and the effects of residual astigmatism, contact lens adaptation, chronic corneal oedema and lens deposits may all contributed to the decline in CS reported in earlier experiments. The visual impairment suggested in former studies was negated by tighter controls, eliminating the effects of residual astigmatism, contact lens adaptation, chronic corneal oedema and deposits on lenses. Teitelbaum et al (1985) used new lenses in 12 adapted contact lens wearers (duration of contact lens wear was not stated) and controlled for adaptation and astigmatism. Measurements were taken after 15 minutes. It was concluded that newly dispensed hydrogel lenses did not alter the CSF and that the CSF was similar for three polymers of differing water content. Likewise, other clinical studies investigating non-astigmatic hydrogel lens wearers have found there to be no difference in CSF between spectacle and hydrogel lens wearers (Tomlinson and Mann 1985; Nowozyckyj et al 1988). In fact, Tomlinson and Mann (1985) reported a statistically significant increase in contrast sensitivity using lathe cut lenses. However, the increase in CS was not clinically significant as defined by a 0.02 log unit difference. Nowozyckyj et al (1988) investigating 14 non-adapted subjects, fitted two types of hydrogel lenses (38% and 67% water content) and measured CS without glare after 0.5 and six hours of lens wear, and CS with glare after 1.5 hours and 7.5 hours. Measurements were repeated seven weeks later. The study reported no significant differences in CS (with or without glare) for lens fit, thickness or water content. It must be stressed that these conclusions were drawn from studies of subjects wearing 'ideal' lenses.

9.5.3.1.2 Studies investigating 'used' hydrogel lenses

The effect of long-term hydrogel lens wear on CS is uncertain as most studies have not specifically investigated the variations in performance in established lens wearers. Woo and Hess (1979) proposed that if a patient suffered from symptoms of visual disturbance whilst wearing hydrogel contact lenses, there was a large reduction in CS. In contrast, if the patient was asymptomatic, no reduction in CS occurred. This conclusion was made after measuring only three hydrogel lens patients (the duration of contact lens wear was not stated), two of whom were asymptomatic whilst one complained of reduced vision (with normal acuity). The subject who complained of blurred vision revealed a reduced CSF which was greatest in the high spatial frequency range. Grey (1987) investigated the CSF in six patients during the first six months of contact lens wear. Subjects were fitted with the CLS 40 hydrogel lens and CS, CT and VA measurements were taken at regular intervals during the six month period. It was reported that a temporary reduction in high spatial frequency CS (16 cpd) occurred during the first two weeks of wear, subsequently recovering to baseline levels. CT increased by 4.9% on the first day of lens wear, thereafter gradually returning to, but never quite attaining, prefitting levels. The study concluded that there was no evidence to support complaints of poor vision resulting from long-term contact lens wear.

9.5.3.1.3 Summary

The effect of hydrogel lens wear on the CSF has been assessed in several studies. These studies vary considerably in their experimental design, choice of subjects and lenses, and sophistication of data analysis. Most studies have evaluated the effect of a hydrogel lens on the CSF following relatively short periods of lens wear. Certain studies have used newly dispensed lenses in non-adapted wearers and reported:-

- Loss at intermediate spatial frequencies after two hours of lens wear (Applegate and Massof (1975)

- No difference between lenses and spectacles over an 18 hour period (measurements taken at two hourly intervals) (Bernstein and Broderick 1981), on the first day of lens wear (following 0.5 and six hours of lens wear) and following seven weeks of lens wear (Nowozyckyj et al 1988)
- reduced CS at all spatial frequencies following one hour of lens wear (Grey 1986).

Other studies have used newly dispensed lenses in adapted wearers and reported:

- CS loss at all spatial frequencies following 30 to 60 minutes of lens wear and two weeks later (Mitra and Lamberts 1981)
- No loss of CS at any spatial frequency after 15 minutes wear (Teitelbaum et al 1985).

The effect of long-term hydrogel wear has not been extensively studied, although:

- a high spatial frequency loss was reported by Grey (1987) after two weeks of lens wear, which subsequently returned to baseline levels following six months wear.
- no reduction in CS was reported by (Gundel et al 1988) following three to nine years lens wear.

No study to date has investigated the effect of hydrogel lens wear on the CSF following long-term established lens wear of greater than ten years duration.

9.5.3.2 Rigid lenses

9.5.3.2.1 Studies investigating newly dispensed rigid lenses

There have been few studies of rigid (PMMA or RGP) contact lenses and their effect on the CSF. Of the few performed, Applegate and Massof (1974) found a decreased sensitivity to intermediate spatial frequencies (2 - 4 cpd) in three non-adapted subjects wearing PMMA lenses compared with spectacles. However, the subjects tested manifested a residual error when wearing lenses, and when this residual error was corrected, there was no change in the CSF. Subjects wore the lenses at least two hours prior to testing. Guillon et al (1983) investigated distance CS (using the Nicolet System 2000) and near CS (using the Arden gratings) in three groups of 20 subjects. Subjects were spectacle or asymptomatic contact lens wearers (the duration of lens wear was not stated). Subjects in Group 1 were corrected by spectacles, Group 2 with RGPs and Group 3 with Hema 38% lenses. Subjects were fitted with lenses and measurements were taken at two different visits (the time scale between the visits was not stated). The study reported that both RGPs and hydrogel lenses induced a decrease in CS for mid spatial frequencies under high illumination levels at distance. Under low levels of illumination, the CSF for high frequencies was reduced for the RGP lens wearers. Even though this study used large diameter optical zones, it was suggested that the decline in the CSF was due to large pupil size, imperfect lens centration and possible off-axis aberrations.

Eggink et al (1990) compared VA and CS in RGP lens-wearing subjects following fitting with Diffrax RGP lenses. The diffractive optics design which, although providing a multi-focal correction using the simultaneous vision concept, provides an equal, but reduced amount of light for distance and near vision images. Twenty-five subjects participated, all of whom had worn RGP lenses for at least one year. The length of adaptation time to the Diffrax lenses was not stated. Eggink et al (1990) reported that the CSF was significantly lower with the diffractive lens than with a conventional RGP lens design. The spatial frequency at which the loss occurred was not stated. Woods (1993) and Woods et al (1993) investigated the optical (Modulation transfer function (MTF) measured using a solid state EROS) and visual performance (monitor based CS, Pelli-Robson, and high-and low-contrast VA) of three types of bifocal lenses (rigid concentric design refractive bifocals, rigid diffractive and soft diffractive bifocals) in a small group of experienced subjects. Each contact lens was worn for a maximum of 45 minutes. The MTF of the rigid type bifocals was investigated by varying the aperture size and amounts of decentration. Decentration was shown to have a much greater effect on the MTF of the refractive than on the MTF of the diffractive bifocals. The MTF of the refractive bifocals was related to the proportion of the aperture covered by the central optical zone. Furthermore, CS at 8 and 16 cpd and VA were better with the centre-distance bifocal, but CS at 2 and 4 cpd and Pelli-Robson were better with the centre-near bifocal. As the central optical zone diameter increased, visual performance improved with the central optical zone forming the focus and reduced with the peripheral optical zone forming the focus with both centre-near and centre-distance for CS at 2, 4, 8 and 16 cpd. There was good agreement between measures of optical and visual performance. For the rigid diffractive lens, the effect of decentration upon optical performance was shown to vary with spatial frequency and again, there was good agreement between optical and visual performance measures. The soft diffractive lens design revealed poor optical quality and optical measures proved more sensitive to manufacturing differences than visual performance measures. In fact, reliability of visual performance measures was reported to be reduced if the bifocals were decentered compared to previous reports with normal well-corrected subjects and the test-retest repeatability coefficients increased as the average visual performance declined.

Tomlinson and Mann (1985) used a short-duration stimulus CSF test to measure temporal fluctuations in vision after the blink in contact lens wearers. Loss of sensitivity occurs for short periods (generally up to 50 msec) after the blink. This is caused by changes to the retinal image during lens movement. Losses were shown for both hydrogel and RGP lenses, but the magnitude of change was greater with RGP lenses due to their greater movement following a blink.

9.5.3.2.2 Studies investigating 'used' rigid lenses

The effect on CSF of rigid extended wear lenses has also been investigated (Ziel et al 1990). Baseline readings were obtained from 13 PMMA, seven hydrogel and four spectacle lens wearers (the duration of contact lens wear was not stated) before subjects were refitted with a rigid extended wear lens (Boston IV). Seventy-seven percent of subjects completed the study and measurements were taken at prior to the initial fitting and then following six and 12 months wear. The authors concluded that refitting yielded an improvement in CSF at all spatial frequencies in each of the three groups after one year of extended RGP lens wear.

9.5.3.2.3 Summary

Few studies into the effect of rigid lens wear on the CSF have been conducted. Again, those that have vary considerably in their experimental design, choice of subjects and lenses, and sophistication of data analysis. In summary:-

- PMMA lens wear has been shown to reduce the CSF at 2 - 4 cpd following two hours wear in non-adapted subjects (Applegate and Massof 1974)
- RGP lenses have been shown to reduce the CSF at mid spatial frequencies at high luminances, and high spatial frequencies at low luminances, in adapted and non-adapted wearers (length of wear not stated) (Guillon et al 1983)

- Diffrax RGP lenses have been shown to reduce the CSF (spatial frequency at which the loss occurred was not stated) in adapted lens wearers (adaptation time not stated) (Eggink et al 1990)
- Extended wear RGP lenses have been shown to improve CS at all spatial frequencies in adapted and non-adapted wearers after 1 year (Ziel et al 1990).

In conclusion, RGP lenses are thought to cause less of a reduction in CSF than hydrophilic contact lenses (Guillon et al 1983; Ziel et al 1990), although they still appear to cause a reduction in the CSF compared to the equivalent spectacle correction (Guillon et al 1983). No study to date has investigated the effect of RGP lens wear on the CSF after initial insertion (following a 30 minute adaptation period) or following long-term established lens wear of greater than five years duration.

9.5.4 The effect of contact lens wear on glare contrast sensitivity

Glare disability can be a problem associated with contact lens wear (Miller et al 1967; Applegate and Massof 1975; Remole 1977; Woo and Hess 1979; Harper and Halliday 1989) and is caused by a reduction in contrast of the retinal image due to a veiling luminance in the eye (Wolf and Gardiner 1965; Abrahamsson and Sjostrand 1986; van den Berg 1986) (section 1.3.2). Glare disability is generally measured as the difference in VA or CS in normal conditions compared with that observed when a nearby bright light source is present (Miller et al 1967; Paulsson and Sjostrand 1980; Abrahamsson and Sjostrand 1986). Most early work on PMMA lenses and glare disability found a reduction in visual performance due to light scatter, caused by corneal oedema (Miller et al 1967; Remole 1977). Glare disability is thought to be less of a problem with the increased use of RGP and hydrophilic lens materials (Polse et al 1975; 1989).

One of the first studies to investigate glare CS in the contact lens-wearing population was conducted by Applegate and Massof (1975). CSFs were measured using a method of increasing contrast in the presence of a glare source. Baseline measurements were performed on six spectacle wearing ametropes and then measured again after three patients were fitted with PMMA lenses and three patients were fitted with hydrogel contact lenses (Bausch and Lomb [B & L] Soflens). Although statistical analysis of the results was not carried out, the CSF curves did show that visual performance was poor whilst wearing contact lenses. This deterioration was greatest in the hydrophilic lens-wearing group and was also greater if the residual error of the contact lens prescription was left uncorrected, thus producing refractive blur. Other studies using CS (without a glare source) provided similar results (Woo and Hess 1977; Mitra and Lamberts 1981) (section 9.5.3.1.2). Tardibuono (1987) compared the effect on CSF and glare (the latter using a two-channel tachistoscope developed by Applegate (Applegate and Massof 1975; Applegate and Jones 1989)) of a tricurve versus a progressive aspheric design, in a flourosilicone/acrylate lens material. The study reported that the aspheric design performed as well as the spherical design.

Nowozyckyj et al (1988) investigating 14 non-adapted subjects, fitted two types of hydrogel lenses (38% and 67% water content) and measured glare CS after 1.5 hours, 7.5 hours and seven weeks. The study reported no significant differences in glare CS for lens fit, thickness or water content.

9.5.5 The effect of contact lens wear on other glare measurements

One of the first investigations into the effect of hard lens wear on glare measurements was conducted by Miller et al (1967). Fifty hard contact lens wearers were investigated using Landolt rings and a glare source. The study tested glare sensitivity before and after fitting (three weeks later) with hard contact lenses and reported a statistically significant increase in glare sensitivity in subjects who developed epithelial oedema whilst wearing their contact lens. No increase in glare sensitivity was found in subjects who did not develop epithelial oedema. In addition to epithelial oedema, it was suggested that the edge of the contact lens not covered by the pupil also contributed to glare sensitivity and photophobia.

Applegate and Wolf (1987), using the two-channel tachistoscope developed by Applegate (Applegate and Massof 1975; Applegate and Jones 1989), investigated five subjects, all of whom had a significant increment loss at low background luminance levels in the presence of a point glare source located one degree nasal to a test disc. Subjects were tested whilst wearing a hydrogel contact lens correction and then whilst wearing a spherical equivalent of their contact lens correction in the trial frame. All subjects were content, long-term wearers (2 to 11 years) of hydrogel lenses. The authors suggested that observed glare sensitivity was due to the contact lens material, lens deposits or corneal oedema, however a subsequent study by Applegate and Jones (1989) found less consistent results. Fifteen subjects (including the original five subjects who participated in the previous study) were examined using the same apparatus and similar protocols. All were satisfied long-term (2 to 8 years) hydrogel lens wearers with good VA 6/6 or better, through both their contact lenses and spherical equivalent trial frame correction. This time, no significant hydrogel contact lens induced increases in disability glare were found but analysis of individual data revealed three classes of effects within the population tested. Subjects either demonstrated a significant glare effect induced by contact lens wear (6 of 15), no increases in disability glare (7 of 15), or a significant decrease in disability glare (2 of 15). The five subjects included in the original study (Applegate and Wolf 1987), were not identified. Extrapolation of the results to the total population of hydrogel lens wearers suggested that at any point in time, approximately 40% of the subjects wearing hydrogel lenses will experience a significant increase in disability glare, 47% will show no significant increases in disability glare and 13% will experience significant decreases in disability glare compared to the disability glare experienced while wearing a spherical equivalent trial frame correction. This finding is consistent with the clinical impression that subjective complaints of decreased tolerance to glare are more common among hydrogel contact lens wearers than among spectacle wearers (Bennett et al 1989). The study concluded that the extrapolation was only a tentative prediction and suggested that hydrogel contact lens-induced disability glare may correlate with the quantity and type of lens deposits.

9.6 Effect of contact lens wear on measures of forward light scatter

Elliott et al (1991) and Mitchell and Elliott (1991) conducted a study of contact lens wearers using the van den Berg straylight meter. Seventeen established hydrophilic contact lens and 15 RGP contact lens-wearing subjects were investigated (all subjects were established wearers of least six months), together with 66 normal subjects (age range 19 to 79 years). Light scatter scores with and without the lens were calculated and the effect of lens deposits, contact lens material and corneal health on light scatter were evaluated. The study reported that light scatter scores were significantly greater in contact lens wearers than in age-matched controls. Pearson correlation coefficients were calculated for light scatter versus estimates of lens deposits, and the results demonstrated that there were no significant correlations for any combination ($p > 0.1$). This was an unexpected result, as previous studies had indicated that a relationship between visual performance and lens deposits existed (McClure et al 1977). The findings may be explained by the fact that significant light scattering may not occur until lens deposits have reached a critical concentration which was not attained by lenses in the chosen subject population. It was also suggested that measurement error could explain the contradictory findings. When light scatter scores with and without the lens were compared, mean straylight values for RGP lenses were significantly greater ($p < 0.001$) than for hydrophilic lenses. This was the basis for the authors' hypothesis that RGP lenses cause increased light scatter due to the lens material and design.

The effect of corneal integrity in contact lens wearers on light scatter was assessed by comparing the light scatter scores approximately 30 seconds after contact lens removal with age-matched normal data. For small and medium angle scatter, there was a significant difference between the hydrophilic group and controls but not between the RGP group and controls. Although none of the hydrophilic contact lens wearers showed clinically visible signs of corneal oedema, five subjects had straylight scores greater than the 95% confidence limits of normal. It was suggested that this was due to sub-clinical levels of corneal oedema. One RGP wearer had clinically visible corneal oedema and had straylight scores greater than the 95% confidence limits of the normal data at both small and medium angles. The study concluded that the corneal oedema produced in RGP wearers is likely to be stromal and due to the smaller size of the RGP lens, visible with slitlamp biomicroscopy. Hence, it was suggested that symptoms of disability glare in RGP lens wearers with normal corneal health are caused by either the rigid lens material, size or fit. Symptoms of glare disability in wearers of hydrophilic lenses were thought to be due to sub-clinical levels of oedema (Elliott et al 1991; Mitchell and Elliott 1991).

Corneal light scattering and visual performance were also investigated by Lohmann et al (1993) in a study of 35 myopic individuals. Subjects were divided into three groups: Group 1 wore spectacles and occasionally contact lenses ($n = 10$), Group 2 exclusively wore contact lenses ($n = 15$); and Group 3 had undergone excimer laser photorefractive keratectomy ($n = 10$). In Group 1, contact lenses were typically used only one to two days per week. In group 2, contact lenses were less than three months old and in daily use. Within Groups 1 and 2, the subjects were further subdivided on the basis of hard and hydrogel lenses. The duration of lens wear was not stated. All subjects underwent VCAC testing using a pyschophysical method designed by Lohmann et al (1991), traditional Snellen acuity, backscattered light using a method designed by Lohmann (1992) and forward scattered light using a method based on the technique of van den Berg (1986). The results of VCAC testing demonstrated that hydrogel lens wearers and the excimer laser group had significantly reduced acuity at 5% contrast. Also, most hydrogel lens wearers revealed higher levels of backscatter than spectacle wearing subjects. When the forward light scatter values obtained for each group were averaged, the hydrogel contact lens wearers revealed higher levels of light scatter than all other groups.

Lohmann et al (1993) concluded that there was no correlation between the magnitude of myopic correction and increased forward light scatter in either contact lens wearers or excimer laser photorefractive keratectomy patients. When the measurements of backscatter and forward light scatter were compared, the groups in which both scatter components were at their highest showed a correlation between these two scatter components. In all other groups, this relationship did not hold. In particular, virtually no backward light scatter was measured in certain subjects in the hydrogel contact lens group, but several individuals had considerable problems with forward light scatter (figure 9.2).

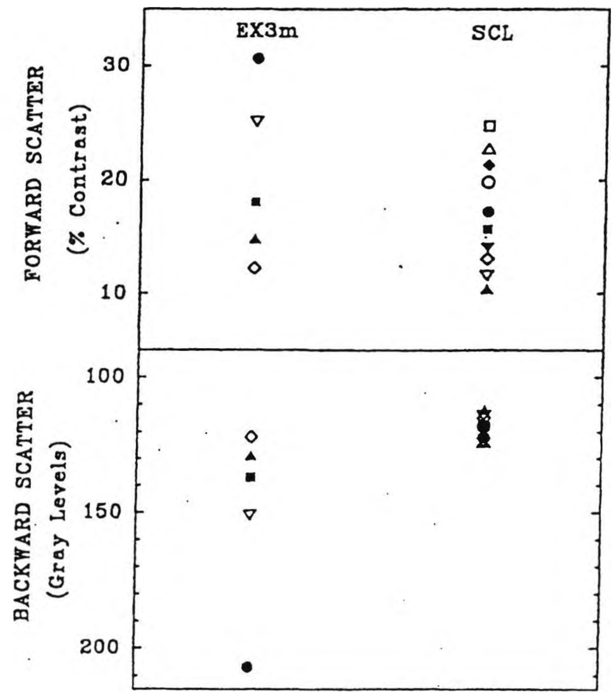


Figure 9.2 - The relationship between forward-scatter and backscattered light. Each data point indicates one subject. EX3m indicates excimer subjects at 3 months postoperatively; SCL indicates hydrogel contact lenses (Lohmann et al 1993).

The study suggested that small changes in hydration levels or in the quality of the tear film resulted in major changes in hydrogel contact lenses, which in turn effect visual performance. This suggestion corroborated with the findings of Timberlake et al (1992) in which a measurable loss of low-contrast VA was identified if the individual being tested did not blink over a period of seven seconds. This was an important observation, given that the investigators measured the average blinking interval in their population at 11 to 12 seconds. Therefore, it may be inferred that a decline in visual performance may result if subjects do not blink frequently during testing. Lohmann et al (1993) concluded that spectacles, hard contact lenses and PRK were all superior to hydrogel lenses in terms of forward light scatter and low-contrast VA.

9.7 Summary

Increased glare disability has been reported in PMMA lens wearers (Miller et al 1967; Remole 1977). RGP and hydrogel lenses are not thought to cause similar increases in glare disability (Polse et al 1975; 1989), although Applegate and Massof (1975) reported a greater deterioration in glare CS in hydrogel wearers when compared to PMMA lens wearers. This was confirmed by Applegate and Wolf (1987) using a two channel tachistoscope. A further study by Applegate and Jones (1989) found less consistent results and suggested that glare disability was dependent upon the individual's response to contact lens wear.

Only two studies to date have investigated the effect of contact lens wear on forward light scatter, and these have produced contradictory results:-

- Long-term (greater than six months) RGP wearers reveal more light scatter than hydrogel wearers and both groups revealed more light scatter than age-matched controls (Elliott et al 1991; Mitchell and Elliott 1991)
- Long-term (duration of lens wear not stated) hydrogel wearers reveal more light scatter than hard (type of lens not stated) lens wearers or spectacle lens wearers (Lohmann et al 1993).

No study to date has investigated the effect of RGP lens wear on measures of light scatter after initial insertion (following a 30 minute adaptation period) or following long-term established lens wear (of all types) within defined durations.

9.8 Study 1 - The effect of long-term contact lens wear on the light scattering characteristics of the eye

9.8.1 Aims

The aim of the Study 1 is to investigate whether long-term contact lens-wearers experience high levels of light scatter as measured by the integrated straylight parameter, k', or suffer CS loss when clinical tests, such as slit lamp biomicroscopy, reveal no significant corneal changes.

The availability of the P_SCAN 100 equipment and a researcher who could conduct the thorough investigation of the full scatter function and CS analysis has allowed the current study to:-

- investigate subjects within a well defined range of periods of lens wear
- investigate subjects wearing a range of contact lens materials
- obtain a direct measure of forward light scatter
- measure k', in addition to n and k

- compare measurements of scatter and the CSF over a wide range of spatial frequencies.

9.8.2 Subject selection

The majority of the contact lens-wearing subjects were recruited from a local contact lens practice or from City University eye clinic. All subjects wearing contact lenses were receiving regular aftercare and the surface quality of the contact lenses was examined to exclude those with protein deposits and/or lens abrasions. Each subject was examined using the slit lamp biomicroscope so that corneal integrity and lens opacification could be evaluated. All subjects underwent scatter and CS testing using the methodology described in section 5.7. Measurements were taken in the afternoon to avoid variability caused by the effects of overnight sleep (as discussed in section 6.13). Wherever possible, male subjects were chosen due to the increased variability noted in female subjects in Chapter 6 and 7. However, in order to complete the data set, five females were included but all were above the age of 40 years. As females are known to have reduced levels of oestrogen during middle age, the results from these five subjects are unlikely to be as variable as those found in younger females in Chapter 7. Therefore, subjects were included in the study if:-

- they had VA of at least 6/9
- they were ophthalmologically normal
- they had no significant lenticular changes (i.e. less than Grade 1 as measured by LOCS II)
- little/no protein deposits/lens abrasions were evident
- they were male
- they were female and over the age of 40.

Subjects were excluded from the study if :-

- they had VA of worse than 6/9
- they were not ophthalmologically normal
- they had significant lenticular changes (i.e. more than Grade 1 as measured by LOCS II)
- extensive protein deposits/lens abrasions were evident
- they were female and under the age of 40.

In all, 43 subjects were evaluated. However, due to the strict inclusion/exclusion criteria, only 29 subjects (54 eyes) were included in the analysis. Wherever possible, subjects were recruited to fit into the following matrix:-

Table 9.2 - The duration of lens wear of subjects included in Study 1.

	Period of lens wear					
Type of lens	maximum of 5 years lens wear - No. of subjects (eyes)	maximum of 10 years lens wear - No. of subjects (eyes)	maximum of 15 years lens wear - No. of subjects (eyes)	maximum of 20 years lens wear - No. of subjects (eyes)	maximum of 25 years lens wear - No. of subjects (eyes)	maximum of 30 years lens wear - No. of subjects (eyes)
Hydrogel	4 (7)	2 (4)	2 (4)	-	-	-
RGP	3 (6)	3 (6)	2 (4)	-	-	-
PMMA	-	-	2 (4)	-	3 (6)	-
Mixture	-	-	2 (4)	2 (3)	2 (4)	2 (2)

NB - Wherever possible recruited subjects had durations of lens wear close to 5, 10, 15, 20, 25 and 30 years.

From the initial stages of the study, it became clear that subjects wearing hydrogel or RGP lenses for periods of 20 years or more would be difficult to recruit. This is understandable, considering the relatively recent advent of hydrogel and RGP lenses. In addition, most long-term contact lens patients have experience of more than one lens type. For example, a patient who began contact lens wear 25 years ago, would normally have been fitted initially with PMMA lenses. Following the advent of more physiologically compatible lenses, most of these patients would have been refitted with either hydrogel or RGP lenses. As many subjects revealed this pattern of contact lens wear, a fourth group was included for investigation which contains those subjects who have experience of more than one type of contact lens. Subjects with only 5 or 10 years PMMA lens wear proved equally problematic to find. Given the range of lenses (which allow a much greater amount of oxygen through to the cornea compared to PMMA lenses) now available, PMMA is the least appropriate material to use when fitting potential contact lens wearers. Therefore, it was not surprising that this category of subjects proved impossible to recruit. Subjects wearing a mixture of lenses for either 5 or 10 years also proved impossible to recruit. This reflects clinical practice, as patients will usually develop clinical problems at the initial stages of contact lens wear (i.e. after a month or two) or following long-term (i.e. 10 years) contact lens wear (e.g. neovascularisation following long-term hydrogel lens wear).

9.8.3 Results of long-term contact lens wear

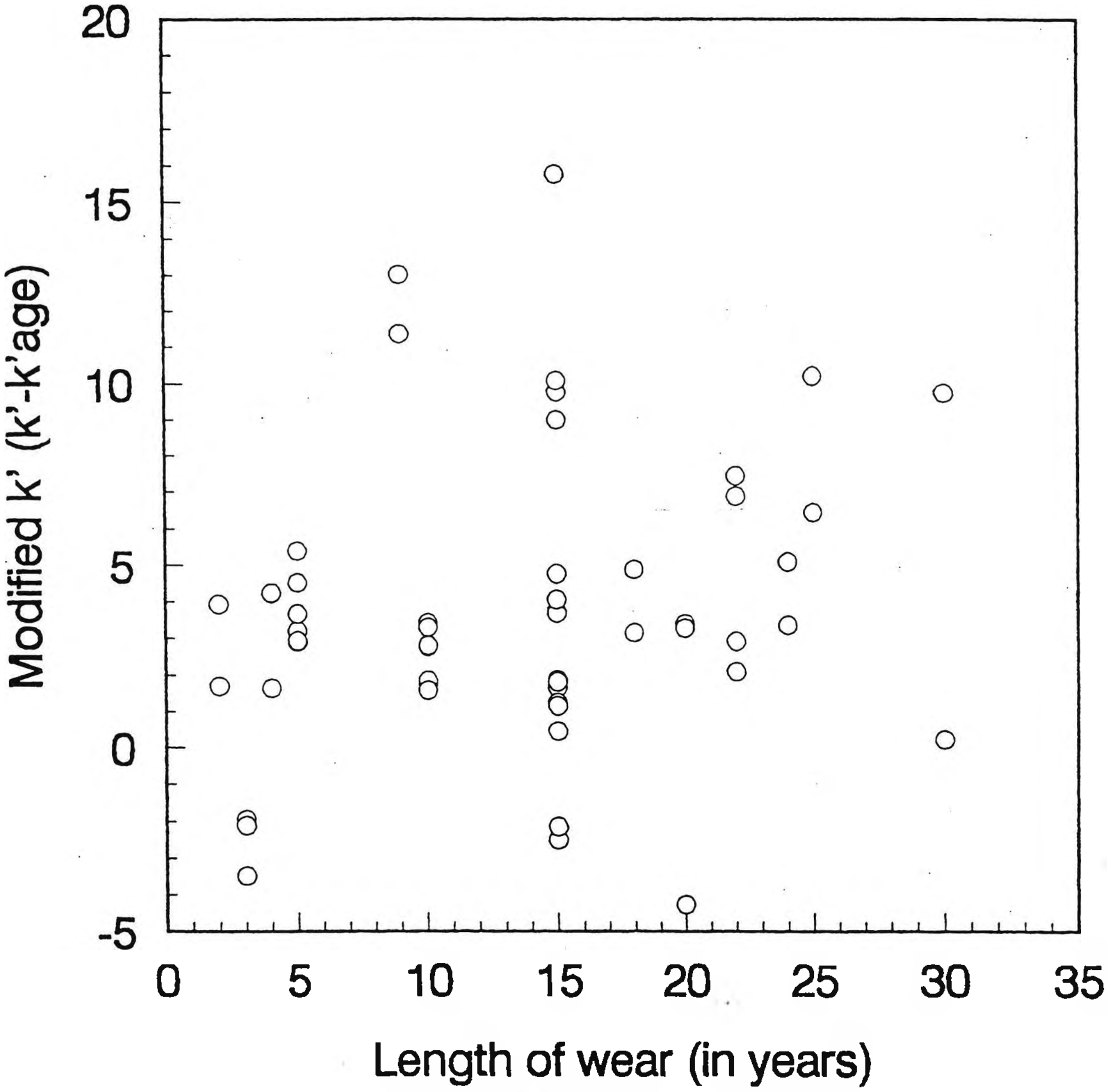
In order to account for the increase in light scatter with age, a modified k' parameter was calculated, that is k'-(k' *age*). The values of 'k' *age*' represent the normal k' for a non lens-wearing subject of the same age as the contact lens-wearing subject. The values for 'k' *age*' were obtained from the study into the effects of age on light scatter and contrast sensitivity (section 5.8, figure 5.2).

The results of all long-term contact lens wearers are shown in figure 9.3. The graph shows the modified k' values plotted against length of contact lens wear. Forty-eight out of the 54 eyes examined reveal increased levels of light scatter compared to age-matched controls. Six eyes (four subjects) reveal lower levels of light scatter than expected for their age (all these subjects were above 50 years of age). In order to evaluate whether long-term contact lens wearers have increased levels of light scatter when compared to control subjects, a t-test was conducted using the normal data described in section 5.8. When the results of long-term contact lens wearers (mean $k' = 13.52$, range 4.24 to 27.78) are compared to non lens-wearing subjects (mean $k' = 9.80$, range 6.42 to 17.59), statistical analysis reveals that contact lens-wearing subjects have significantly higher levels of light scatter than non lens-wearing subjects (two sample t-test $p < 0.001$, $t = 4.78$).

One way analysis of variance showed no statistically significant differences between the k' means for varying durations of lens wear (i.e. between a maximum of 5, 10, 15, 20, 25 and 30 years of lens wear), regardless of the type of lens worn ($p = 0.40$, F+1.05 Fishers LSD). These data should be interpreted with caution given the non-independence of data introduced by the use of both eyes of most subjects in the analysis and the small samples.

Table 9.3 shows the mean k'-(k' *age*) and s.d. obtained from contact lens-wearing subjects grouped according to age. No statistically significant differences were found, using one way analysis of variance, between the k'-(k' *age*) means for the five age groups ($p = 0.13$, F+1.88 Fishers LSD). Again, these data should be interpreted with caution given the non-independence of data introduced by the use of both eyes of most subjects in the analysis and the small samples.

Figure 9.3 *Change in modified k' for contact lens-wearing subjects over time in years*



○ Modified k' values obtained from 54 contact lens wearing eyes.

Table 9.3 - Mean *k'-(k' age)* and s.d. obtained from contact lens-wearing subjects grouped according to age.

Group (Age range in years)	**No. of subjects (eyes)**	**Mean *k'-(k' age)* (s.d.)**	**Mean s.d.** (s.d.)
Group 1 (20-29)	7 (14)	2.7 (1.31)	0.84 (0.52)
Group 2 (30-39)	3 (6)	3.5 (1.10)	0.74 (0.66)
Group 3 (40-49)	6 (11)	4.26 (3.13)	0.90 (0.78)
Group 4 (50-59)	12 (21)	4.71 (5.45)	1.36 (1.17)
Group 5 (60-69)	1 (2)	-2.33 (0.25)	1.3 (0.10)

The long-term effects of contact lens wear on the CSF appeared to vary markedly between individuals (section 9.8.3.1 - 12). Although classification is somewhat arbitrary, thirteen eyes revealed no CS loss, whilst 19 eyes showed loss at all spatial frequencies tested. Seven eyes revealed loss at high and intermediate frequencies, six at high and low spatial frequencies, five at low spatial frequencies only and two at intermediate and low spatial frequencies. One eye revealed loss at intermediate spatial frequencies only and one eye revealed loss at high spatial frequencies only. Therefore, in general, most contact lens wearers showed some degree of CS loss, compared to age-matched controls. Although pre-fitting CS results would have proved useful for comparison purposes, this was clearly impossible given the long-term contact lens wearing nature of the cohort.

In order to fully appreciate the changes in light scatter and CS that occur during long-term contact lens wear, the subjects have been classified into groups according to duration of lens wear. The individual scatter and CS results obtained from each subject are shown (figures 9.4 - 9.32).

9.8.3.1 Results of subjects wearing hydrogel lenses for a maximum of 5 years

Table 9.4 - Scatter results from four subjects wearing hydrogel lenses for a maximum of 5 years

Subject	Gender	Age (years)	Eye	*n*	s.d.	*k*	s.d.	*k'*	s.d.	*k'-k'(age)*
EP	Male	29	RE	2.03	0.20	28.29	14.88	11.38	1.81	4.52
			LE	2.15	0.17	28.23	7.41	9.76	0.24	2.90
PG	Male	30	RE	2.36	0.03	40.35	4.38	11.15	1.44	4.24
			LE	2.23	0.14	28.06	7.03	8.55	0.40	1.64
BH	Male	55	RE	1.60	0.03	14.54	2.22	14.95	1.46	1.70
			LE	1.60	0.08	16.60	3.36	17.20	0.34	3.95
WR	Male	56	RE	2.21	0.13	37.60	5.20	12.00	1.01	-1.95

Three of the four subjects (6 out of 7 eyes) who had worn hydrogel lenses for a maximum of 5 years reveal increased levels of light scatter compared to an age-matched control (figures 9.4 - 9.7). The exception is subject WR, who had a modest reduction in scatter compared to an age-matched control. The left eye of subject WR was not tested as the patient received PRK surgery to correct myopia one year previously. Two out of four subjects reveal CS loss at all spatial frequencies (i.e. EP and WR). BH reveals a bilateral CS loss at all spatial frequencies apart from 1.5 cpd (and 3 cpd in the left eye), whilst only the left eye of subject PG reveals any CS loss, at 10 cpd only.

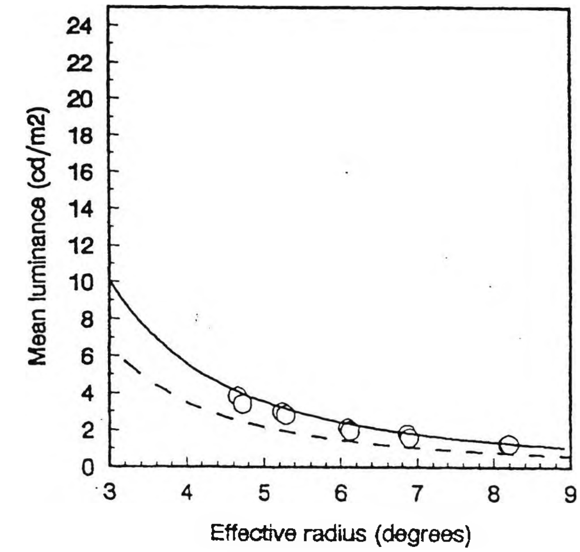
Subject EP showed the greatest increase in *k'* in this group of subjects. Figures 9.4a, b show higher levels of scatter in the right eye compared to both an age-matched control and to the left eye. A similar pattern is observed for subject PG (figure 9.5). Subject BH produced low *n* values in both eyes and this is reflected in figure 9.6a, b. The low *n* values indicate that the light scatter has a wide angular distribution (that is, a large spread).

9.8.3.2 Results of subjects wearing hydrogel lenses for a maximum of 10 years

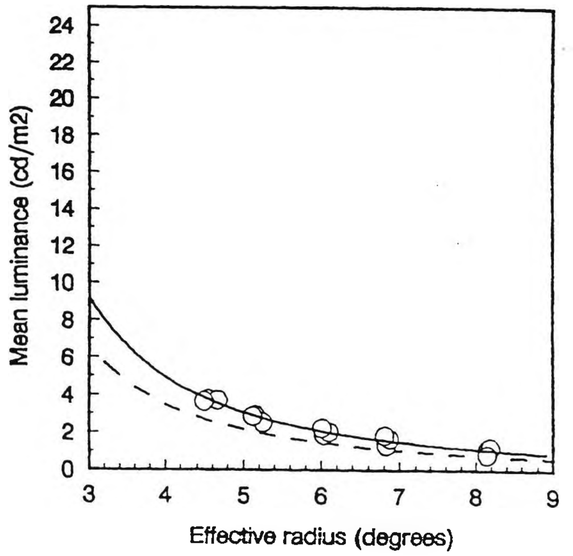
Table 9.5 - Scatter results from two subjects wearing hydrogel lenses for a maximum of 10 years

Subject	Gender	Age (years)	Eye	*n*	s.d.	*k*	s.d.	*k'*	s.d.	*k'-k'(age)*
AH	Male	24	RE	2.00	0.21	22.74	7.02	10.06	0.68	3.42
			LE	2.06	0.01	21.77	1.04	8.38	0.59	1.74
PB	Male	25	RE	2.12	0.16	27.05	6.63	9.97	0.57	3.29
			LE	2.12	0.08	25.56	2.60	9.44	0.27	2.76

Figure 9.4 *Scatter profile and contrast sensitivity results for Subject EP*

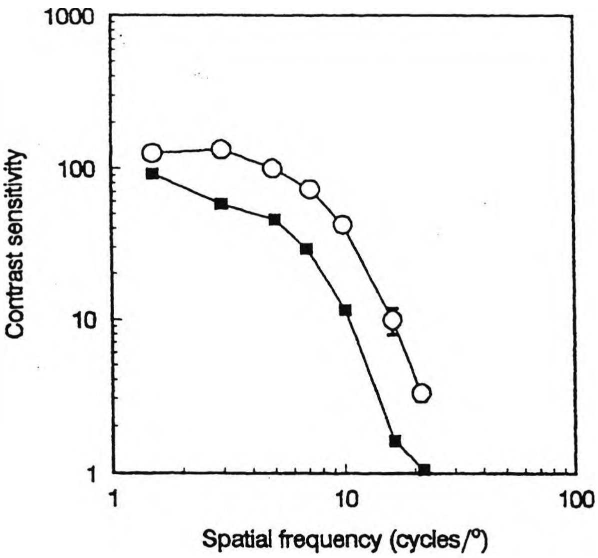


(a) Right eye scatter (O)

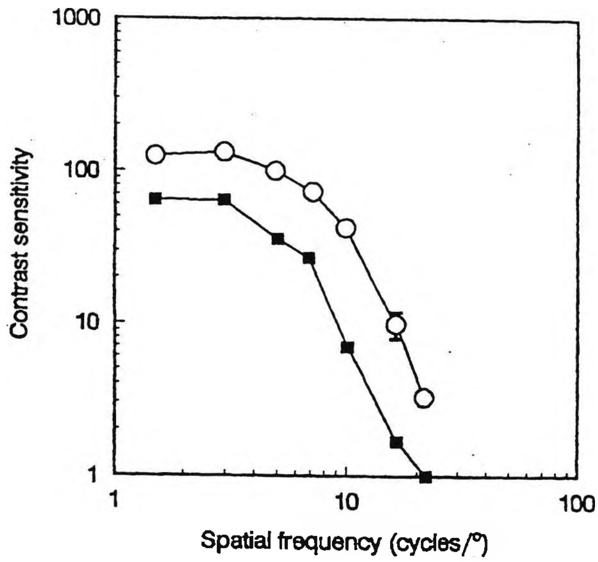


(b) Left eye scatter (O)

(- - - Age-matched control scatter values)



(c) Right eye contrast sensitivity (■)

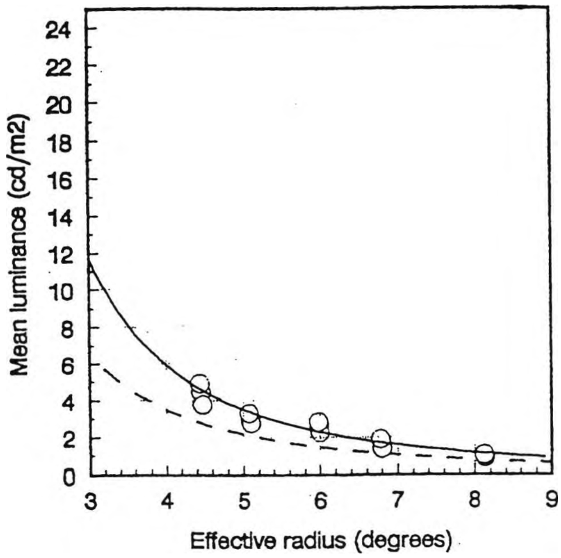


(d) Left eye contrast sensitivity (■)

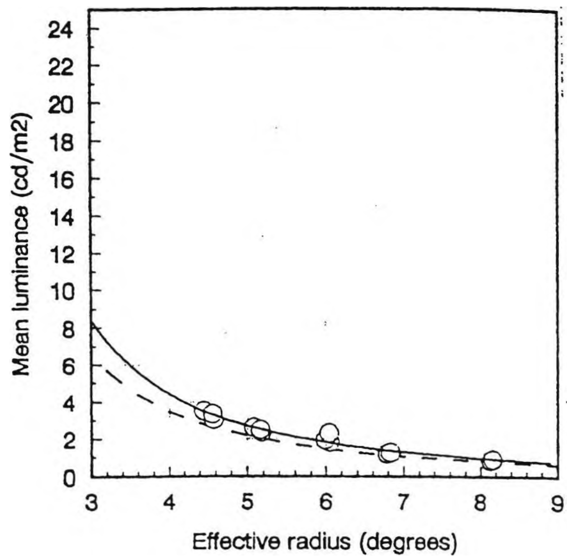
(O Age-matched control contrast sensitivity values)

Subject EP, male, Caucasian, 29 years.		
	Right eye	Left eye
Visual acuity	6/4	6/4
Contact lens type	Hydrogel	Hydrogel
Length of wear	5 years	5 years

Figure 9.5 *Scatter profile and contrast sensitivity results for Subject PG*

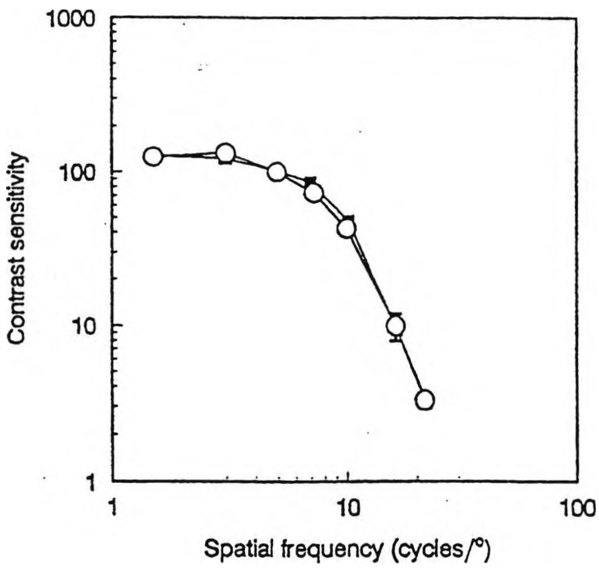


(a) Right eye scatter (O)

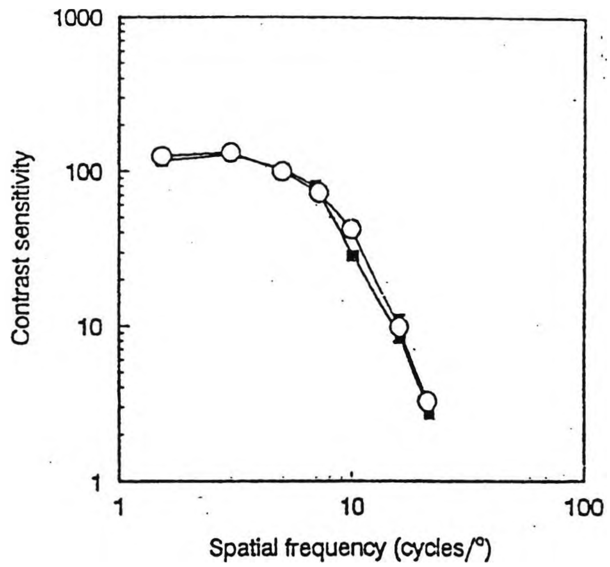


(b) Left eye scatter (O)

(- - - Age-matched control scatter values)



(c) Right eye contrast sensitivity (■)

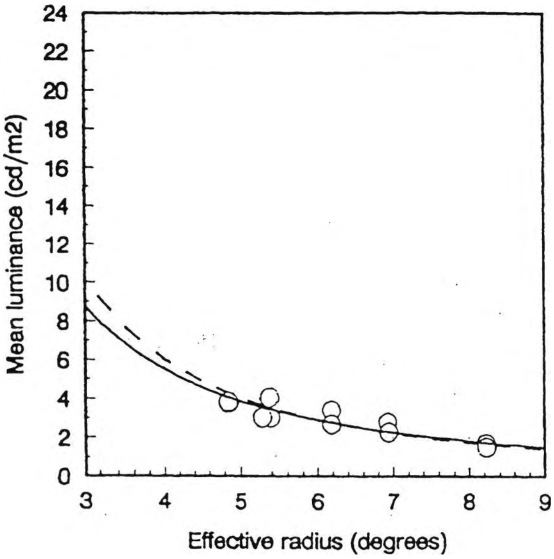


(d) Left eye contrast sensitivity (■)

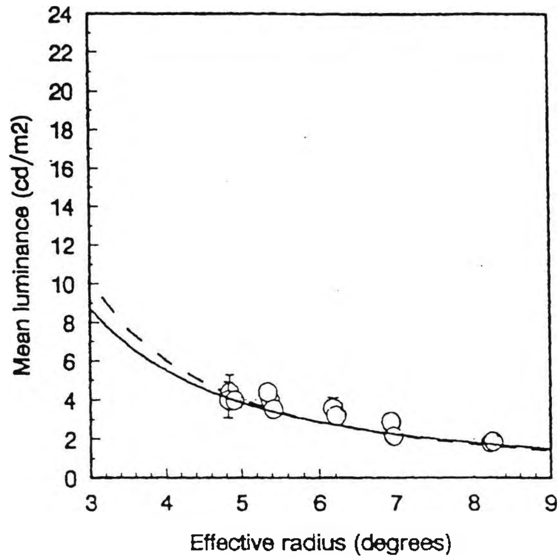
(O Age-matched control contrast sensitivity values)

Subject PG, male, Caucasian, 30 years.		
	Right eye	Left eye
Visual acuity	6/5	6/5
Contact lens type	Hydrogel	Hydrogel
Length of wear	4 years	4 years

Figure 9.6 *Scatter profile and contrast sensitivity results for Subject BH*

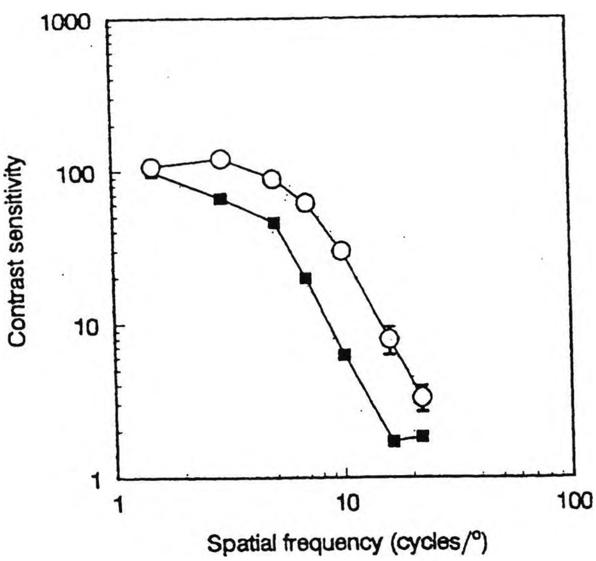


(a) Right eye scatter (O)

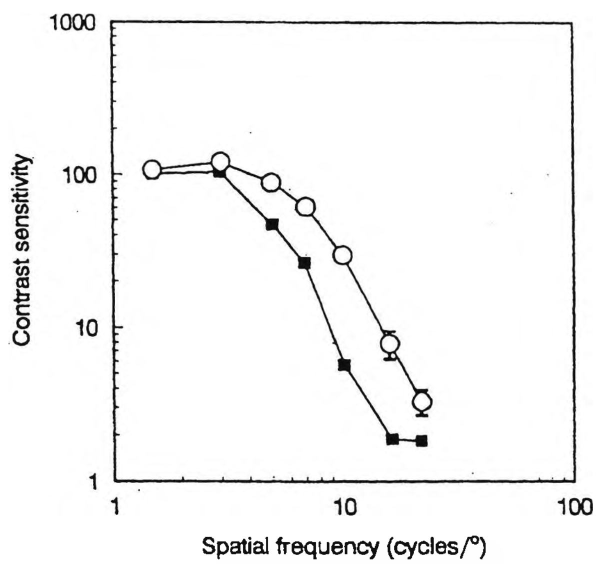


(b) Left eye scatter (O)

(- - - Age-matched control scatter values)



(c) Right eye contrast sensitivity (■)

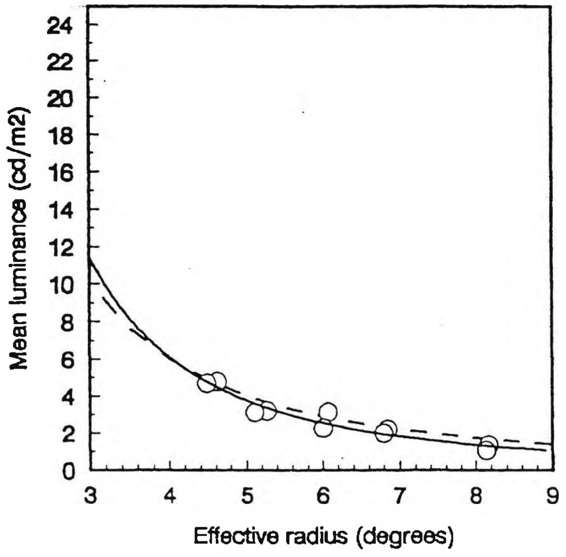


(d) Left eye contrast sensitivity (■)

(O Age-matched control contrast sensitivity values)

Subject BH, male, Caucasian, 55 years.		
	Right eye	Left eye
Visual acuity	6/5	6/5
Contact lens type	Hydrogel	Hydrogel
Length of wear	2 years	2 years

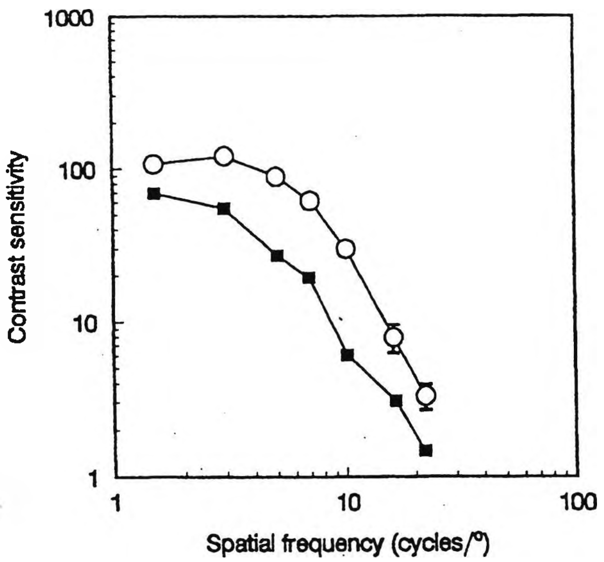
Figure 9.7 *Scatter profile and contrast sensitivity results for Subject WR*



(a) Right eye scatter (O)

(b) Left eye scatter (O)

(- - - Age-matched control scatter values)



(c) Right eye contrast sensitivity (■)

(d) Left eye contrast sensitivity (■)

(O Age-matched control contrast sensitivity values)

Subject WR, male, Caucasian, 56 years.		
	Right eye	Left eye
Visual acuity	6/5	6/5
Contact lens type	Hydrogel	Hydrogel
Length of wear	3 years	3 years

Both subjects who had worn hydrogel lenses for 10 years show increased levels of light scatter compared to age-matched controls. Figures 9.8a, b reveal elevated levels of scatter for subject AH in both eyes compared to age-matched controls, whilst the CSF reveals a better CS than would be expected for this subject's age (figures 9.8c, d). Such variability in CS measurements is well documented (Virsu et al 1975; Cohen et al 1976; Ginsburg et al 1984; Arden 1988) and is thought to reflect genuine biological variability. In contrast, subject PB shows reduced sensitivity at 16 and 22 cpd in both eyes, with the left eye also showing sensitivity loss at 10 cpd (figures 9.9c, d).

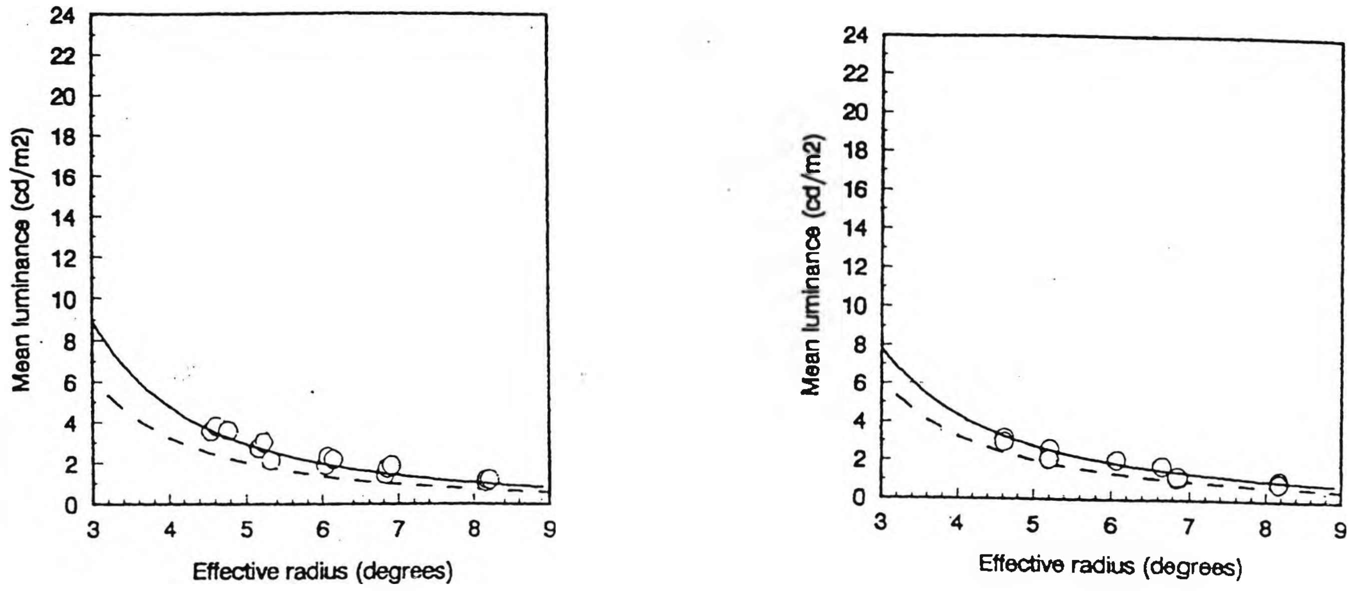
9.8.3.3 Results of subjects wearing hydrogel lenses for a maximum of 15 years

Table 9.6 - Scatter results from two subjects wearing hydrogel lenses for a maximum of 15 years

Subject	Gender	Age (years)	Eye	*n*	s.d.	*k*	s.d.	*k'*	s.d.	*k'-k' (age)*
IW	Male	30	RE	2.14	0.23	31.28	13.76	10.65	0.53	3.74
			LE	2.04	0.06	27.46	2.48	11.67	1.67	4.76
PM	Male	60	RE	1.76	0.33	26.83	5.83	15.08	1.23	-2.50
			LE	1.77	0.10	27.97	4.82	19.73	1.37	-2.15

Of the subjects who had worn hydrogel lenses for a maximum of 15 years, subject IW reveals an increase in the level of light scatter compared to an age-matched control (figures 9.10a, b), and the CSF shows reduced sensitivity at all spatial frequencies tested (figures 9.10c, d). Interestingly, subject PM reveals better than expected levels of light scatter for the subject's age (figures 9.11a, b) but also reveals a CS loss at all spatial frequencies tested (figures 9.11c, d). This finding may indicate that the cause of the reduction in CS is due to optical aberrations caused by the contact lens (Mitra and Lamberts 1981; Guillon et al 1983). Measures of visual performance (such as CS) has been shown to be affected by aberrations in the absence of increases in scattered light (Chisholm et al 2000; Maeda et al 2000).

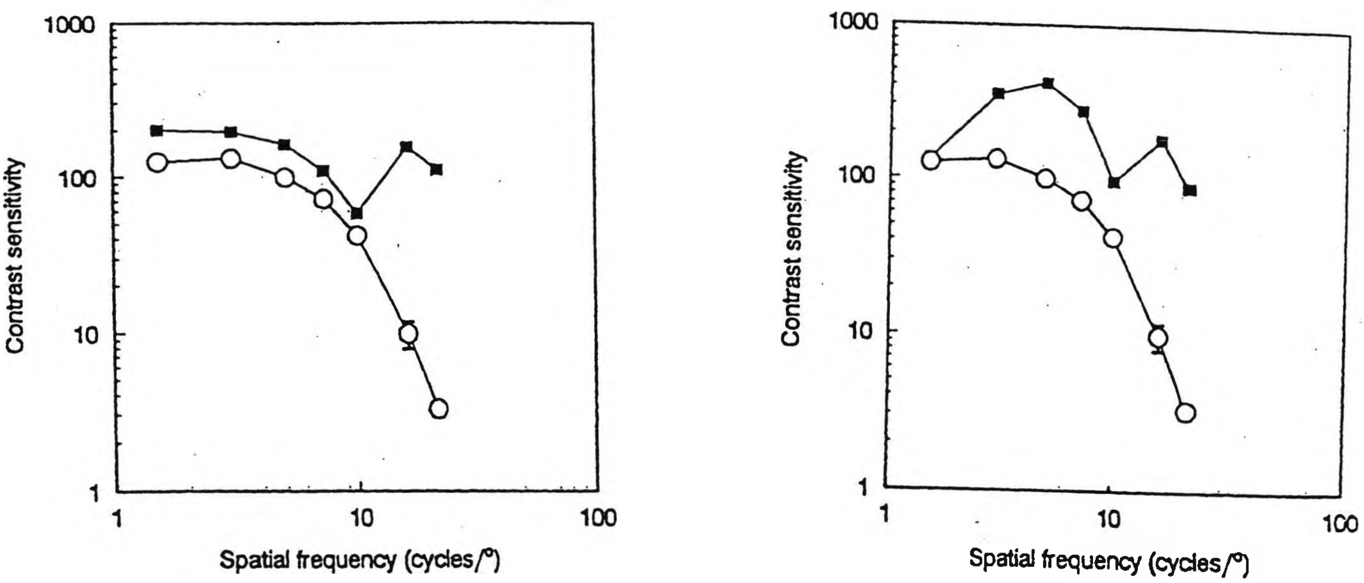
Figure 9.8 *Scatter profile and contrast sensitivity results for Subject AH*



(a) Right eye scatter (O)

(b) Left eye scatter (O)

(- - - Age-matched control scatter values)



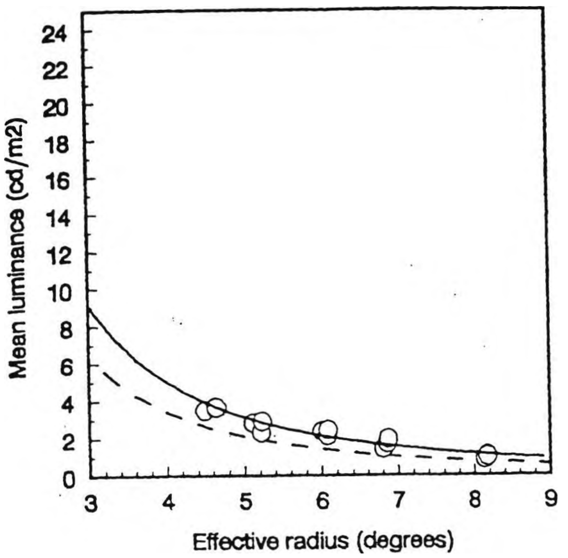
(c) Right eye contrast sensitivity (■)

(d) Left eye contrast sensitivity (■)

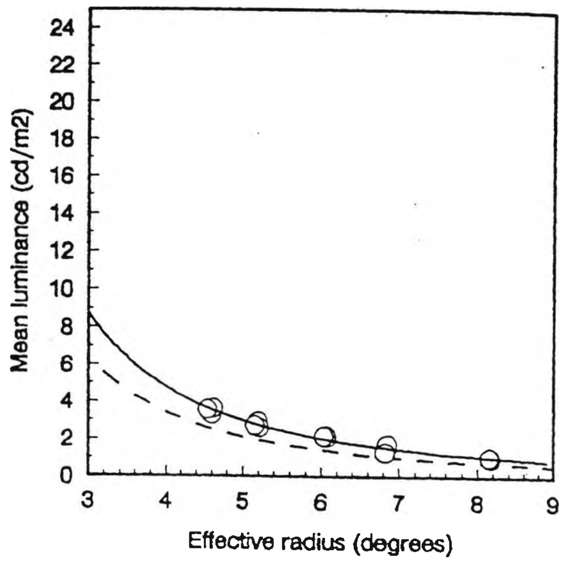
(O Age-matched control contrast sensitivity values)

Subject AH, male, Caucasian, 24 years.		
	Right eye	Left eye
Visual acuity	6/5	6/5
Contact lens type	Hydrogel	Hydrogel
Length of wear	10 years	10 years

Figure 9.9 *Scatter profile and contrast sensitivity results for Subject PB*

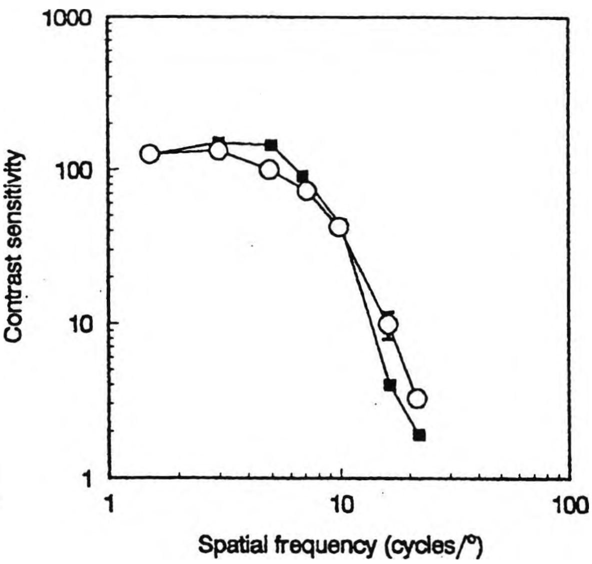


(a) Right eye scatter (O)

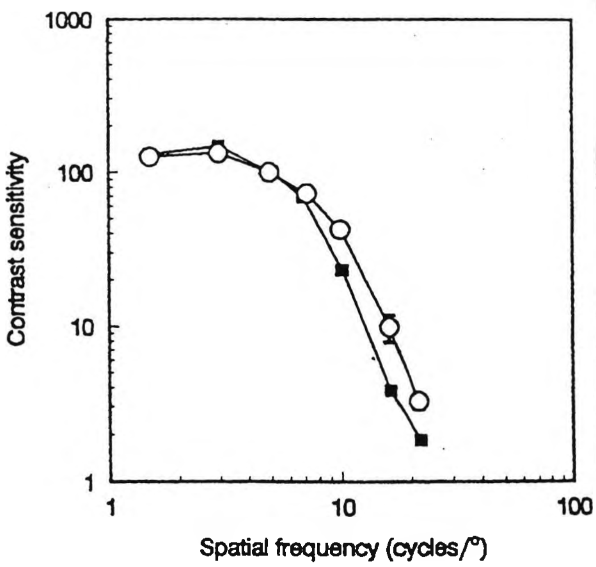


(b) Left eye scatter (O)

(- - - Age-matched control scatter values)



(c) Right eye contrast sensitivity (■)

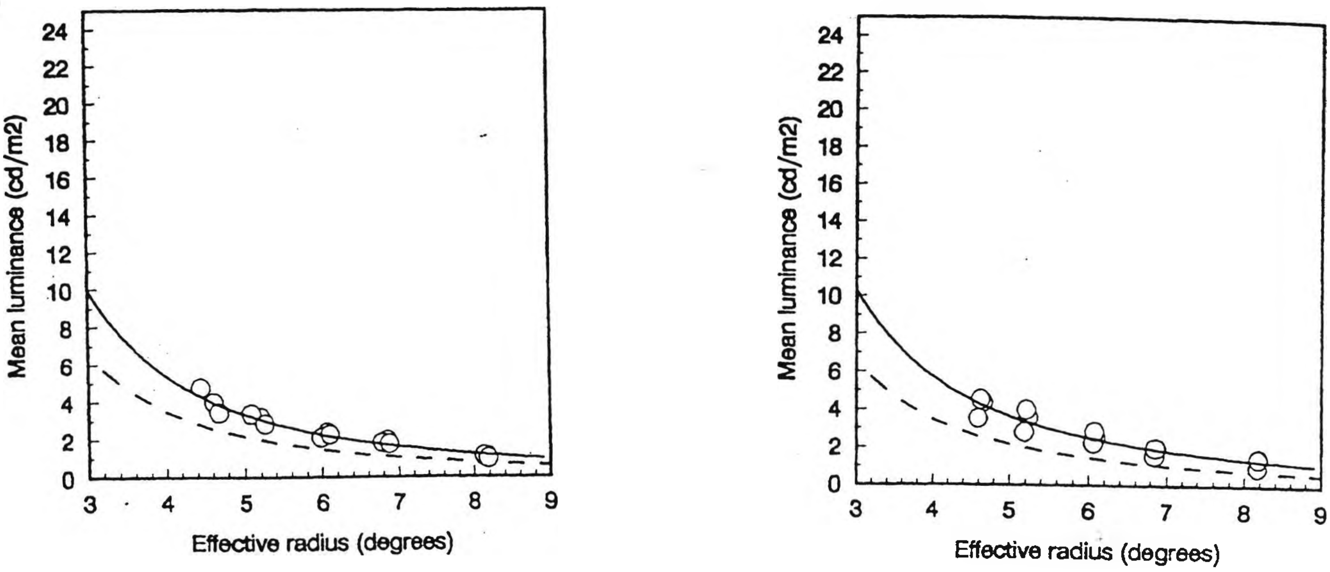


(d) Left eye contrast sensitivity (■)

(O Age-matched control contrast sensitivity values)

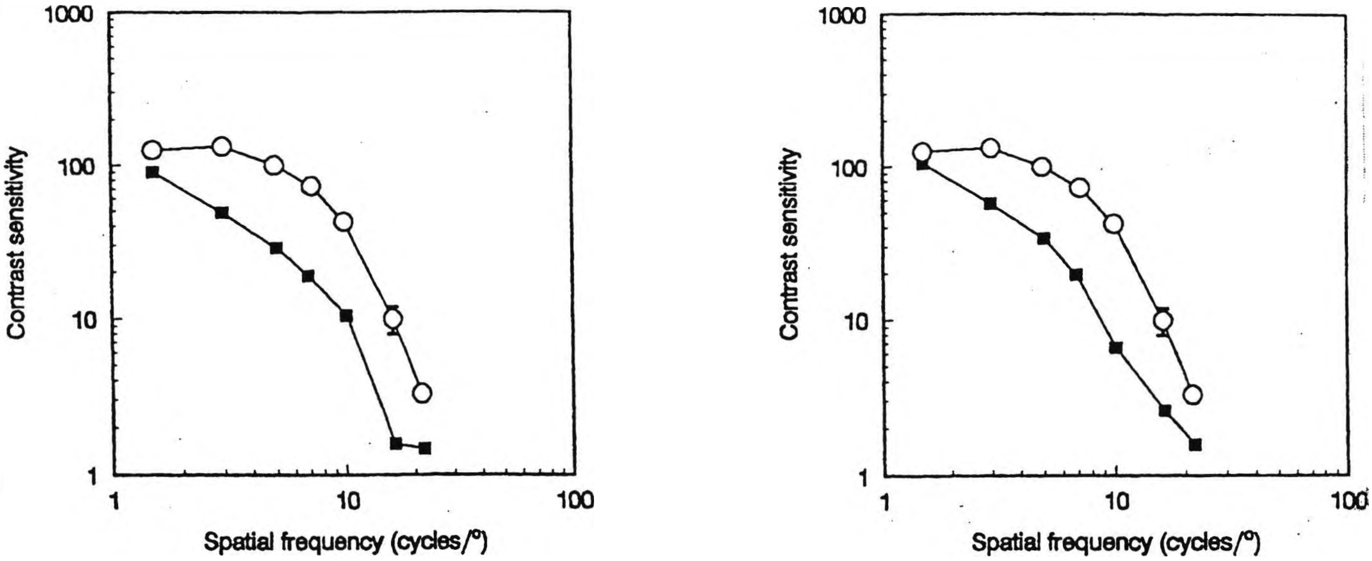
Subject PB, male, Caucasian, 25 years.		
	Right eye	Left eye
Visual acuity	6/5	6/5
Contact lens type	Hydrogel	Hydrogel
Length of wear	10 years	10 years

Figure 9.10 *Scatter profile and contrast sensitivity results for Subject IW*



(a) Right eye scatter (O) (b) Left eye scatter (O)

(- - - Age-matched control scatter values)

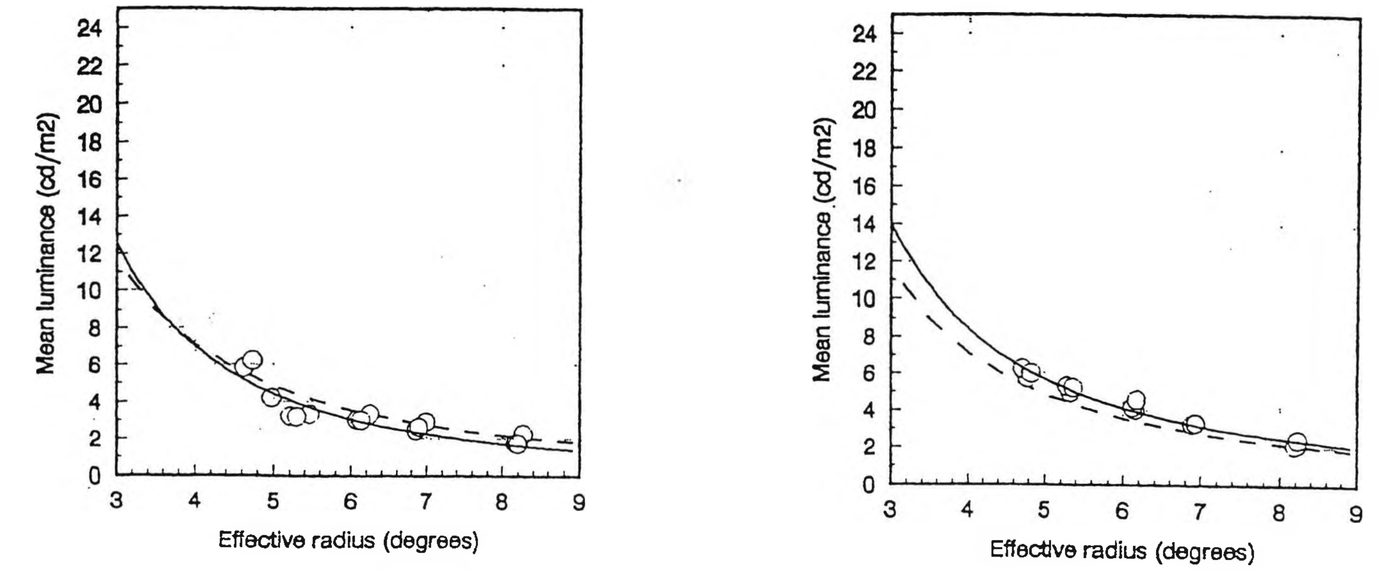


(c) Right eye contrast sensitivity (■) (d) Left eye contrast sensitivity (■)

(O Age-matched control contrast sensitivity values)

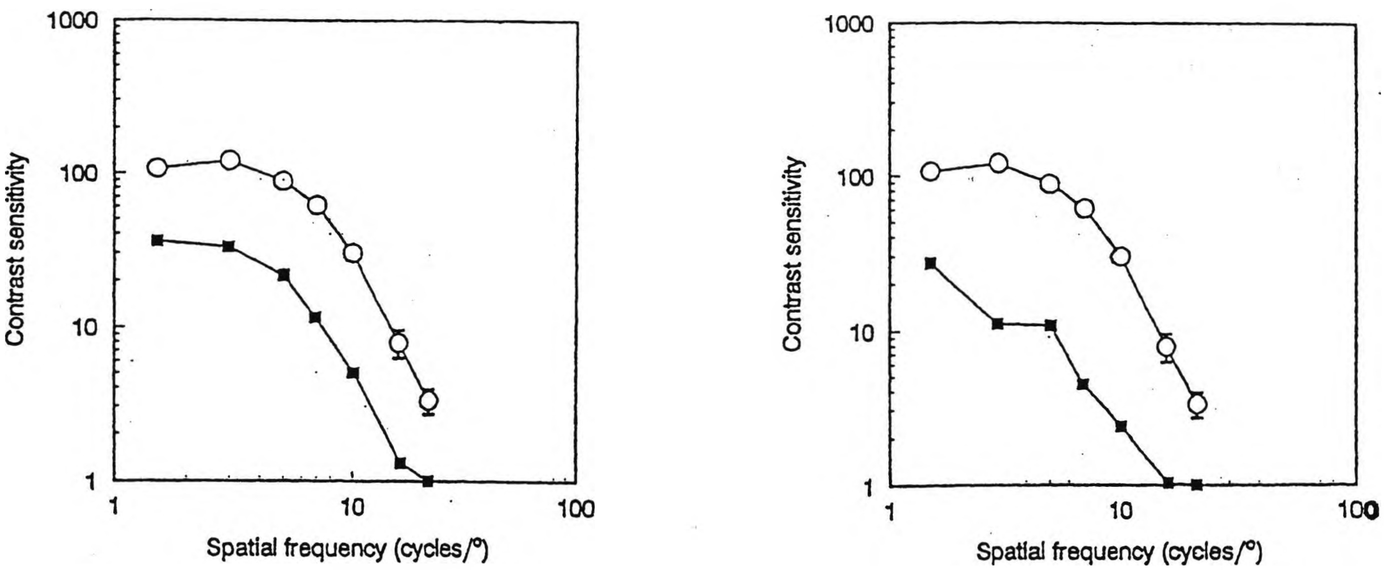
Subject IW, male, Caucasian, 30 years.		
	Right eye	Left eye
Visual acuity	6/4	6/4
Contact lens type	Hydrogel	Hydrogel
Length of wear	15 years	15 years

Figure 9.11 *Scatter profile and contrast sensitivity results for Subject PM*



(a) Right eye scatter (O) (b) Left eye scatter (O)

(- - - Age-matched control scatter values)



(c) Right eye contrast sensitivity (■) (d) Left eye contrast sensitivity (■)

(O Age-matched control contrast sensitivity values)

Subject PM, male, Caucasian, 60 years.		
	Right eye	Left eye
Visual acuity	6/9	6/6-3
Contact lens type	Hydrogel	Hydrogel
Length of wear	15 years	15 years

9.8.3.4 Results of subjects wearing RGP lenses for a maximum of 5 years

Table 9.7 - Scatter results from three subjects wearing hydrogel lenses for a maximum of 5 years

Subject	Gender	Age (years)	Eye	*n*	s.d.	*k*	s.d.	*k'*	s.d.	*k'-k'(age)*
PC	Male	24	RE	1.60	0.29	12.09	7.01	12.03	1.59	5.39
			LE	1.91	0.16	16.29	4.19	9.84	1.04	3.20
AB	Male	30	RE	2.39	0.21	45.29	14.12	10.58	0.07	3.67
			LE	2.17	0.10	29.32	4.79	9.84	0.31	2.93
AR	Male	52	RE	2.13	0.04	26.01	5.60	9.38	1.65	-2.11
			LE	2.41	0.07	34.25	2.81	8.01	0.38	-3.48

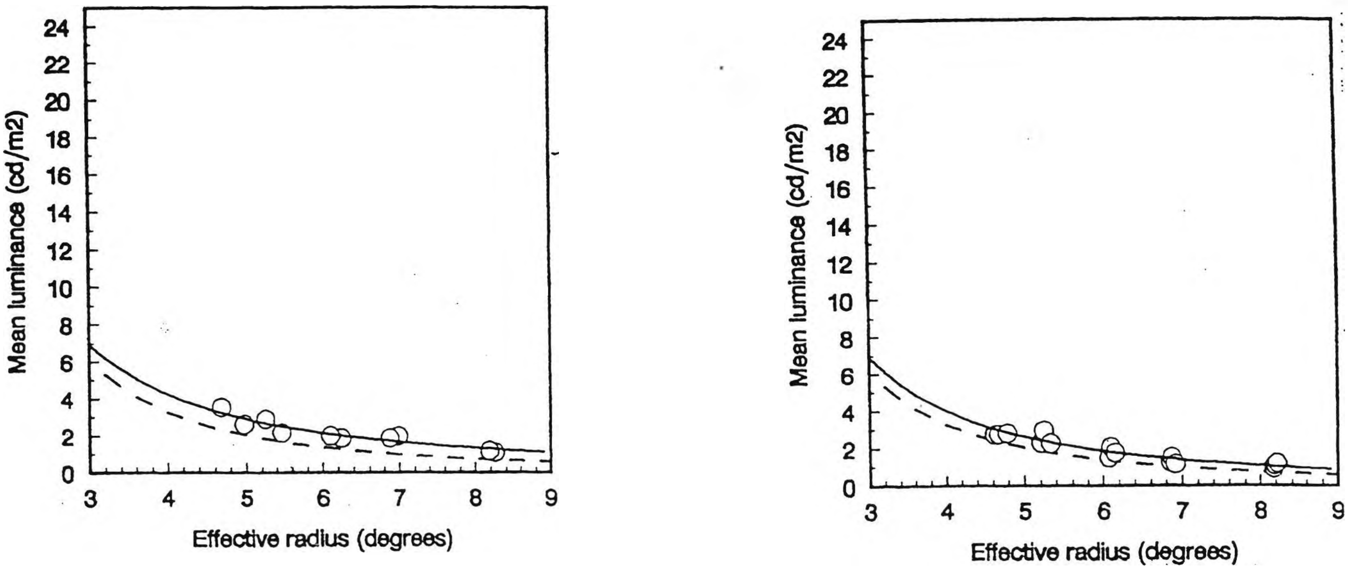
Two out of three subjects who had worn RGP lenses for a maximum of 5 years reveal increased levels of light scatter compared to age-matched controls. The spatial frequency at which CS loss occurs varies between subjects. Figure 9.12 shows the results from subject PC who shows the greatest bilateral increase in *k'*, compared to an age-matched control. Due to the low *n* values obtained from the right eye (1.60), the scatter has a wider angular distribution than the left eye (1.91). The CSF shows no reduction in CS at any spatial frequencies tested. This may due to the biological variability inherent in measures of CS. In contrast, subject AB reveals loss at every spatial frequency tested (figures 9.13c, d). Whilst subject AR shows reduced light scatter compared with age-matched controls, the CSF reveals loss at low spatial frequencies in both eyes (figure 9.14c, d). Again, this may be due to the presence of optical aberrations caused by the contact lens, which have been shown to reduce visual performance in the absence of increased light scatter.

9.8.3.5 Results of subjects wearing RGP lenses for a maximum of 10 years

Table 9.8 - Scatter results from three subjects wearing RGP lenses for a maximum of 10 years

Subject	Gender	Age (years)	Eye	*n*	s.d.	*k*	s.d.	*k'*	s.d.	*k'-k'(age)*
SH	Female	52	RE	1.60	0.07	22.71	3.50	22.71	0.01	11.37
			LE	1.43	0.04	20.20	4.29	24.51	2.50	13.02
TT	Male	25	RE	2.13	0.17	25.92	3.30	9.49	1.76	2.81
			LE	2.06	0.08	23.58	4.81	9.47	0.91	2.79
MK	Male	24	RE	2.10	0.36	24.21	14.88	8.48	0.40	1.84
			LE	1.88	0.01	13.74	0.87	8.21	0.66	1.57

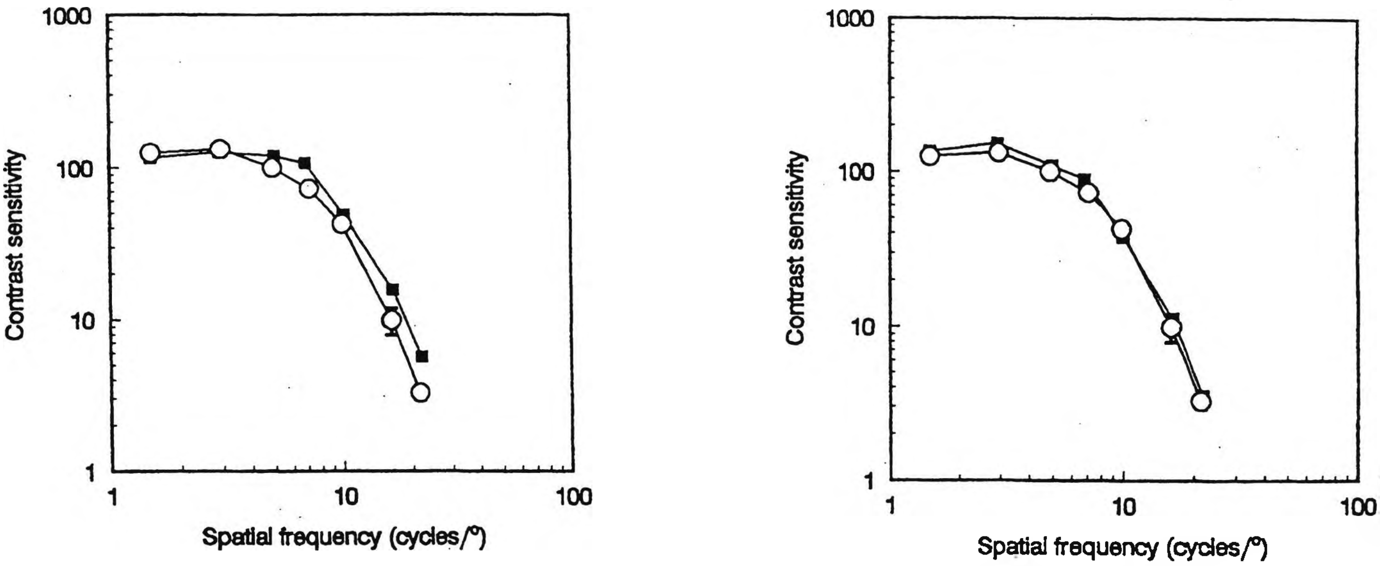
Figure 9.12 *Scatter profile and contrast sensitivity results for Subject PC*



(a) Right eye scatter (O)

(b) Left eye scatter (O)

(- - - Age-matched control scatter values)



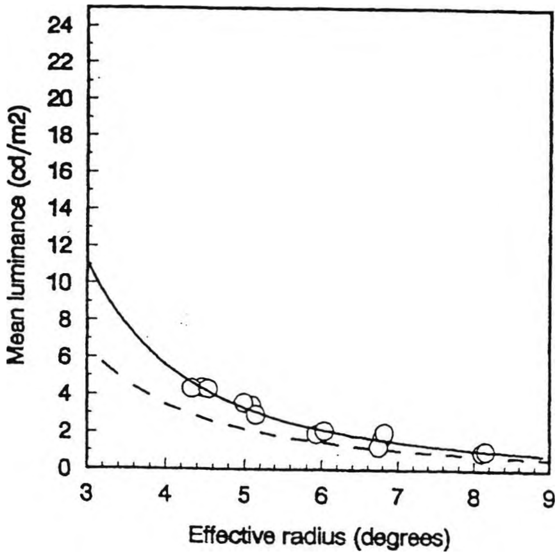
(c) Right eye contrast sensitivity (■)

(d) Left eye contrast sensitivity (■)

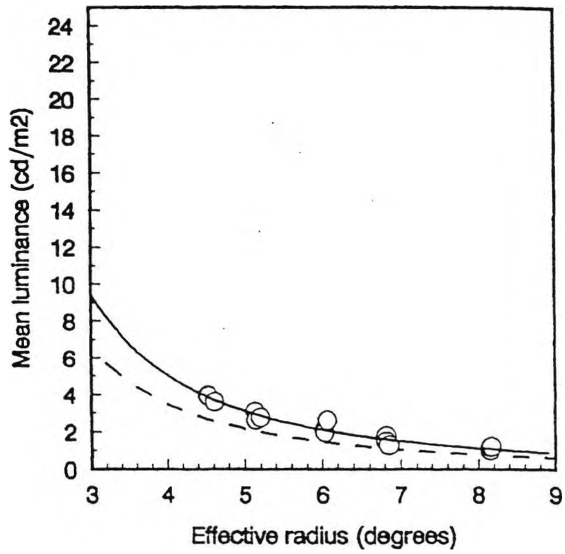
(O Age-matched control contrast sensitivity values)

Subject PC, male, Caucasian, 24 years.		
	Right eye	Left eye
Visual acuity	6/5	6/5
Contact lens type	RGP	RGP
Length of wear	5 years	5 years

Figure 9.13 *Scatter profile and contrast sensitivity results for Subject AB*

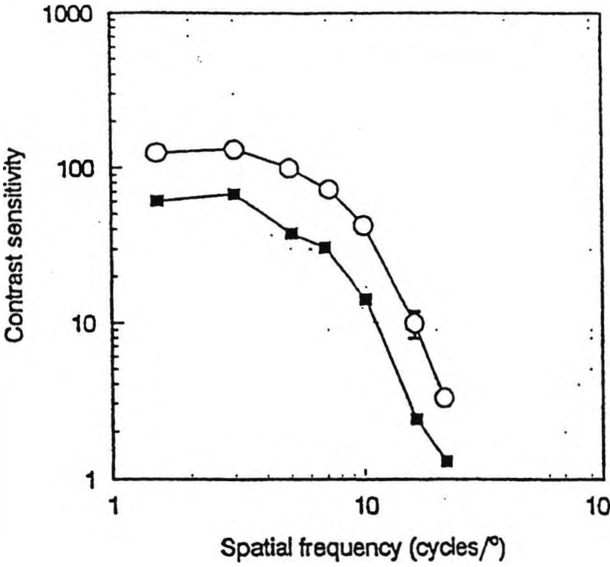


(a) Right eye scatter (O)

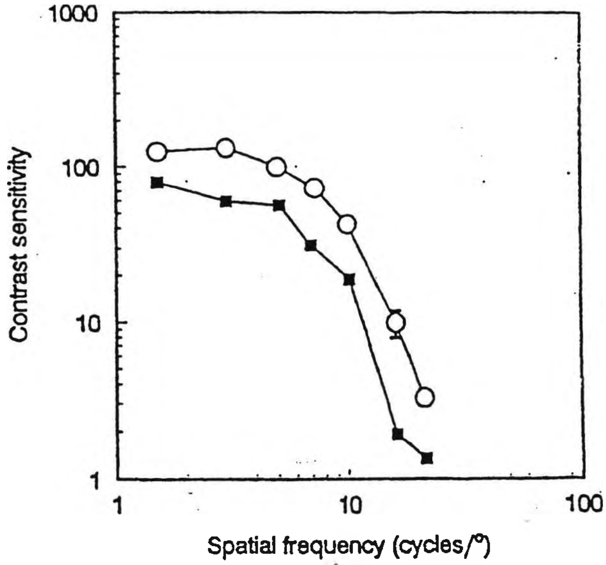


(b) Left eye scatter (O)

(- - - Age-matched control scatter values)



(c) Right eye contrast sensitivity (■)

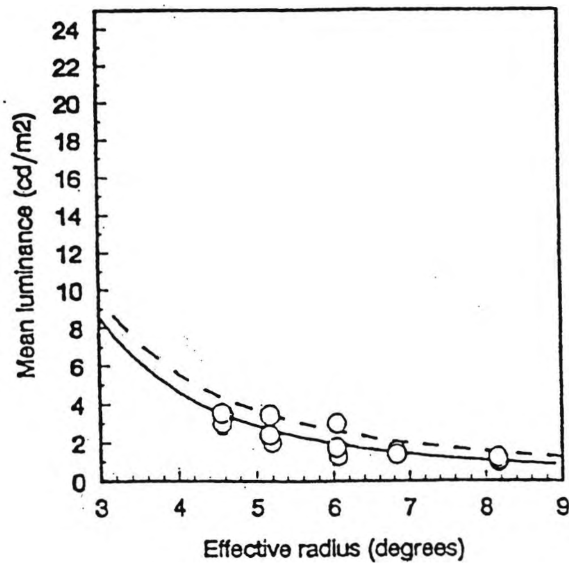


(d) Left eye contrast sensitivity (■)

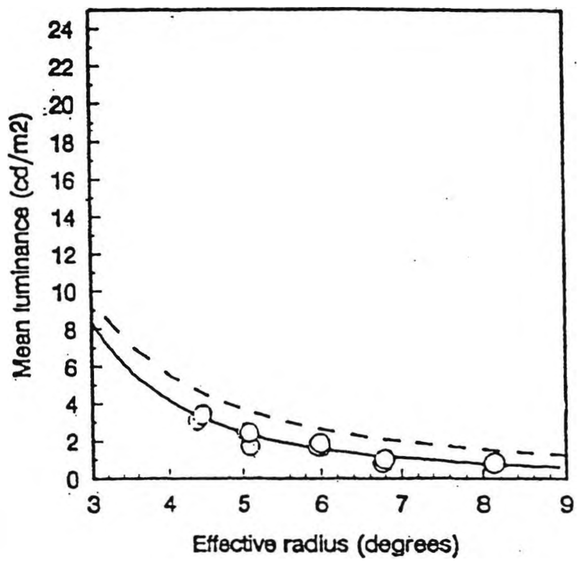
(O Age-matched control contrast sensitivity values)

Subject AB, male, Caucasian, 30 years.		
	Right eye	Left eye
Visual acuity	6/5	6/5
Contact lens type	RGP	RGP
Length of wear	5 years	5 years

Figure 9.14 Scatter profile and contrast sensitivity results for Subject AR

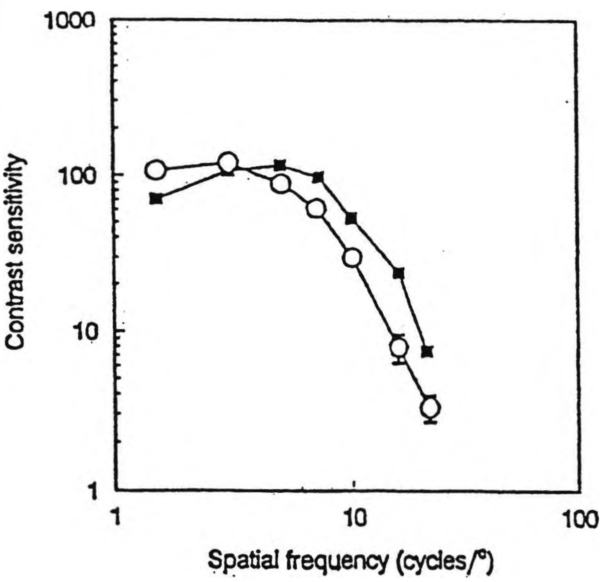


(a) Right eye scatter (O)

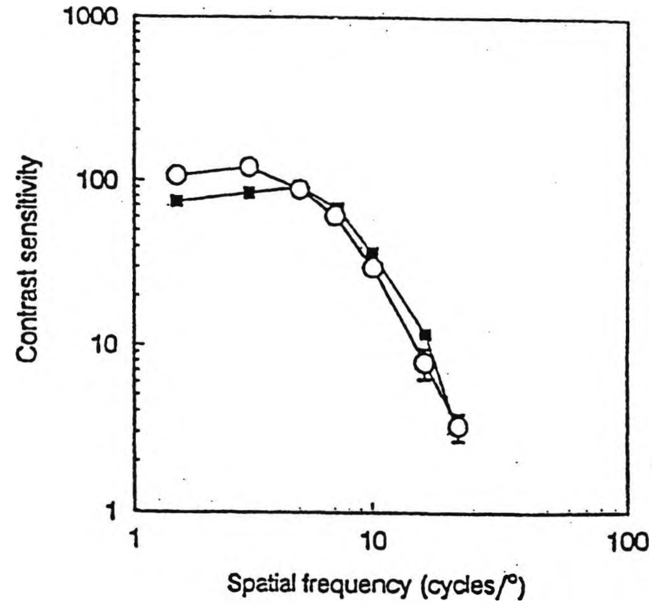


(b) Left eye scatter (O)

(- - - Age-matched control scatter values)



(c) Right eye contrast sensitivity (■)



(d) Left eye contrast sensitivity (■)

(O Age-matched control contrast sensitivity values)

Subject AR, male, Caucasian, 52 years.		
	Right eye	Left eye
Visual acuity	6/5-2	6/6-2
Contact lens type	RGP	RGP
Length of wear	3 years	3 years

All subjects who had worn RGP lenses for a maximum of 10 years reveal increased levels of light scatter, compared to age-matched controls. Subject SH reveals the greatest increase in light scatter for this group of subjects. From figure 9.15, it can be seen that there are elevated levels of scatter in both eyes, compared to an age-matched control, which is accompanied by CS loss at all spatial frequencies (apart from 1.5 cpd in the left eye). In contrast, despite an increase in light scatter, subject TT reveals a better level of CS than would be expected for the subject's age (figure 9.16). Again, this may reflect the biological variability inherent in measures of CS. Subject MK has a bilateral reduction in the CSF at all spatial frequencies tested but reveals only a modest increase in light scatter (figure 9.17). Again, this may be due to the presence of optical aberrations which may reduce visual performance in the absence of increased light scatter.

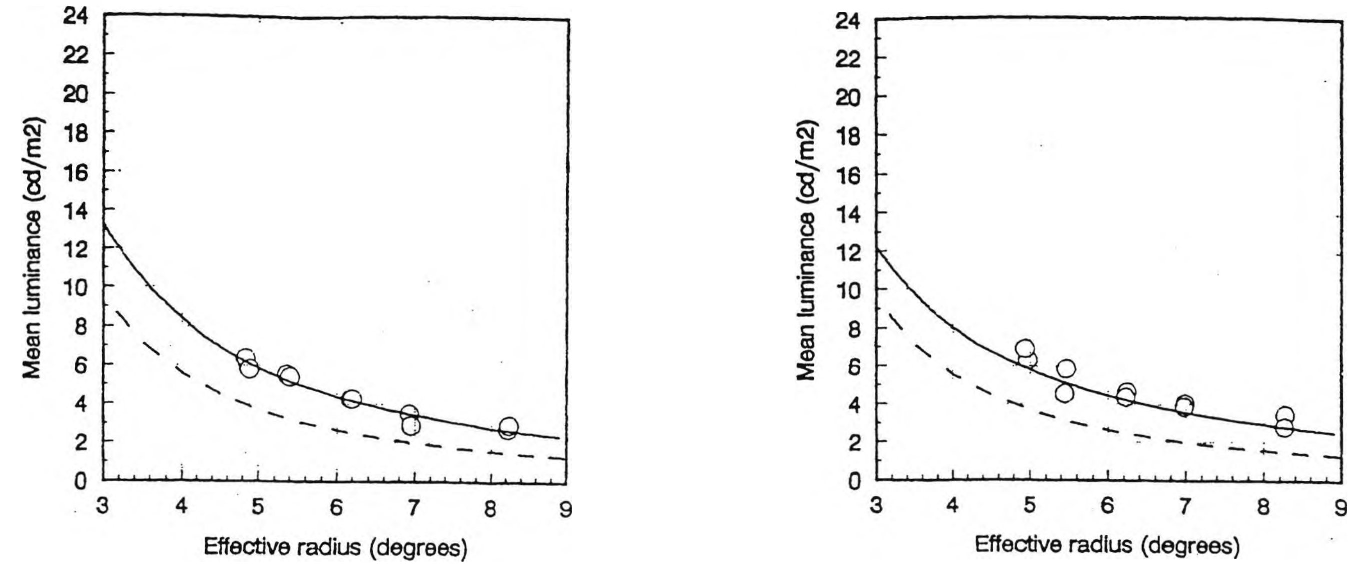
9.8.3.6 Results of subjects wearing RGP lenses for a maximum of 15 years

Table 9.9 - Scatter results from two subjects wearing RGP lenses for a maximum of 15 years

Subject	Gender	Age (years)	Eye	*n*	s.d.	*k*	s.d.	*k'*	s.d.	k'-k'(age)
EL	Male	47	RE	1.99	0.39	26.61	17.06	11.36	2.04	1.87
			LE	1.77	0.03	15.04	2.13	11.15	1.15	1.66
MH	Male	55	RE	1.84	0.12	24.48	3.73	15.05	1.31	1.81
			LE	1.88	0.15	25.33	5.44	14.48	1.04	1.24

Both subjects who had worn RGP lenses for a maximum of 15 years reveal modest increases in light scatter compared to age-matched controls. Figure 9.18 shows the results of subject EL who had the greatest bilateral increase in light scatter. Figure 9.18a reflects the modest increase in light scatter, whilst the low *n* value obtained for the left eye (1.77) causes a wider angular distribution of light scatter when compared to the right eye (1.99) (figure 9.18b). The CSF shows a better than expected level of sensitivity compared to age-matched controls, at all spatial frequencies tested. Subject MH reveals CS loss at low spatial frequencies only (figures 9.19c, d).

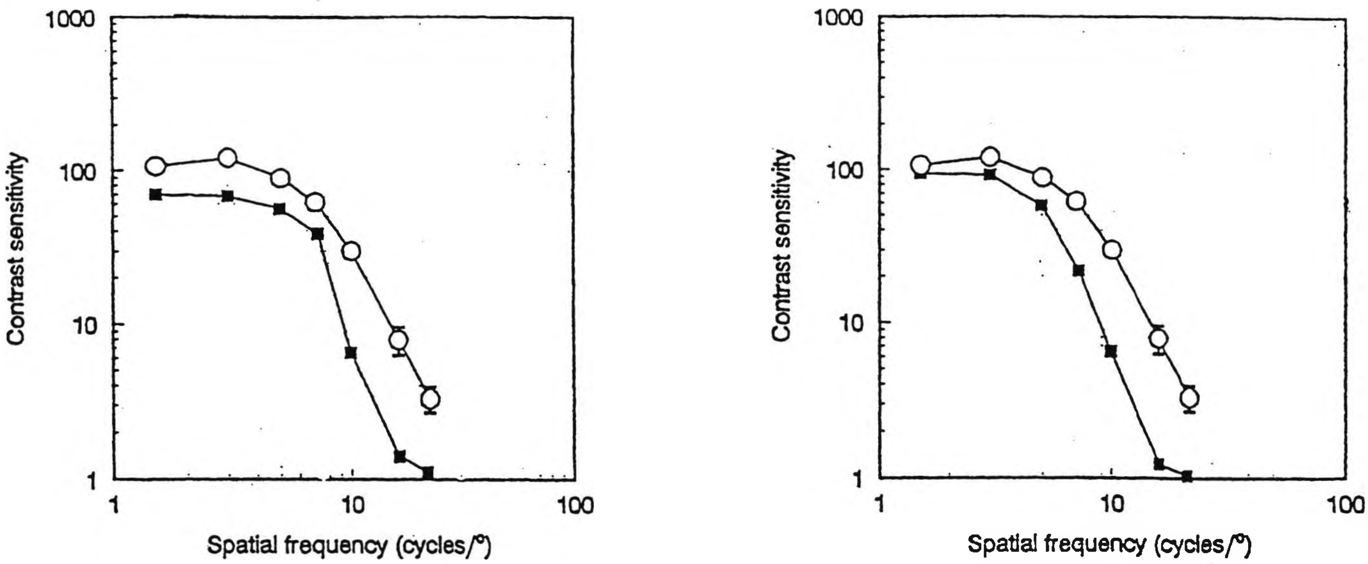
Figure 9.15 Scatter profile and contrast sensitivity results for Subject SH



(a) Right eye scatter (O)

(b) Left eye scatter (O)

(- - - Age-matched control scatter values)



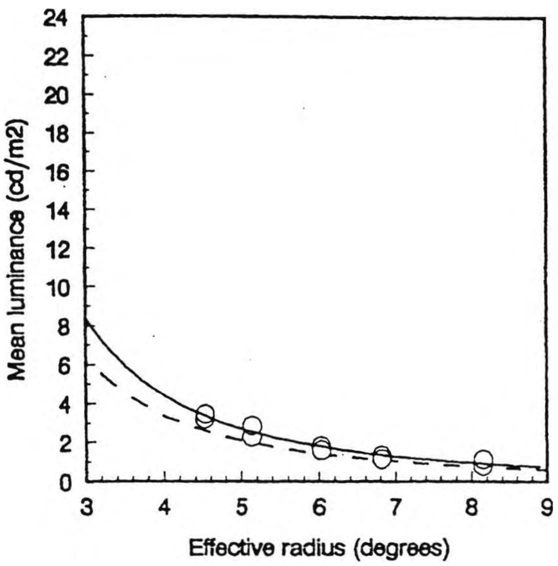
(c) Right eye contrast sensitivity (■)

(d) Left eye contrast sensitivity (■)

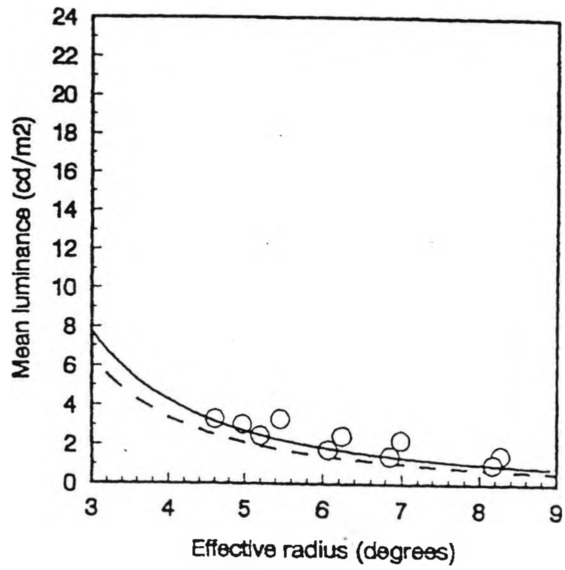
(O Age-matched control contrast sensitivity values)

Subject SH, female, Caucasian, 52 years.		
	Right eye	Left eye
Visual acuity	6/6	6/6
Contact lens type	RGP	RGP
Length of wear	9 years	9 years

Figure 9.16 *Scatter profile and contrast sensitivity results for Subject TT*

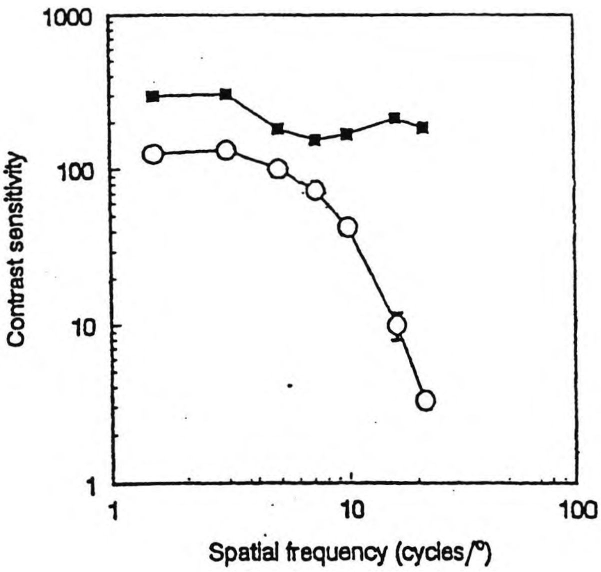


(a) Right eye scatter (O)

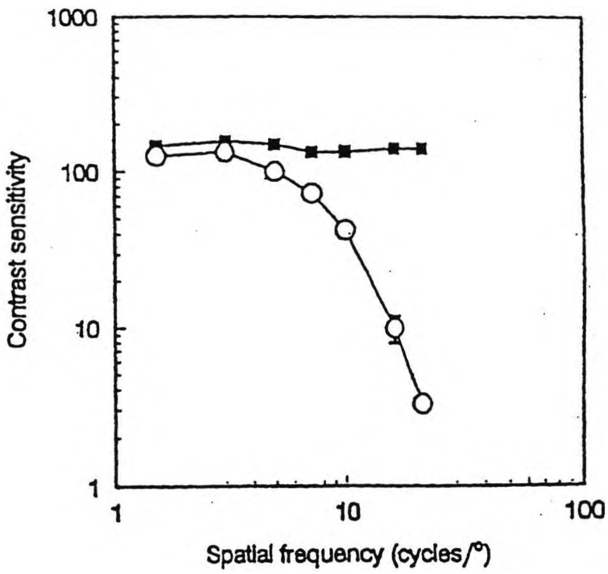


(b) Left eye scatter (O)

(- - - Age-matched control scatter values)



(c) Right eye contrast sensitivity (■)

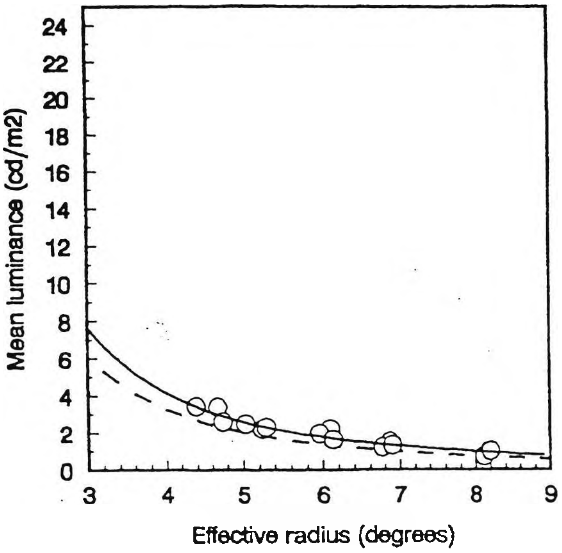


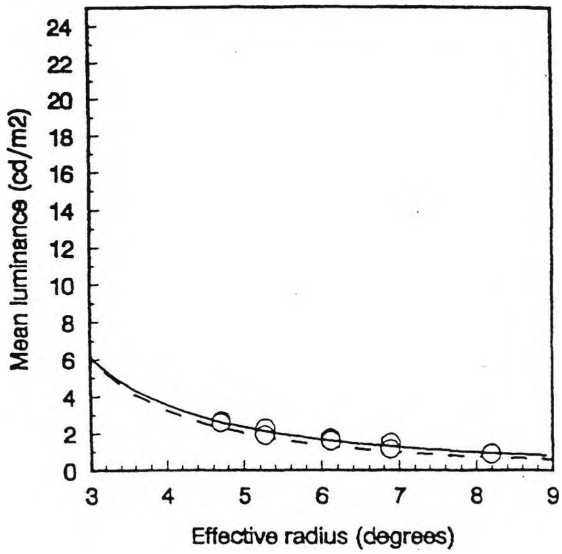
(d) Left eye contrast sensitivity (■)

(O Age-matched control contrast sensitivity values)

Subject TT, male, Caucasian, 25 years.		
	Right eye	Left eye
Visual acuity	6/5	6/5
Contact lens type	RGP	RGP
Length of wear	10 years	10 years

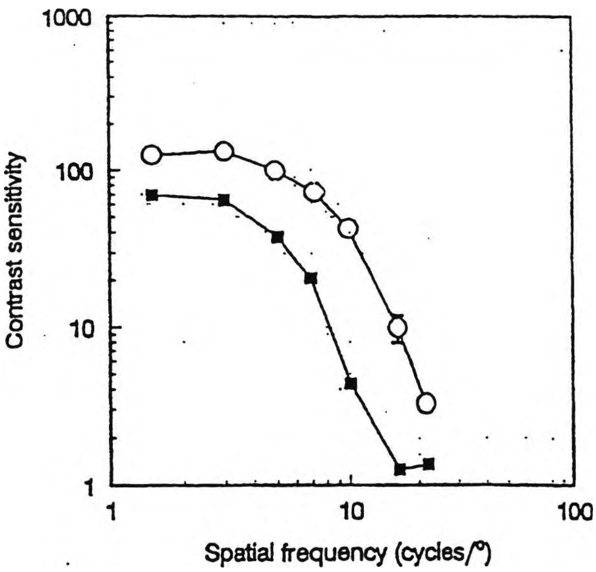
Figure 9.17 *Scatter profile and contrast sensitivity results for Subject MK*

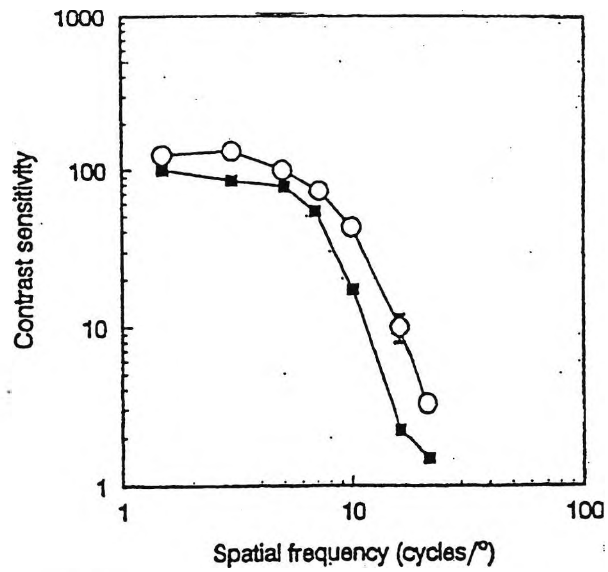




(a) Right eye scatter (O) (b) Left eye scatter (O)

(- - - Age-matched control scatter values)



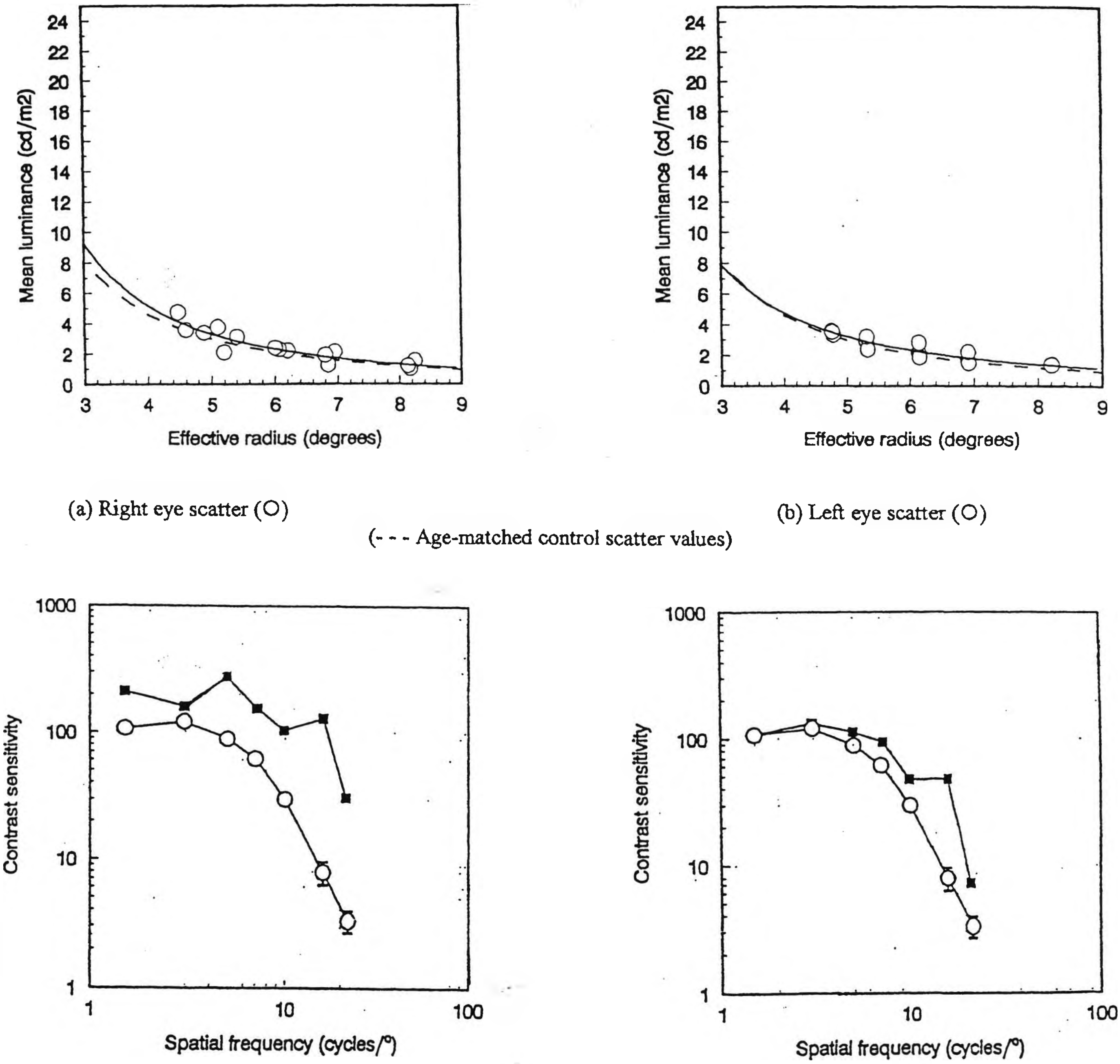


(c) Right eye contrast sensitivity (■) (d) Left eye contrast sensitivity (■)

(O Age-matched control contrast sensitivity values)

Subject MK, male, Caucasian, 24 years.		
	Right eye	Left eye
Visual acuity	6/5	6/5
Contact lens type	RGP	RGP
Length of wear	10 years	10 years

Figure 9.18 *Scatter profile and contrast sensitivity results for Subject EL*



(a) Right eye scatter (O) (b) Left eye scatter (O)

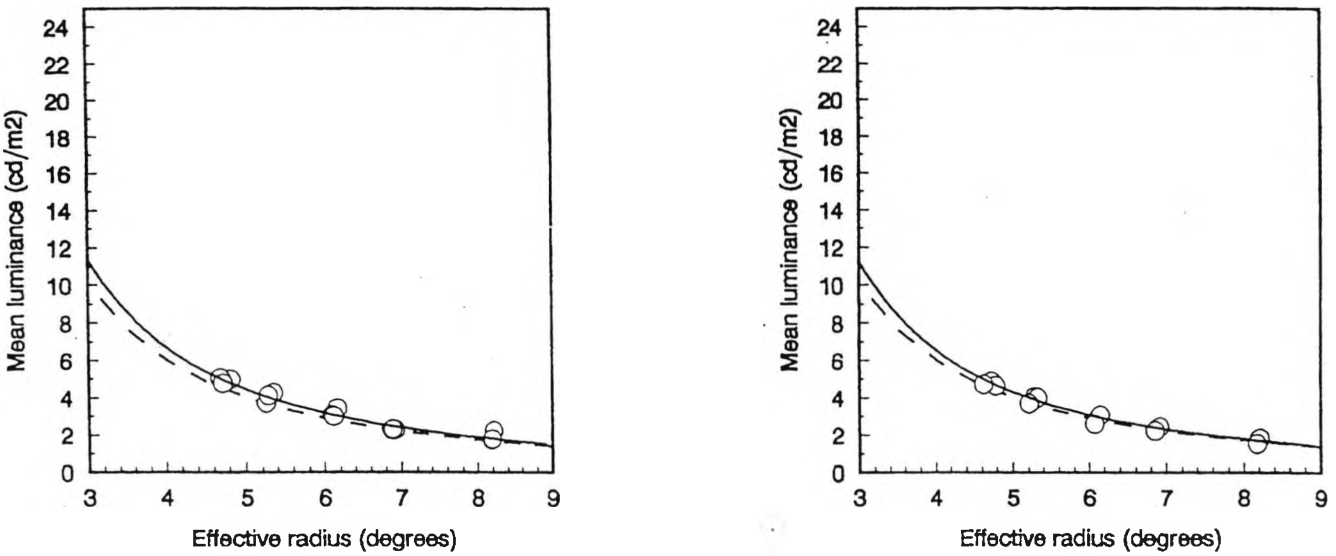
(- - - Age-matched control scatter values)

(c) Right eye contrast sensitivity (■) (d) Left eye contrast sensitivity (■)

(O Age-matched control contrast sensitivity values)

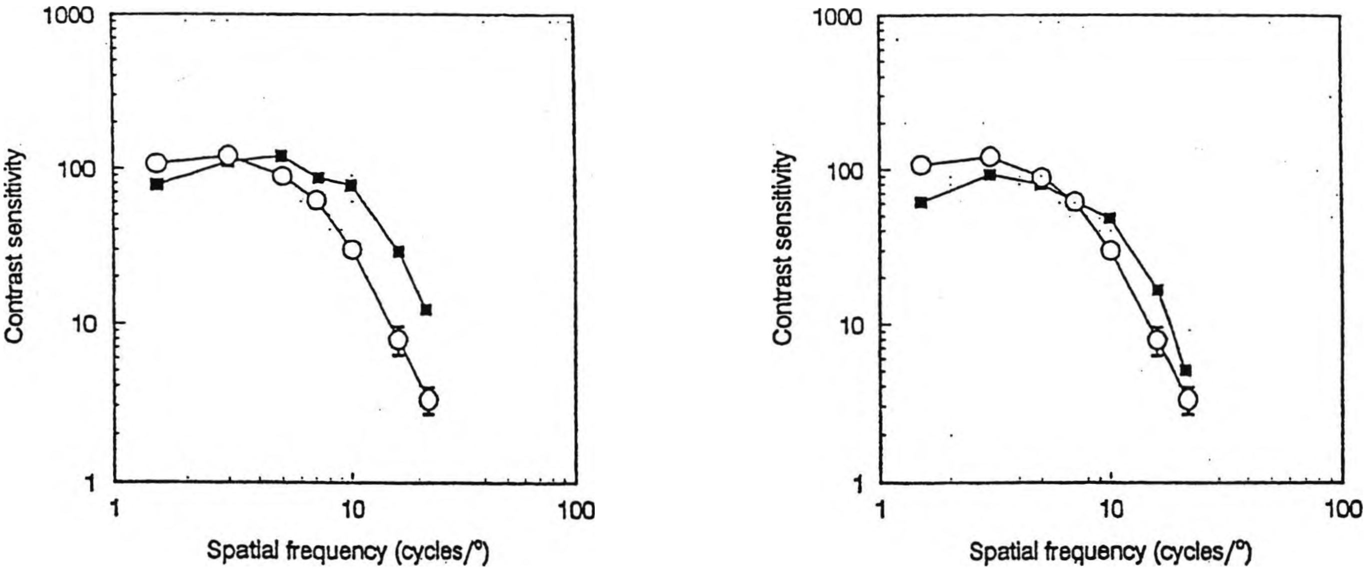
Subject EL, male, Caucasian, 47 years.		
	Right eye	Left eye
Visual acuity	6/6	6/6
Contact lens type	RGP	RGP
Length of wear	15 years	15 years

Figure 9.19 *Scatter profile and contrast sensitivity results for Subject MH*



(a) Right eye scatter (O) (b) Left eye scatter (O)

(- - - Age-matched control scatter values)



(c) Right eye contrast sensitivity (■) (d) Left eye contrast sensitivity (■)

(O Age-matched control contrast sensitivity values)

Subject MH, male, Caucasian, 55 years.		
	Right eye	Left eye
Visual acuity	6/6	6/6
Contact lens type	RGP	RGP
Length of wear	15 years	15 years

9.8.3.7 Results of subjects wearing PMMA lenses for a maximum of 15 years

Table 9.10 - Scatter results from two subjects wearing RGP lenses for a maximum of 15 years

Subject	Gender	Age (years)	Eye	*n*	s.d.	*k*	s.d.	*k'*	s.d.	*k'-k'(age)*
MD	Female	48	RE	2.49	0.29	67.05	27.39	13.51	0.02	3.69
			LE	2.07	0.09	49.33	8.39	19.59	0.39	9.77
JS	Female	51	RE	1.64	0.05	21.23	2.78	20.01	0.51	9.00
			LE	1.80	0.15	22.93	5.36	15.07	0.89	4.06

Both eyes of subjects who had worn PMMA lenses for 15 years show increased levels of light scatter compared to age-matched controls and a depression of CS is observed at most spatial frequencies. Figure 9.20 shows the results of subject MD who exhibited elevated levels of scatter in both eyes and a reduced CSF at all spatial frequencies tested, apart from 3 and 5 cpd in the right eye. Figure 9.21 shows the results for subject JS. The right eye reveals a greater angular light scatter distribution than the left eye due to the relatively low n values obtained (1.64 and 1.80 respectively). The CSF is reduced at all spatial frequencies apart from 1.5 and 7 cpd in the left eye.

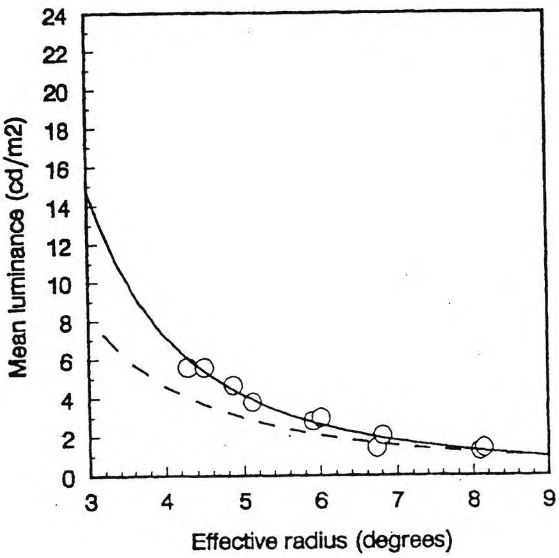
9.8.3.8 Results of subjects wearing PMMA lenses for a maximum of 25 years

Table 9.11 - Scatter results from three subjects wearing PMMA lenses for a maximum of 25 years

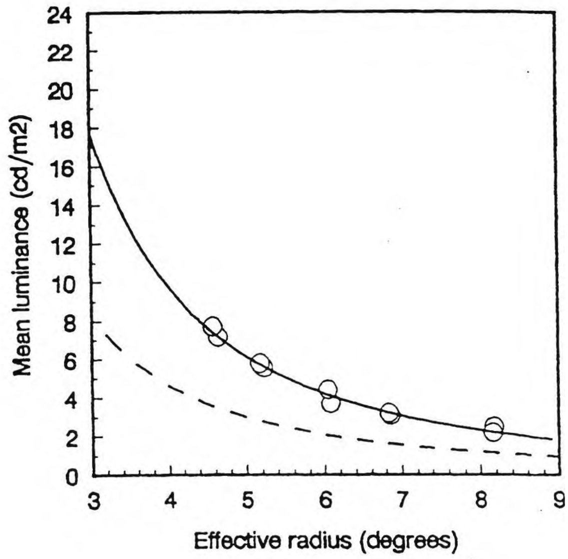
Subject	Gender	Age (years)	Eye	*n*	s.d.	*k*	s.d.	*k'*	s.d.	*k'-k'(age)*
DK	Male	53	RE	1.64	0.21	19.82	5.93	18.90	3.27	6.88
			LE	1.52	0.25	15.07	7.29	19.46	3.99	7.44
JR	Male	53	RE	2.13	0.16	48.12	11.71	15.42	0.63	3.40
			LE	2.35	0.14	60.73	14.55	15.28	0.51	3.27
CG	Male	49	RE	2.07	0.05	32.50	3.33	13.08	0.42	2.91
			LE	2.03	0.05	28.33	2.46	12.25	0.71	2.08

All subjects who had worn PMMA lenses for a maximum of 25 years revealed elevated levels of forward light scatter. Figure 9.22 shows the results of subject DK who showed the greatest amount of light scatter in both eyes, compared to an age-matched control. The low n values obtained indicate that both eyes have a wide angular distribution of light scatter, with the left eye showing a wider distribution than the right. The right CSF shows reduced sensitivity at low spatial frequencies, whilst the left CSE shows reduced sensitivity

Figure 9.20 *Scatter profile and contrast sensitivity results for Subject MD*

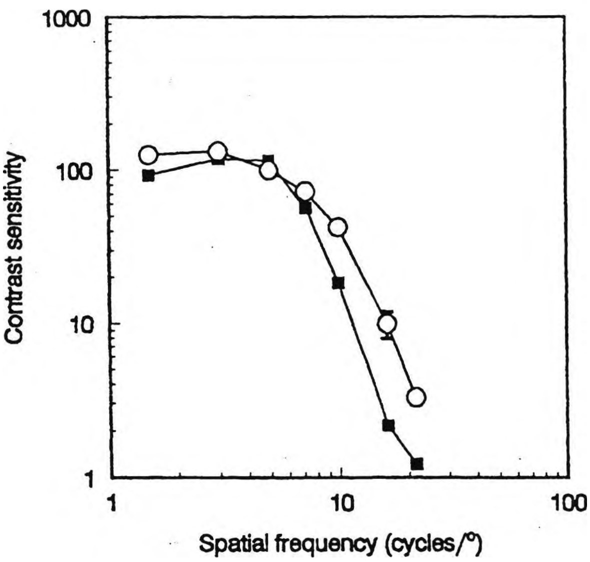


(a) Right eye scatter (O)

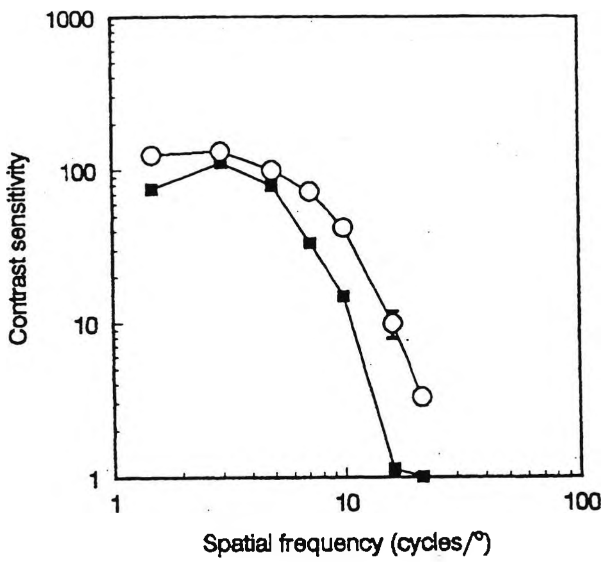


(b) Left eye scatter (O)

(- - - Age-matched control scatter values)



(c) Right eye contrast sensitivity (■)

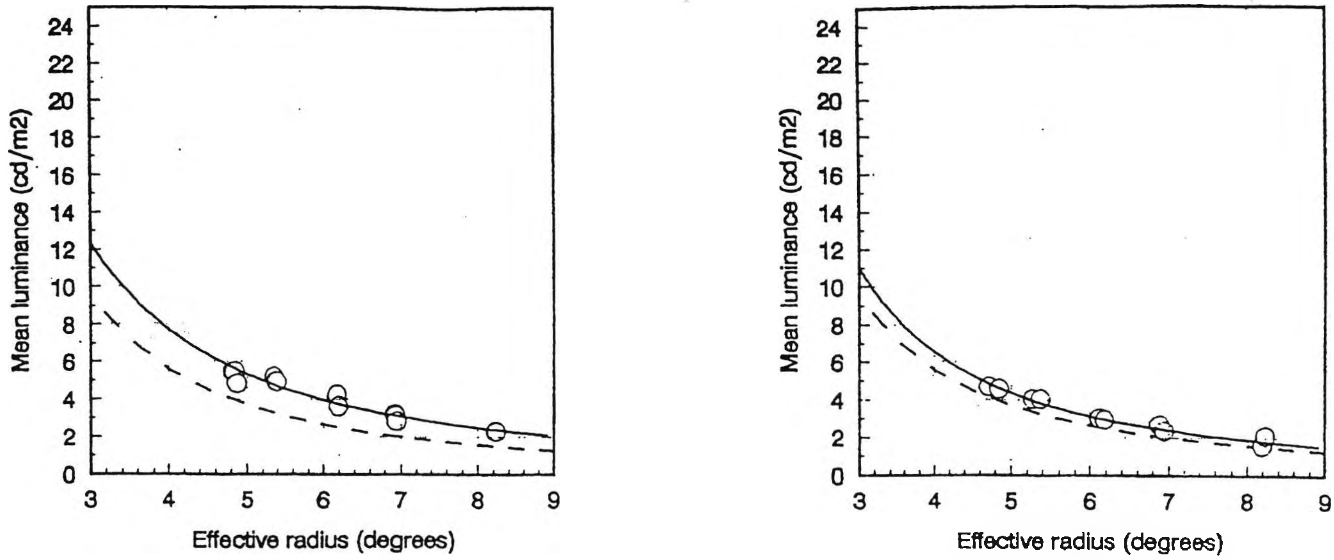


(d) Left eye contrast sensitivity (■)

(O Age-matched control contrast sensitivity values)

Subject MD, female, Asian, 48 years.		
	Right eye	Left eye
Visual acuity	6/6	6/5-3
Contact lens type	PMMA	PMMA
Length of wear	15 years	15 years

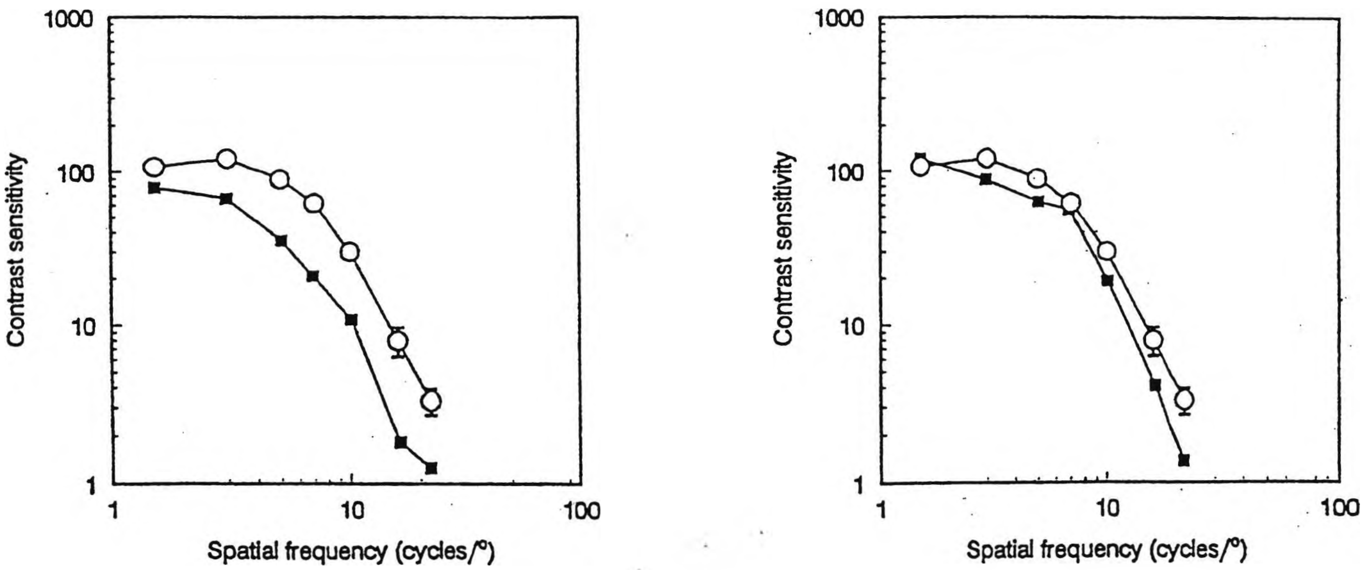
Figure 9.21 *Scatter profile and contrast sensitivity results for Subject JS*



(a) Right eye scatter (O)

(b) Left eye scatter (O)

(- - - Age-matched control scatter values)



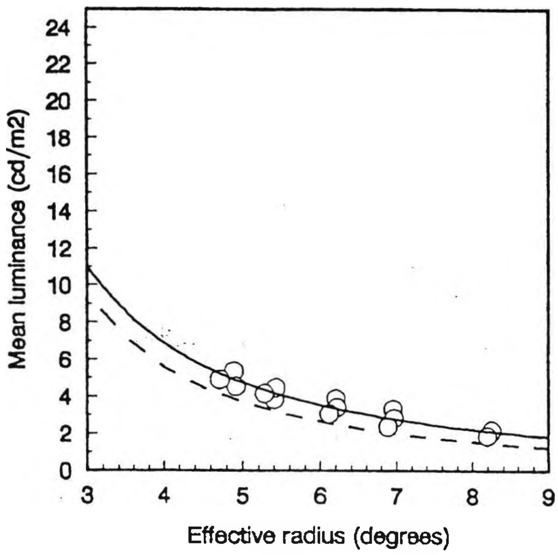
(c) Right eye contrast sensitivity (■)

(d) Left eye contrast sensitivity (■)

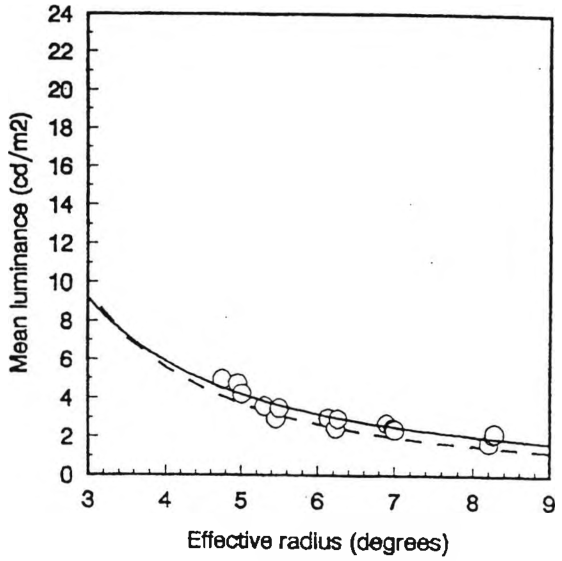
(O Age-matched control contrast sensitivity values)

Subject JS, female, Caucasian, 51 years.		
	Right eye	Left eye
Visual acuity	6/5	6/5
Contact lens type	PMMA	PMMA
Length of wear	15 years	15 years

Figure 9.22 *Scatter profile and contrast sensitivity results for Subject DK*

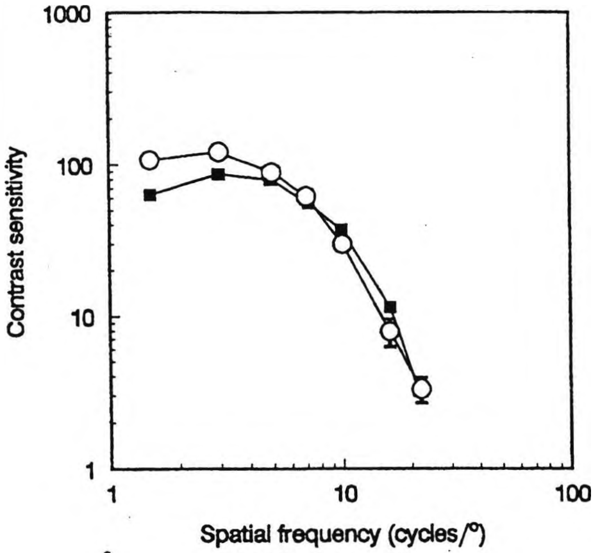


(a) Right eye scatter (O)

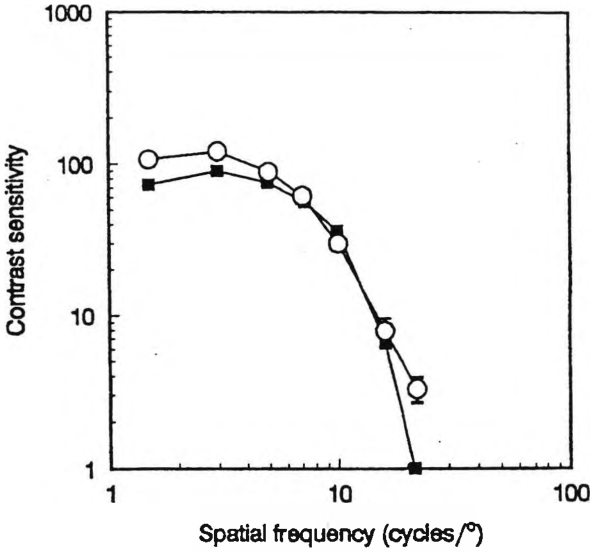


(b) Left eye scatter (O)

(- - - Age-matched control scatter values)



(c) Right eye contrast sensitivity (■)

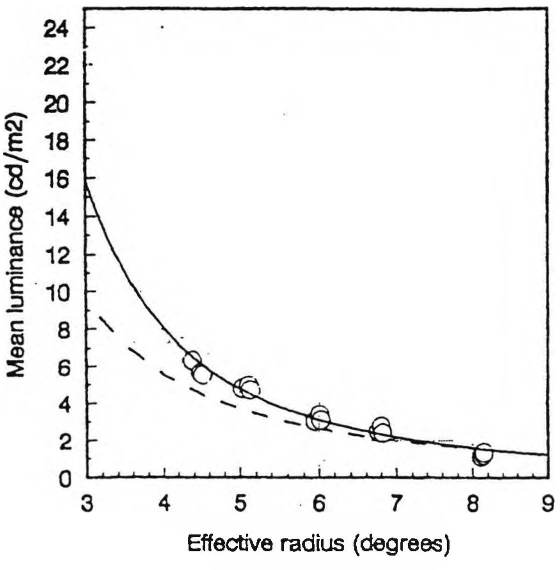


(d) Left eye contrast sensitivity (■)

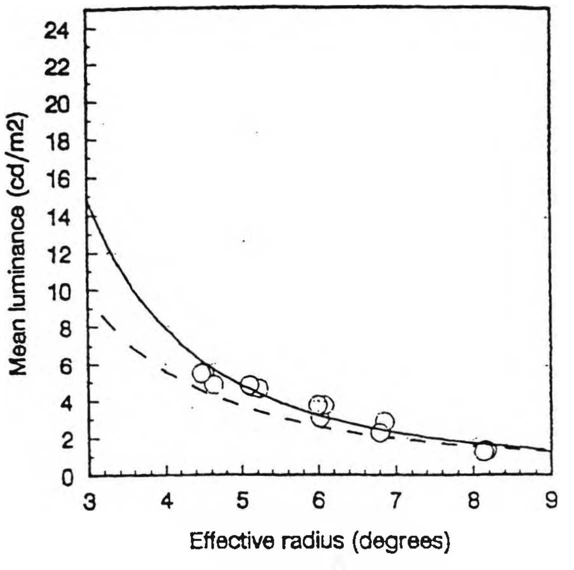
(O Age-matched control contrast sensitivity values)

Subject DK, male, Caucasian, 53 years.		
	Right eye	Left eye
Visual acuity	6/5	6/4
Contact lens type	PMMA	PMMA
Length of wear	22 years	22 years

Figure 9.23 *Scatter profile and contrast sensitivity results for Subject JR*

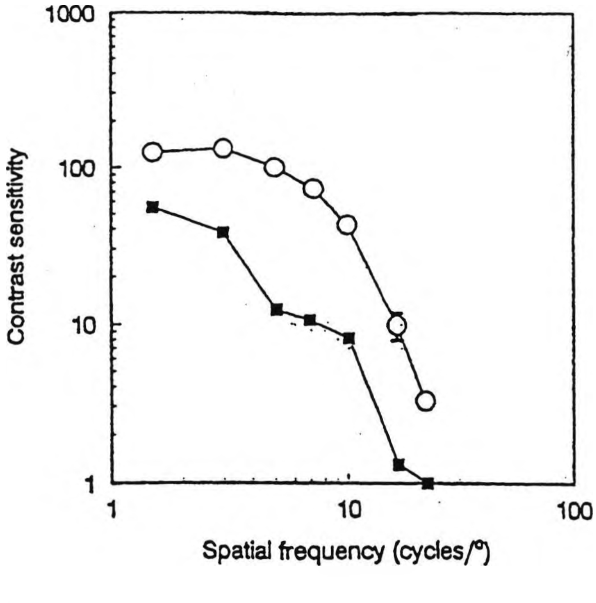


(a) Right eye scatter (O)

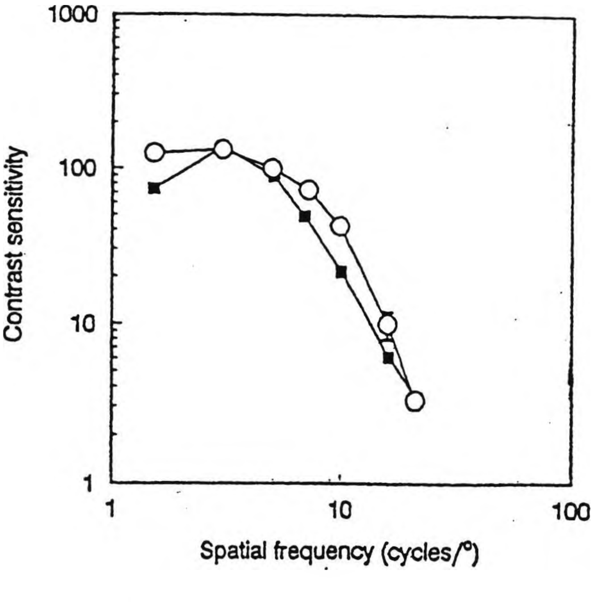


(b) Left eye scatter (O)

(- - - Age-matched control scatter values)



(c) Right eye contrast sensitivity (■)

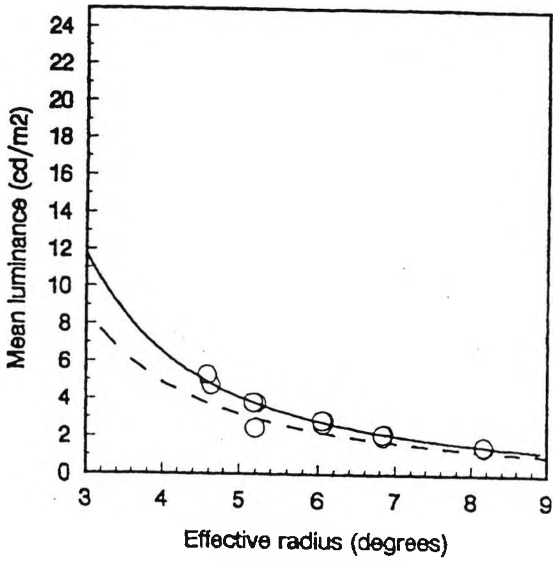


(d) Left eye contrast sensitivity (■)

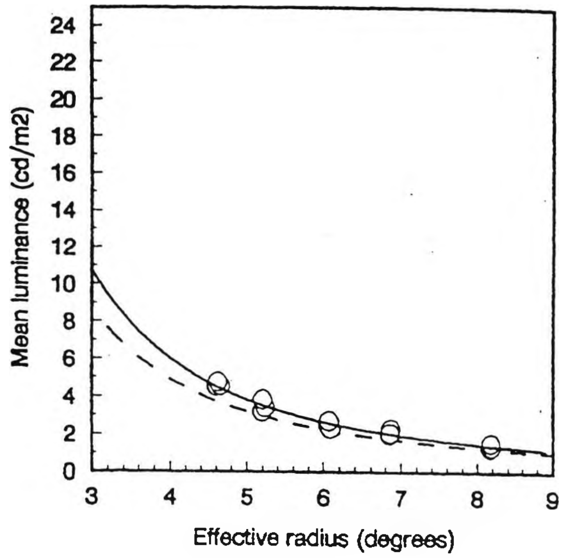
(O Age-matched control contrast sensitivity values)

Subject JR, male, Causasian, 53 years.		
	Right eye	Left eye
Visual acuity	6/9+1	6/6
Contact lens type	PMMA	PMMA
Length of wear	22 years	22 years

Figure 9.24 *Scatter profile and contrast sensitivity results for Subject CG*

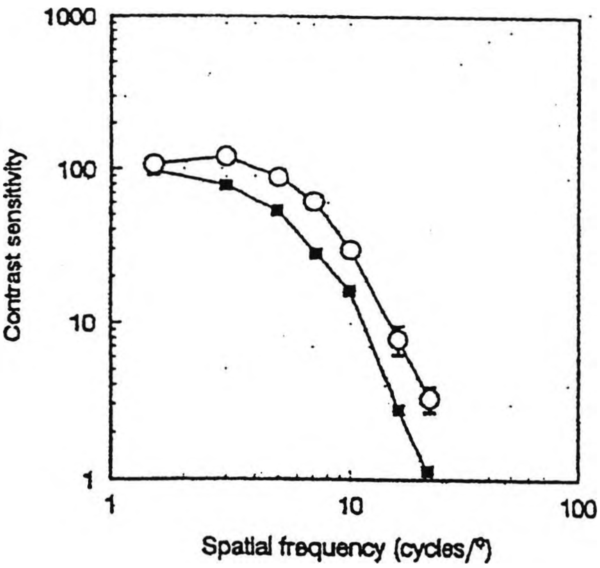


(a) Right eye scatter (O)

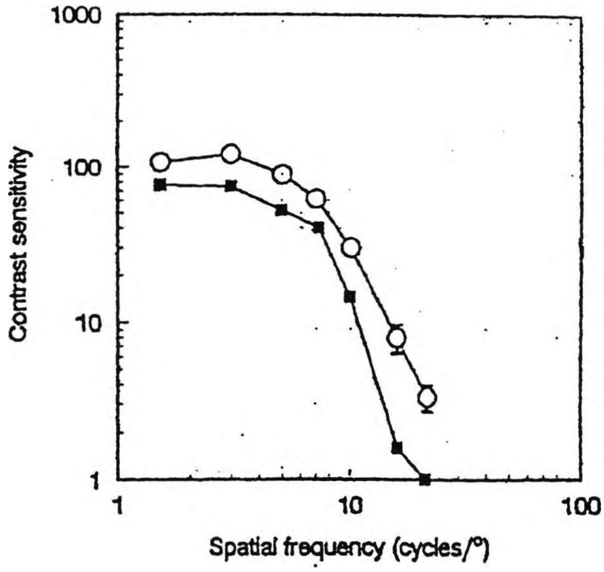


(b) Left eye scatter (O)

(- - - Age-matched control scatter values)



(c) Right eye contrast sensitivity (■)



(d) Left eye contrast sensitivity (■)

(O Age-matched control contrast sensitivity values)

Subject CG, male, Caucasian, 49 years.		
	Right eye	Left eye
Visual acuity	6/5	6/5
Contact lens type	PMMA	PMMA
Length of wear	22 years	22 years

at low and high spatial frequencies. Subject JR also shows increased light scatter levels compared to age-matched controls (figures 9.23a, b). The right eye shows CS loss at all spatial frequencies tested, whilst the left eye reveals loss at 1.5, 7, 10 and 16 cpd (figures 9.23c, d). The results from subject CG reveal elevated levels of scatter in both eyes, compared to an age-matched control, (figures 9.24a, b) and the CSF shows reduced sensitivity at all spatial frequencies tested (apart from 1.5 cpd in the right eye) (figures 9.24c, d).

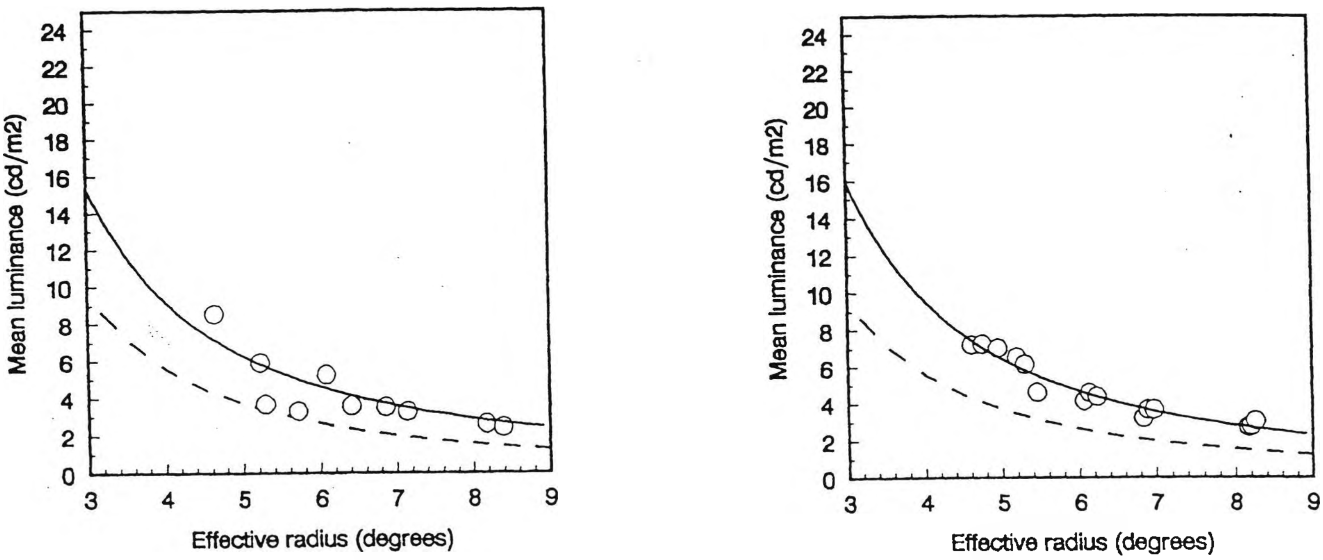
9.8.3.9 Results of subjects wearing a mixture of lens types for a maximum of 15 years

Table 9.12 - Scatter results from two subjects wearing a mixture of lens types for a maximum of 15 years

Subject	Gender	Age (years)	Eye	*n*	s.d.	*k*	s.d.	*k'*	s.d.	*k'-k'(age)*
GR	Male	53	RE	1.65	0.35	31.46	20.82	27.78	2.18	15.77
			LE	1.95	0.14	44.68	9.48	22.09	1.03	10.08
SL	Male	26	RE	1.99	0.11	16.85	2.55	7.86	0.61	1.15
			LE	2.28	6.03	24.88	1.26	7.16	0.62	0.45

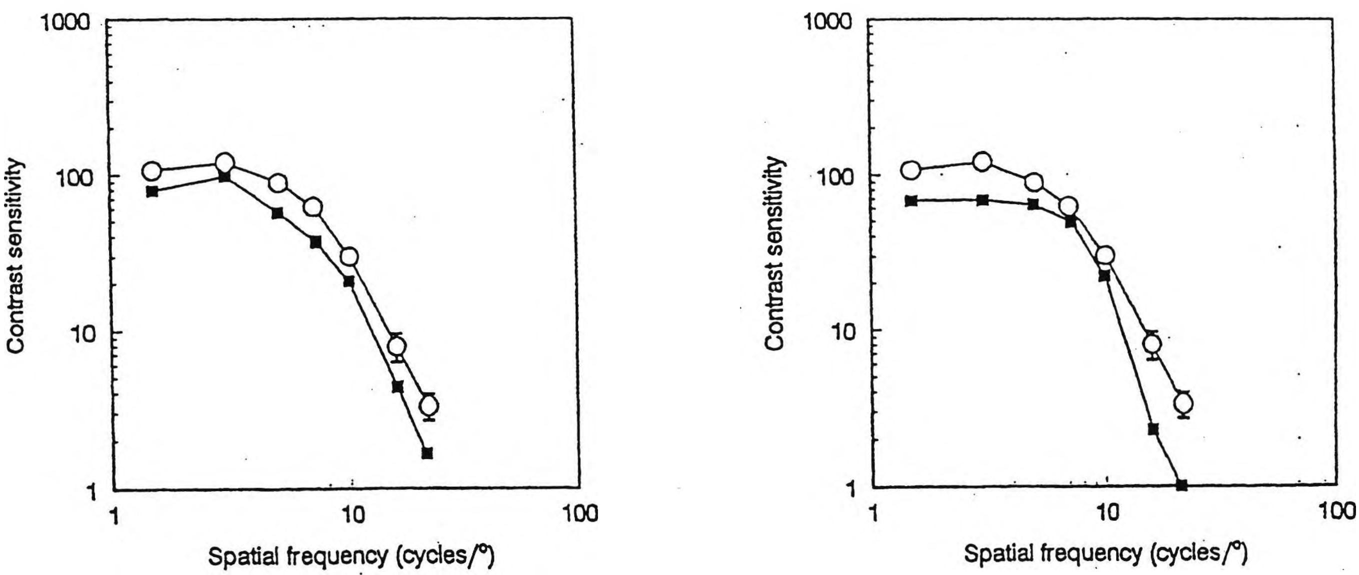
Both subjects who had worn a mixture of lens types for a maximum of 15 years reveal varying amounts of light scatter compared to an age-matched control. Figure 9.25 shows the results of subject GR who shows the greatest amount of light scatter in both eyes compared to an age-matched control. Due to the low *n* values obtained for this subject (1.65 and 1.95 respectively), the distribution of light scatter is different in the two eyes, with the right eye showing a wider angular distribution than the left eye. The CSF shows reduced sensitivity at all spatial frequencies tested. Figures 9.26a, b reflect the modest increase in light scatter for subject SL whilst figures 9.26c, d, reveal CS loss at all spatial frequencies apart from 5 cpd in the right eye and 3 cpd in the left eye. It should be noted that there is a large age difference (27 years) between the two subjects. Therefore, the results of subject GR (aged 53 years) may also reflect ocular changes related to age despite subtracting the *k'* values of an age-matched control (*k'-k'(age)*). The variable rate of ageing between individuals is well documented (Johnson and Choy 1987; Lachenmayr et al 1994). In addition, Johnson and Choy (1987) state that because of a large number of factors conspiring to produce age-related changes in visual function, there is often greater variability in data obtained from older individuals.

Figure 9.25 *Scatter profile and contrast sensitivity results for Subject GR*



(a) Right eye scatter (O) (b) Left eye scatter (O)

(- - - Age-matched control scatter values)

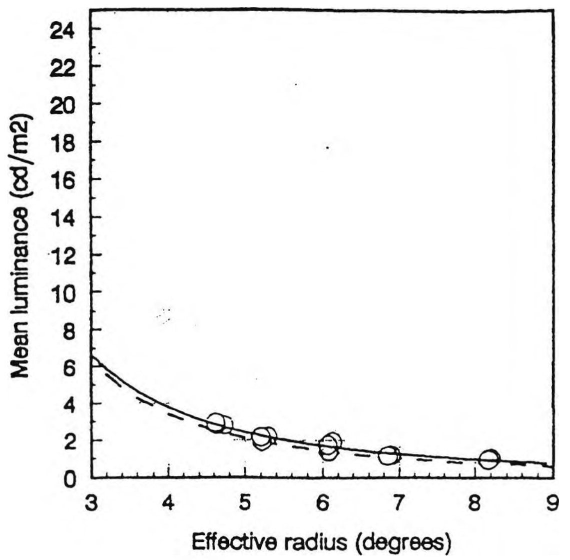


(c) Right eye contrast sensitivity (■) (d) Left eye contrast sensitivity (■)

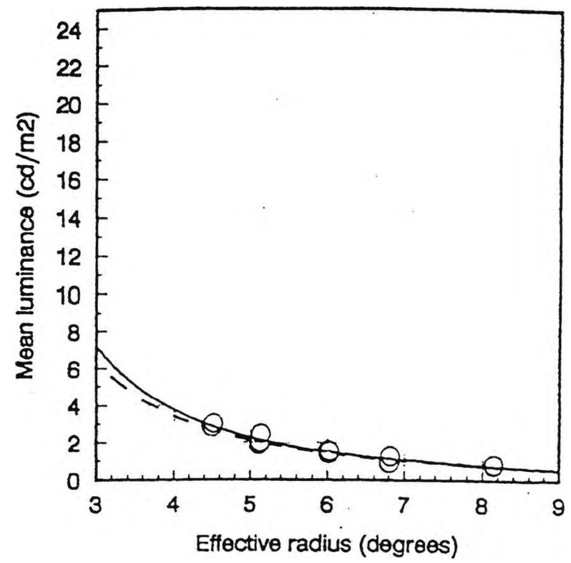
(O Age-matched control contrast sensitivity values)

Subject GR, male, Caucasian, 53 years.		
	Right eye	Left eye
Visual acuity	6/6	6/5
Contact lens type	PMMA/RGP	PMMA/RGP
Length of wear	10/5 years	10/5 years

Figure 9.26 *Scatter profile and contrast sensitivity results for Subject SL*

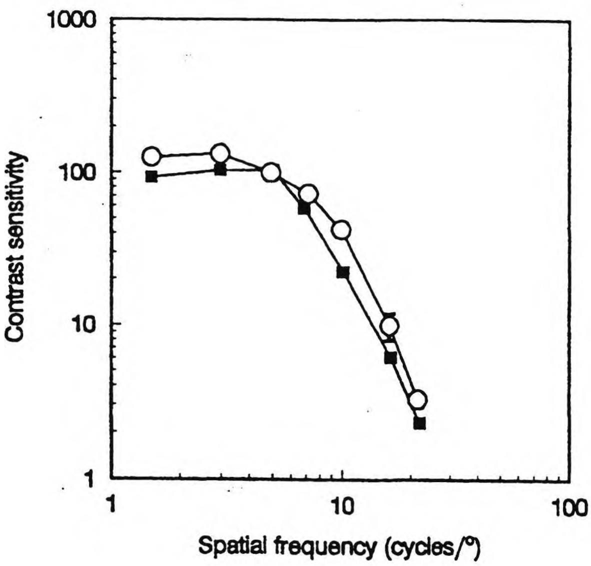


(a) Right eye scatter (O)

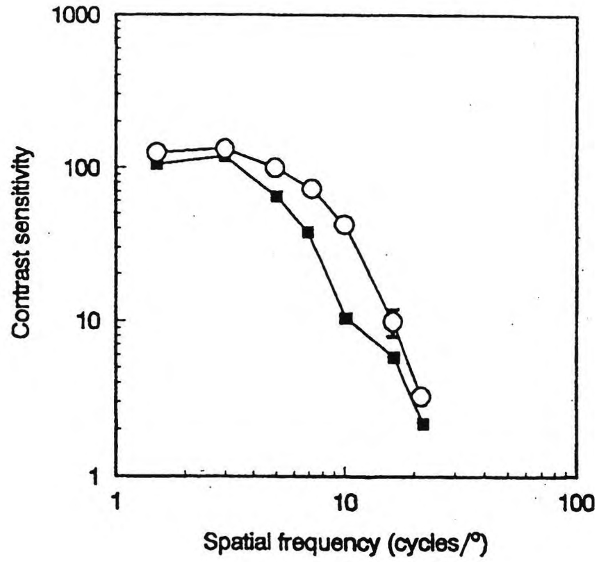


(b) Left eye scatter (O)

(- - - Age-matched control scatter values)



(c) Right eye contrast sensitivity (■)



(d) Left eye contrast sensitivity (■)

(O Age-matched control contrast sensitivity values)

Subject SL, male, Caucasian, 26 years.		
	Right eye	Left eye
Visual acuity	6/5	6/5
Contact lens type	Hydrogel/RGP	Hydrogel/RGP
Length of wear	10/5 years	10/5 years

9.8.3.10 Results of subjects wearing a mixture of lens types for a maximum of 20 years

Table 9.13 - Scatter results from two subjects wearing a mixture of lens types for a maximum of 20 years

Subject	Gender	Age (years)	Eye	*n*	s.d.	*k*	s.d.	*k'*	s.d.	*k'-k'(age)*
RF	Male	44	RE	1.98	0.29	30.14	16.31	13.33	0.46	4.87
			LE	2.30	0.20	33.53	13.59	11.61	0.03	3.15
ED	Male	56	RE	1.72	0.27	18.73	2.38	9.69	0.80	-4.26

Figure 9.27 shows the results of subject RF who revealed elevated levels of scatter in both eyes compared to an age-matched control. Due to the high *n* value obtained from the left eye (2.30), the spread of light scatter is less than that obtained from the right eye (1.98). The CSF shows reduced sensitivity at all spatial frequencies tested (apart from 10 cpd in both eyes and 5 cpd in the left eye). Subject ED has lower levels of light scatter and a better CSF compared to an age-matched control (figure 9.28). This finding may reflect the documented individual response to reduced oxygen levels (Holden et al 1984). No data were recorded for the left eye of ED, which has low visual acuity.

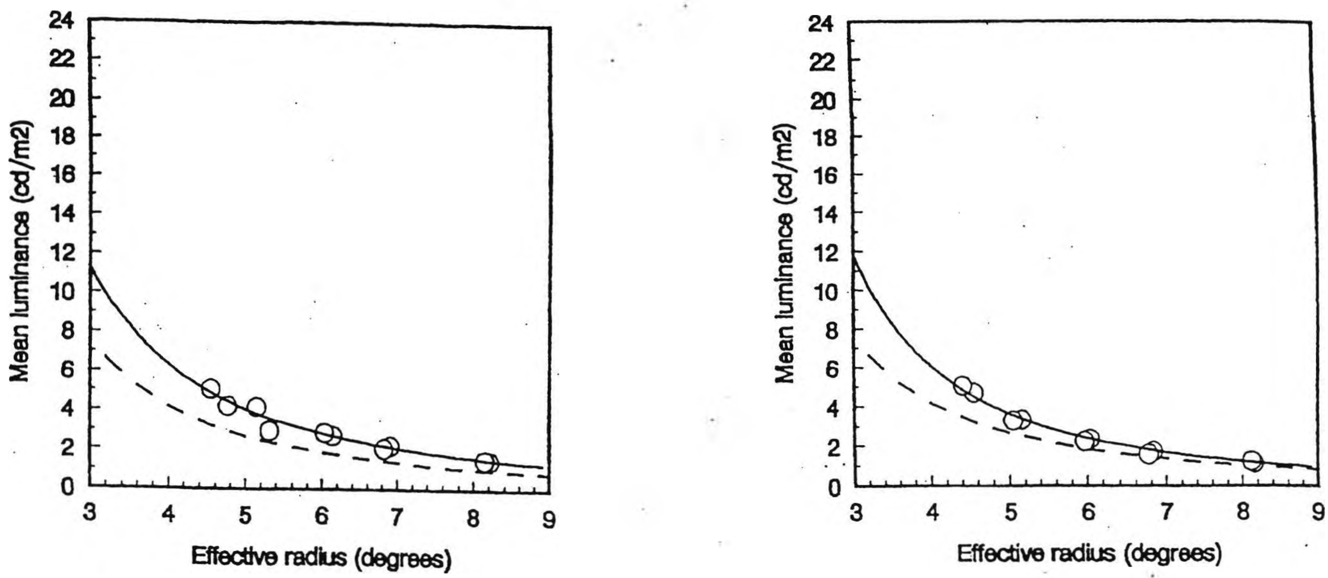
9.8.3.11 Results of subjects wearing a mixture of lens types for a maximum of 25 years

Table 9.14 - Scatter results from two subjects wearing a mixture of lens types for a maximum of 25 years

Subject	Gender	Age (years)	Eye	*n*	s.d.	*k*	s.d.	*k'*	s.d.	*k' -k' (age)*
TJ	Female	44	RE	1.82	0.09	29.75	3.32	18.89	1.44	10.20
			LE	2.03	0.16	35.14	6.57	15.13	2.38	6.44
DE	Female	53	RE	1.83	0.10	25.07	6.36	16.25	0.34	4.23
			LE	1.56	0.21	12.39	3.33	15.88	3.93	3.87

Figure 9.29 shows the results of subject TJ who experienced the greatest amount of light scatter in this group of subjects and had worn a mixture of lens types for 25 years. There are elevated levels of scatter in both eyes, compared to an age-matched control, and the CSF shows reduced sensitivity at low and high spatial frequencies in the right eye and all spatial frequencies (apart from 5 and 22 cpd) in the left eye. Figure 9.30 shows the results of subject DE. Due to the relatively low *n* value obtained from the left eye (1.56), the angular distribution of light scatter is wider in the left eye than the right eye (1.83). The

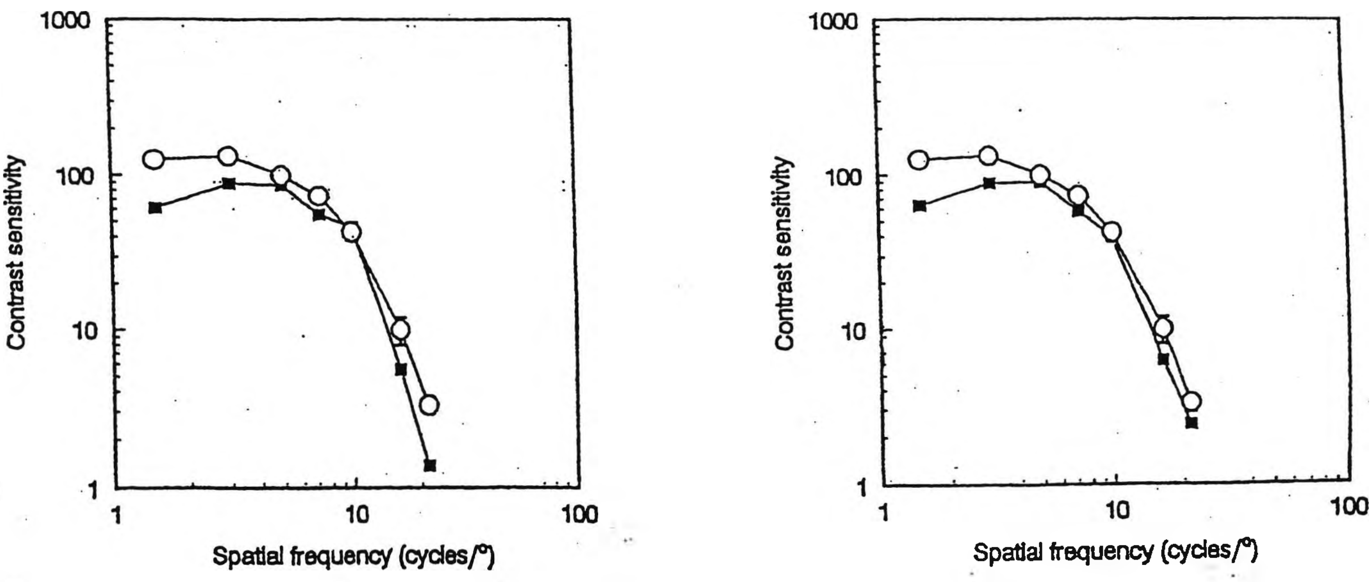
Figure 9.27 *Scatter profile and contrast sensitivity results for Subject RF*



(a) Right eye scatter (O)

(b) Left eye scatter (O)

(- - - Age-matched control scatter values)



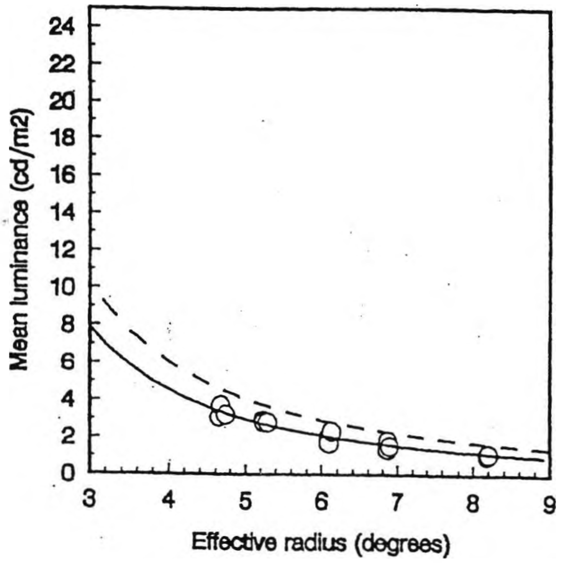
(c) Right eye contrast sensitivity (■)

(d) Left eye contrast sensitivity (■)

(O Age-matched control contrast sensitivity values)

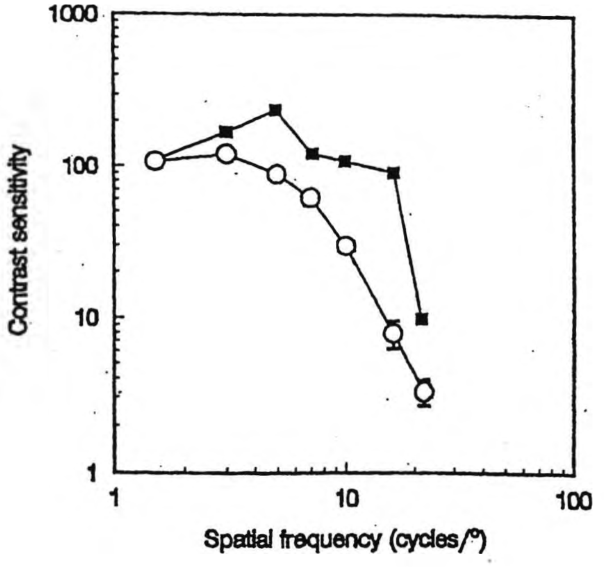
Subject RF, male, Caucasian, 44 years.		
	Right eye	Left eye
Visual acuity	6/4	6/4
Contact lens type	Hydrogel/RGP	Hydrogel/RGP
Length of wear	10/8 years	10/8 years

Figure 9.28 *Scatter profile and contrast sensitivity results for Subject ED*



(a) Right eye scatter (O) (b) Left eye scatter (O)

(- - - Age-matched control scatter values)

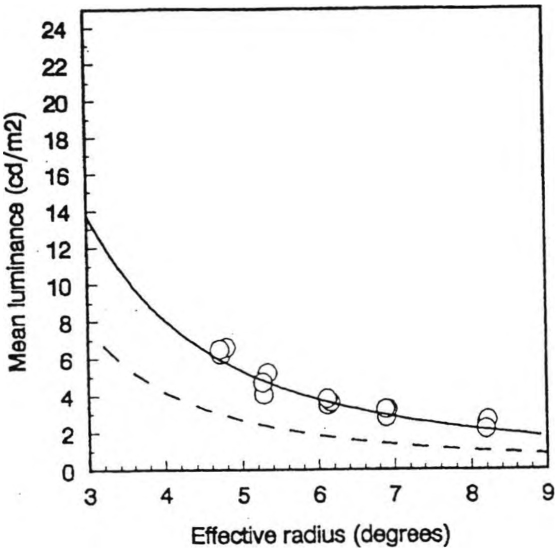


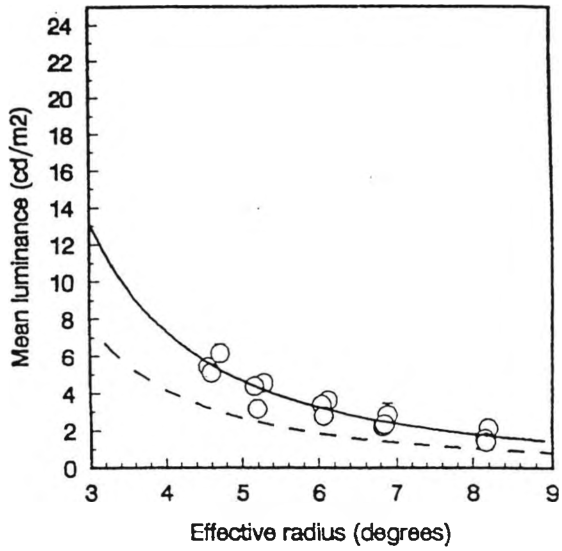
(c) Right eye contrast sensitivity (■) (d) Left eye contrast sensitivity (■)

(O Age-matched control contrast sensitivity values)

Subject ED, male, Caucasian, 56 years.		
	Right eye	Left eye
Visual acuity	6/5	6/60
Contact lens type	PMMA/RGP	-
Length of wear	10/10 years	-

Figure 9.29 *Scatter profile and contrast sensitivity results for Subject TJ*

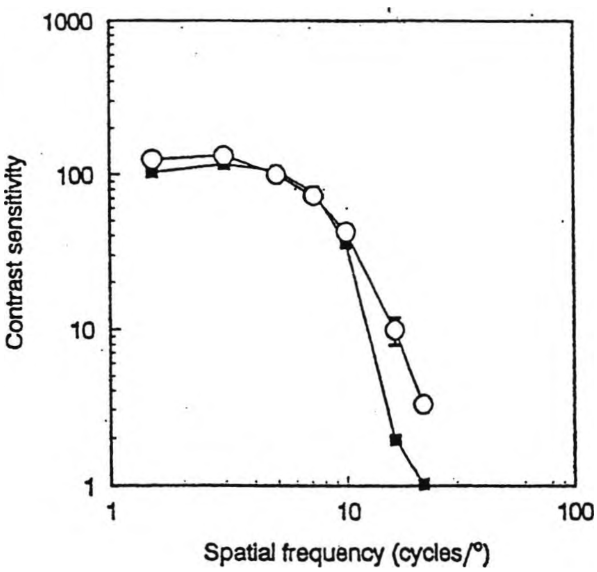


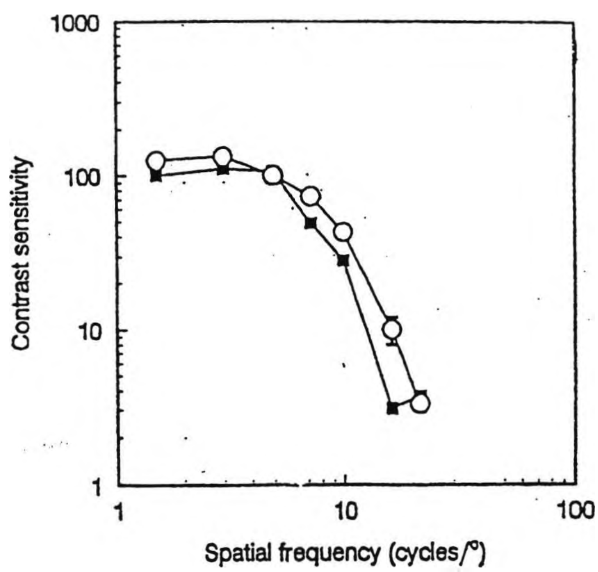


(a) Right eye scatter (O)

(b) Left eye scatter (O)

(- - - Age-matched control scatter values)





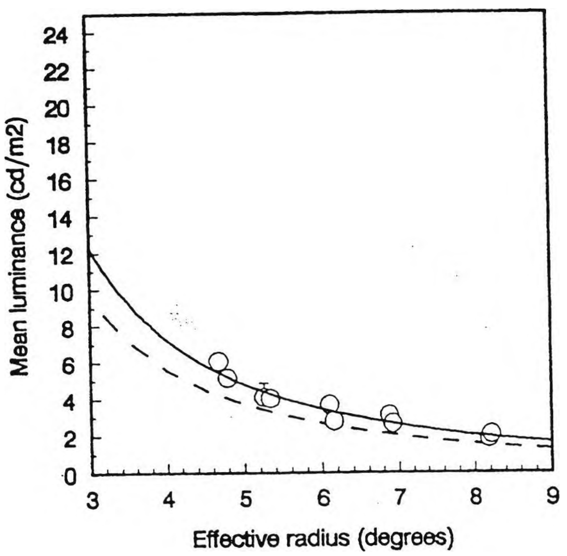
(c) Right eye contrast sensitivity (■)

(d) Left eye contrast sensitivity (■)

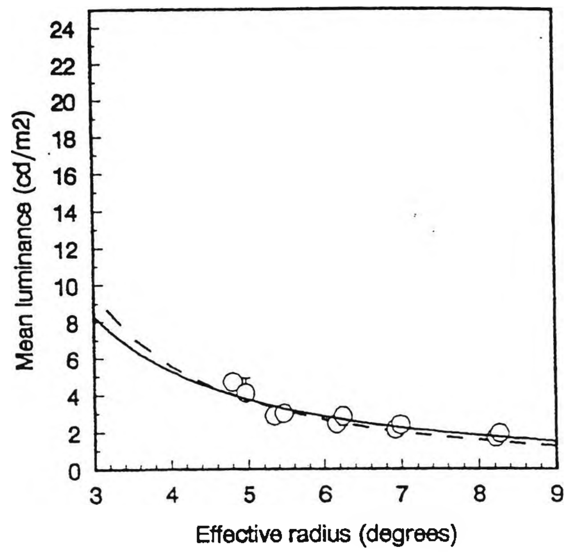
(O Age-matched control contrast sensitivity values)

Subject TJ, female, Caucasian, 44 years.		
	Right eye	Left eye
Visual acuity	6/6-3	6/6-2
Contact lens type	PMMA/RGP	PMMA/RGP
Length of wear	15/10 years	15/10 years

Figure 9.30 *Scatter profile and contrast sensitivity results for Subject DE*

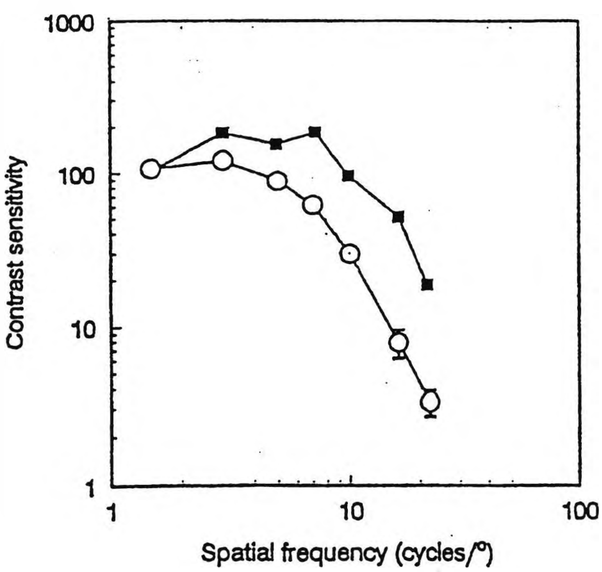


(a) Right eye scatter (O)

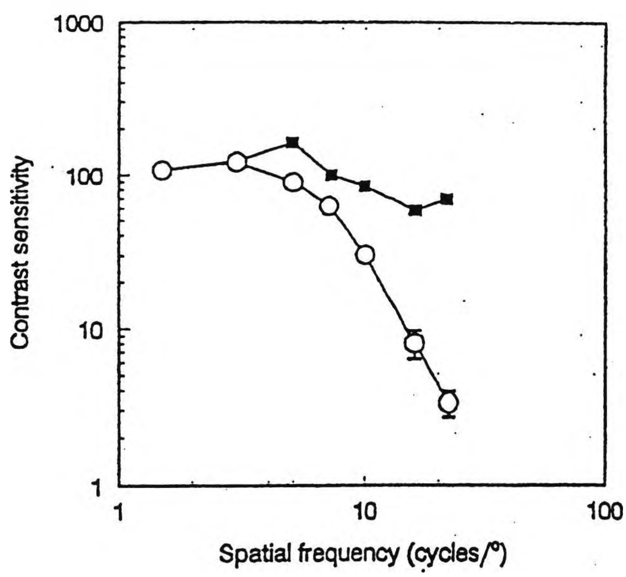


(b) Left eye scatter (O)

(- - - Age-matched control scatter values)



(c) Right eye contrast sensitivity (■)



(d) Left eye contrast sensitivity (■)

(O Age-matched control contrast sensitivity values)

Subject DE, female, Caucasian, 53 years.		
	Right eye	Left eye
Visual acuity	6/5+2	6/5
Contact lens type	PMMA/RGP	PMMA/RGP
Length of wear	20/4 years	20/4 years

CSF shows a better than expected level of CS in both eyes, compared to age-matched controls.

9.8.3.12 Results of subjects wearing a mixture of lens types for a maximum of 30 years

Table 9.15 - Scatter results from two subjects wearing a mixture of lens types for a maximum of 30 years

Subject	Gender	Age (years)	Eye	*n*	s.d.	*k*	s.d.	*k'*	s.d.	*k' - k'(age)*
CM	Male	52	RE	1.88	0.29	42.82	13.71	21.22	0.78	9.73
DL	Male	49	RE	1.66	0.17	17.37	13.33	10.39	0.90	0.22

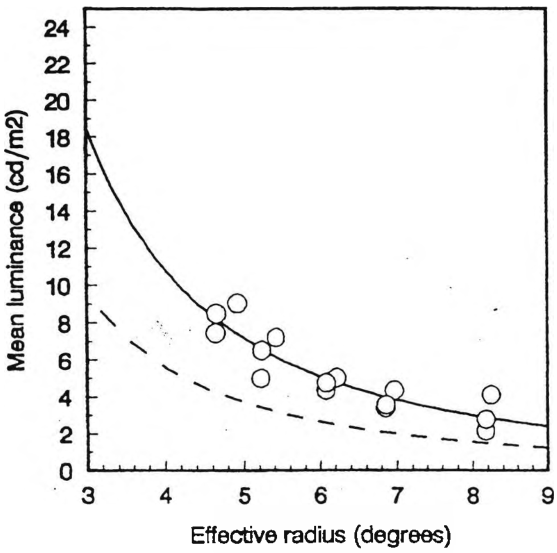
Figure 9.31 shows the results of subject CM who yielded an elevated level of scatter compared to an age-matched control. No data were recorded for the left eye of subject CM which has low visual acuity. Interestingly, the CSF shows a better CSF than an age-matched control. Again, this may reflect genuine biological variability. Although DL does not reveal raised light scatter, the CSF reveals loss at all spatial frequencies tested (figure 9.32). Again, this may be due to the presence of optical aberrations which may reduce visual performance in the absence of increased light scatter. No data were recorded for the left eye of subject CM, due to the presence of excessive deposits/abrasions on the contact lens.

9.8.4 Discussion

The main conclusion from the results obtained in this study is that most contact lens wearers (48 out of 54 eyes) suffer from increased levels of intraocular light scatter compared to age-matched non-lens wearers, regardless of the type of lens worn. This result concurs with the findings of Elliott et al (1991) and Mitchell and Elliott (1991).

Six contact lens wearing eyes (four subjects) out of the 54 eyes investigated exhibited reduced levels of light scatter compared to age-matched controls (all subjects were above 50 years of age). This finding in these four subjects may have been due to a number of factors. Firstly, pupil dilation is known to increase light scatter (Barbur et al 1993; Edgar et al 2000) and therefore the subjects involved in investigating the effect of age on the light scattering characteristics of the eye were not dilated prior to assessment with LOCS II.

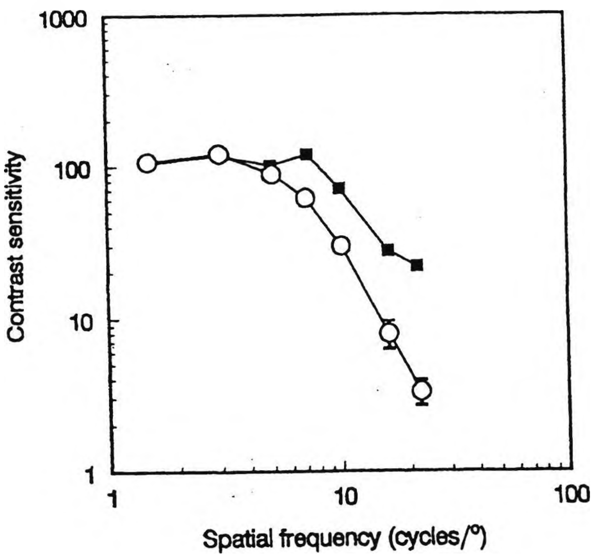
Figure 9.31 *Scatter profile and contrast sensitivity results for Subject CM*



(a) Right eye scatter (O)

(b) Left eye scatter (O)

(- - - Age-matched control scatter values)



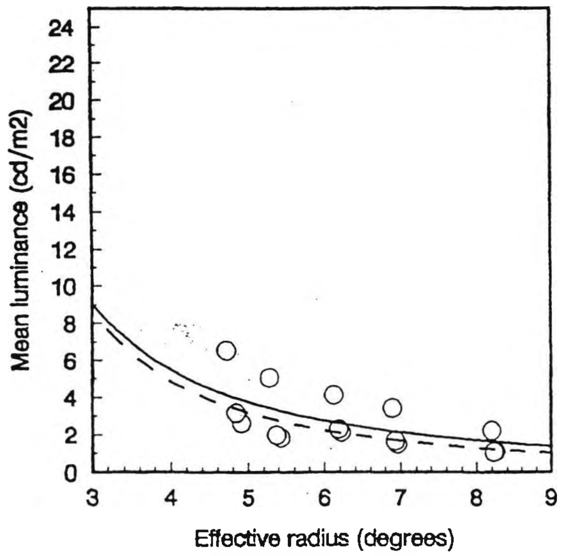
(c) Right eye contrast sensitivity (■)

(d) Left eye contrast sensitivity (■)

(O Age-matched control contrast sensitivity values)

Subject CM, male, Caucasian, 52 years.		
	Right eye	Left eye
Visual acuity	6/6+3	6/60
Contact lens type	PMMA/RGP	-
Length of wear	5/25 years	-

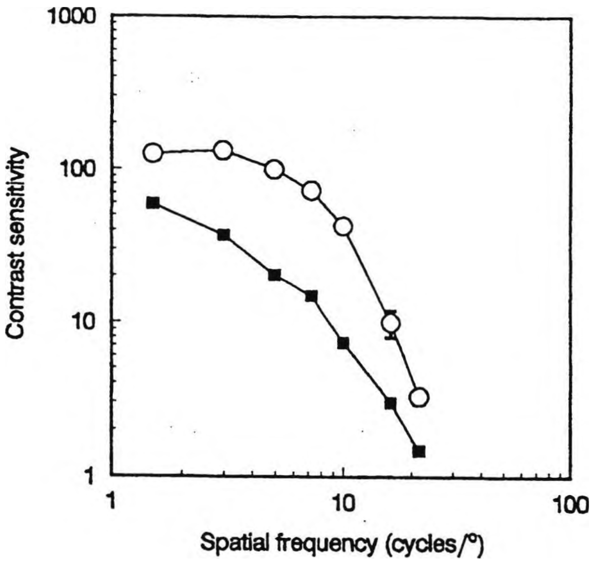
Figure 9.32 *Scatter profile and contrast sensitivity results for Subject DL*



(a) Right eye scatter (O)

(b) Left eye scatter (O)

(- - - Age-matched control scatter values)



(c) Right eye contrast sensitivity (■)

(d) Left eye contrast sensitivity (■)

(O Age-matched control contrast sensitivity values)

Subject DL, male, Caucasian, 49 years.		
	Right eye	
Visual acuity	6/6	
Contact lens type	PMMA/RGP	
Length of wear	20/10 years	

Therefore, peripheral lens opacities may have been evident in the older age groups (i.e. Groups 4 and 5) contributing to the normal database, which may have elevated the measured k' values in this population. As a result, the crystalline lenses measured in the older age groups may not have been truly representative of subjects with less than Grade 1 lens changes, as measured by LOCS II. In addition, there was a great deal of variability in this older population, compared to younger normal subjects. Furthermore, the rate and effects of ageing varies between individuals, as has been reported by many authors (e.g. Johnson and Choy 1987; Lachenmayr et al 1994).

Eight scatter values (six subjects) recorded in the contact lens-wearing population were within the range of values obtained from keratoconic wearers who complained of symptoms of glare (section 8.10.1.1). Despite this, none of the contact lens-wearing subjects investigated complained of glare symptoms. This may be due to the fact that the visual and cosmetic advantages of contact lens wear, as opposed to spectacle wear, outweigh the disadvantage of increased light scatter. As a consequence, contact lens-wearing subjects may be less likely to complain of glare symptoms. Conversely, keratoconics are perhaps more visually aware of light scatter changes due to the nature of their condition and are therefore more likely to complain of increased light scatter.

The long-term effect of contact lens wear on the CSF varied markedly between individuals. Thirteen eyes revealed no CS loss, whilst 19 eyes showed loss at all spatial frequencies tested. Seven eyes revealed loss at high and intermediate frequencies, six at high and low spatial frequencies, five at low spatial frequencies only, and two at intermediate and low spatial frequencies. One eye revealed loss at intermediate spatial frequencies only and one eye revealed loss at high spatial frequencies only. Therefore, in general, most contact lens wearers showed some degree of CS loss, compared to age-matched controls.

Three studies that investigated the effect of contact lens wear on the CSF following long-term wear reported no CS loss (Grey 1987; Gundel et al 1988; Ziel et al 1990), although direct comparisons are difficult due to methodological differences. The present findings are also at odds with the results of Woo and Hess (1979), who stated that contact lens wearers only suffer from a reduced CSF if they suffer symptoms of glare. None of the subjects tested for this study reported any glare symptoms, despite 41 eyes exhibiting a certain degree of CS loss.

Three eyes revealed no increase in light scatter but showed CS losses (subjects WR and AR). The reduction in CS may be due to optical aberrations caused by the contact lens (Mitra and Lamberts 1981; Guillon et al 1983) as measures of visual performance (such as CS) have been shown to be affected by optical aberrations in the absence of increased scattered light (Chisholm et al 2000; Maeda et al 2000). Furthermore, it is possible that factors such as lens induced flexure or poor surface wettability may influence measures of CS, without necessarily causing an increase in intraocular light scatter. Thirteen eyes revealed an increase in light scatter but no reduction in CS (subjects PG, PC, AH, EL, TT, DE and CM). These subjects had worn a range of lens types for varying durations and it is, therefore, impossible to state clear causative factors. However, the subjects may simply reflect the known biological variability inherent in measures of CS. One subject (ED) revealed lower levels of light scatter and a better CSF compared to an age-matched control. This subject had worn contact lenses for a total of 20 years (10 years of PMMA wear followed by 10 years of RGP wear). This finding may reflect the documented individual response to reduced oxygen levels (Holden et al 1984).

Due to the small numbers of eyes examined within each subgroup, characterised by either hydrogel, RGP, PMMA or a mixture of lens types worn for either 5, 10, 15, 20, 25 or 30 years, it would be statistically invalid to examine differences in k' using the 12 cells which contain data in Table 9.2. In addition, the classification of subjects was complicated by the fact that a patient's contact lens history may involve periods of lens wear with different types of lenses or different modes of wear. Also, the impact of the lens on the eye may differ, depending on such factors as average duration of lens wear, the nature of the lens fit, the companion solutions used and other parameters connected with wearing and maintenance. Consequently, a contact lens wear history is often complex and multidimensional (Polse et al 1990).

It is well known that contact lenses provide a barrier to atmospheric oxygen which results in varying levels of corneal oedema (Smelser and Ozanics 1953; Smelser and Shen 1955; Korb and Exford 1968; Mandell et al 1970; Schauer et al 1973; O'Neal et al 1984).

Therefore, a possible cause of elevated light scatter in long-term contact lens-wearing subjects is corneal hypoxia in response to the contact lens wear. The corneal consequences of chronic hypoxia in response to contact lens wear are many and varied. Holden et al (1985) reported epithelial thinning as a result of contact lens wear and suggested that this was due to chronic hypoxia. Stromal thinning was also observed, and was attributed to stomal keratocytes undergoing morphological alterations in response to oedema (Kanai and Kaufman 1973). In addition to the epithelial and stromal thinning that occurs in response to chronic corneal oedema, endothelial changes may also affect visual performance. However, even though a number of physiological causes may underlie the increased levels of light scatter found in the contact lens-wearing population, the most obvious cause of increased light scatter is the physical presence of the contact lens itself. To investigate the possibility of increased light scatter caused by the physical presence of a contact lens, non-lens wearing subjects were recruited and tested before and after fitting with either a hydrogel or RGP contact lens.

9.9 Study 2 - The effect of contact lens wear on the light scattering characteristics of non-lens wearing subjects

9.9.1 Aims

The aim of this study was to investigate whether light scatter increases following insertion of either a RGP or hydrogel contact lens. The effects of a contact lens on light scatter and CS were measured in a non-contact lens-wearing population in order to differentiate between light scatter and CS changes that occur due to the physical presence of a contact lens and chronic physiological changes that occur in response to long-term contact lens wear.

Subjects were included in the study if they:-

- had VA of at least 6/9
- were ophthalmologically normal
- had no significant lenticular changes (i.e. less than Grade 1 as measured by LOCS II)
- had no history of contact lens wear
- were female above the age of 40 years

- had a spherical refractive error between +0.50 DS and -0.25 DS and astigmatism of less than 0.50 DC.

Subjects were excluded from the study if they:-

- had VA of worse than 6/9
- were not ophthalmologically normal
- had significant lenticular changes (i.e. more than Grade 1 as measured by LOCS II)
- had a history of contact lens wear
- were female under the age of 40 years
- had a spherical refractive error above +0.50 DS and -0.25 DS and astigmatism of more than 0.50 DC.

9.9.2 Methods

In total, 10 male and four female non-contact lens-wearing subjects were recruited. The female subjects were above the age of 40 years and so the results from these four subjects are unlikely to be as variable as those found in younger females in Chapter 7. Each subject was evaluated using the slit lamp biomicroscope to evaluate corneal integrity and lens opacification. All subjects underwent scatter and CS testing using the methodology described in section 5.7. Measurements were taken in the afternoon to avoid the previously observed variability caused by the effects of overnight sleep (as discussed in section 6.13).

Following scatter and CS baseline measurements in the non lens-wearing population, keratometry was performed and the subjects were fitted with either a plano hydrogel (B&L soflens 38.6% water, polymacon material) or a plano RGP (C3 lens diameter 9.80, Boston ES material) lens. Scatter and CS measurements were then repeated following a period of adaptation (approximately half an hour). Wherever possible, three scatter runs were taken.

9.9.3 Results of fitting contact lenses in a non lens-wearing population

The following tables show the results of scatter testing prior to and following fitting with a hydrogel or a RGP lens in a non lens-wearing population. '1° ' represents the k' values obtained prior to lens insertion, '2°' represents the k' values following lens insertion. Figures 9.33 - 9.46 show the results from each individual subject.

9.9.3.1 Hydrogel lens insertion

9.9.3.1.1 Results

Table 9.16 - Scatter results from seven non-adapted subjects before and after fitting with a hydrogel lens.

Subject	Age (years)	Gender	Point of measurement	*n*	s.d.	*k*	s.d.	*k'*	s.d.	2° - 1°
SW	19	Male	1°	1.99	0.15	17.43	3.26	8.13	0.73	0.04
			2°	2.10	0.03	21.32	2.82	8.17	0.63	
MB	30	Male	1°	2.07	0.10	20.23	2.68	8.07	0.36	0.32
			2°	2.03	0.17	19.66	5.62	8.39	0.22	
RT	30	Male	1°	2.20	0.02	24.16	0.26	7.78	0.24	-0.16
			2°	p = 2.21	0.18	24.15	6.70	7.62	0.48	
AH	48	Female	1°	1.62	0.19	19.18	0.82	11.55	2.32	1.58
			2°	1.85	0.04	13.17	4.07	13.13	2.42	
PT	60	Male	1°	1.76	0.01	27.35	1.76	19.72	1.40	-5.02
			2°	1.97	0.38	30.91	15.60	14.70	3.41	
KJ	60	Female	1°	1.16	2.18	18.25	11.36	21.68	4.36	3.26
			2°	1.52	0.28	19.13	10.02	24.94	5.94	
TJ	60	Male	1°	1.91	0.24	35.08	10.04	18.90	2.94	2.11
			2°	1.71	0.31	25.24	9.75	21.01	5.60	

Mean age = 43.7 years (17.17)

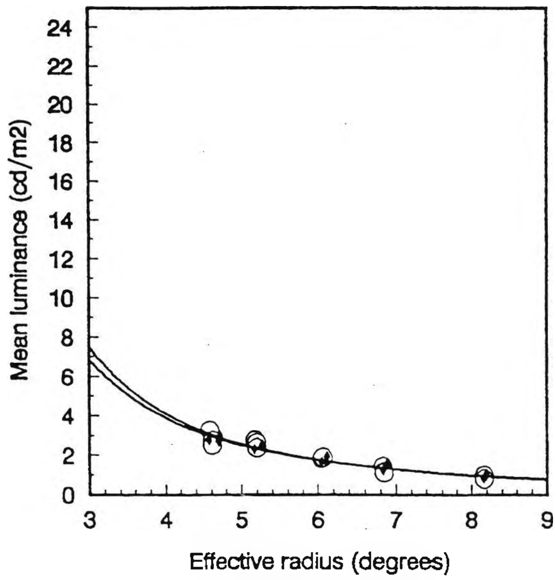
Mean k' 1° = 13.69 (6.18)

Mean k' 2° = 13.99 (6.78)

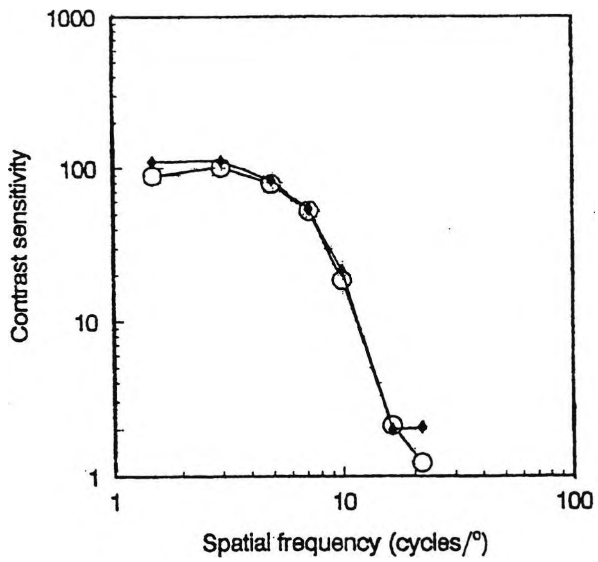
9.9.3.1.2 Discussion

For this small group of subjects, the presence of a hydrogel lens in the eye does not cause a statistically significant change in intraocular light scatter (paired t-test, $p = 0.77$, $t = -0.30$). However, there was variability in the effects of lens wear on scattered light. The mean change in k' produced by hydrogel lens wear in this non lens-wearing population is +0.30 (2.2%). In the three youngest subjects (SW, MB and RT) clinically insignificant changes in scattered light occurred (figures 9.33, 9.34 and 9.35). All three subjects had low standard deviations associated with the scatter measurements. Of the four older subjects, three showed increases in light scatter of 11.2% (AH) (figure 9.36), 13.7% (TJ) (figure 9.39) and 15.0% (KJ) (figure 9.38). One subject (PT) (figure 9.37) showed a 34.2% reduction in light scatter after lens insertion. The scatter measurements are accompanied by large

Figure 9.33 *Change in (a) light scatter and (b) contrast sensitivity following insertion of a hydrogel contact lens for Subject SW*



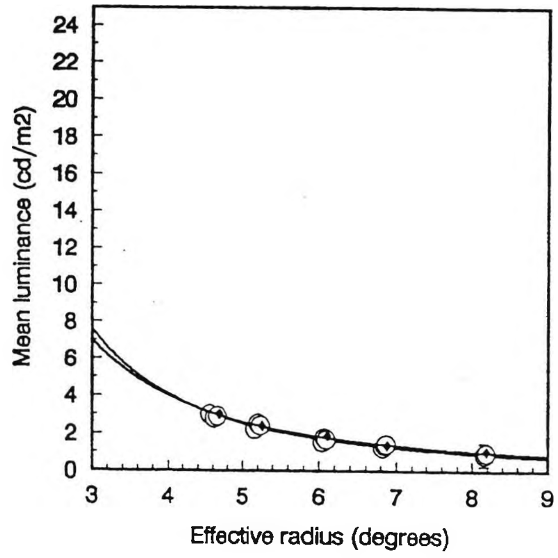
(a) Before insertion (O), after insertion (◆)



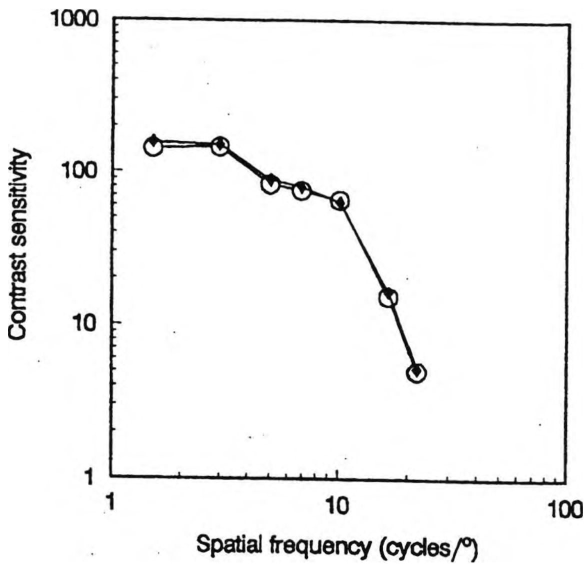
(b) Before insertion (O), after insertion (◆)

Three measurements were taken from a randomly chosen eye before and after hydrogel contact lens insertion.

Figure 9.34 *Change in (a) light scatter and (b) contrast sensitivity following insertion of a hydrogel contact lens for Subject MB*



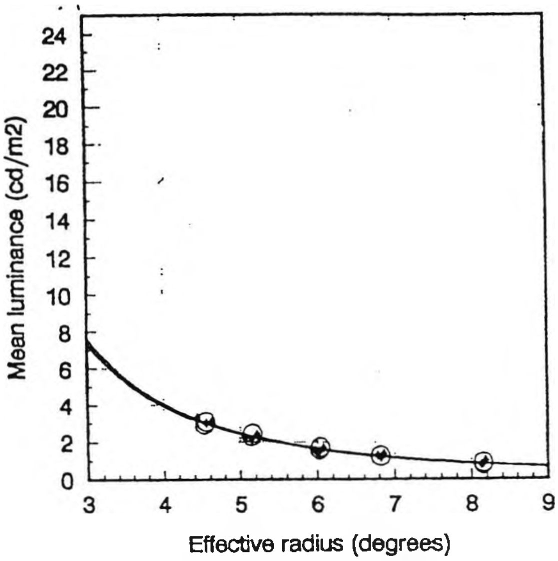
(a) Before insertion (O), after insertion (◆)



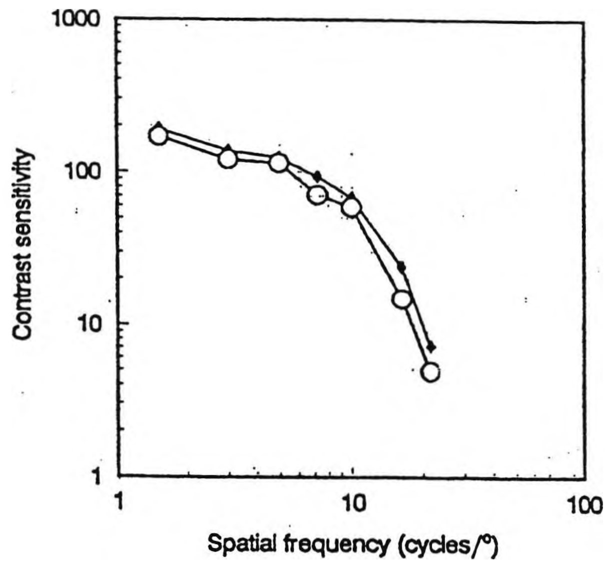
(b) Before insertion (O), after insertion (◆)

Three measurements were taken from a randomly chosen eye before and after hydrogel contact lens insertion.

Figure 9.35 *Change in (a) light scatter and (b) contrast sensitivity following insertion of a hydrogel contact lens for Subject RT*



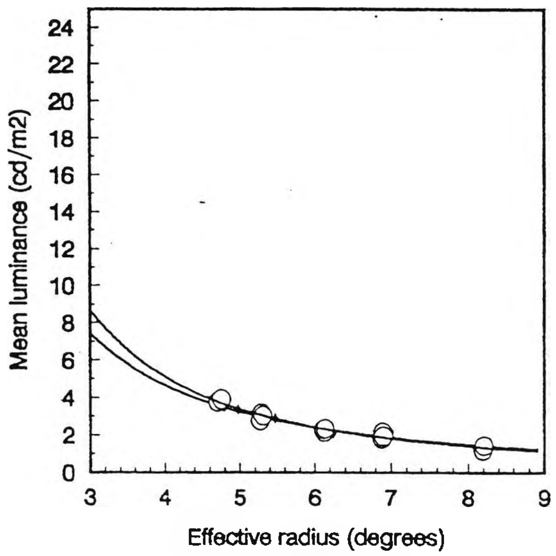
(a) Before insertion (O), after insertion (◆)



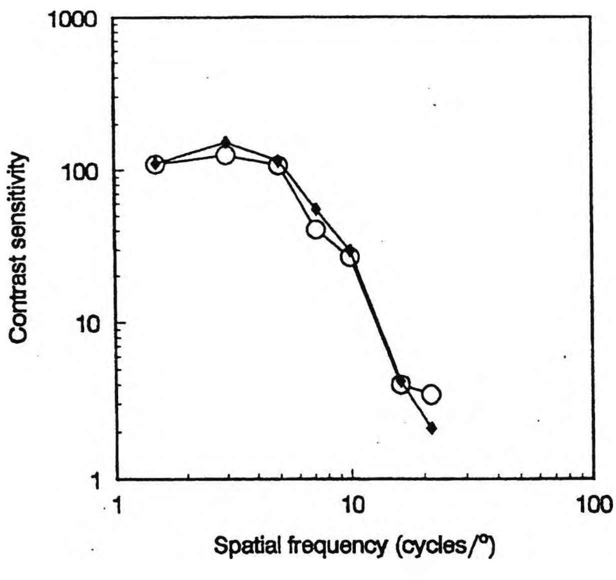
(b) Before insertion (O), after insertion (◆)

Three measurements were taken from a randomly chosen eye before and after hydrogel contact lens insertion.

Figure 9.36 *Change in (a) light scatter and (b) contrast sensitivity following insertion of a hydrogel contact lens for Subject AH*



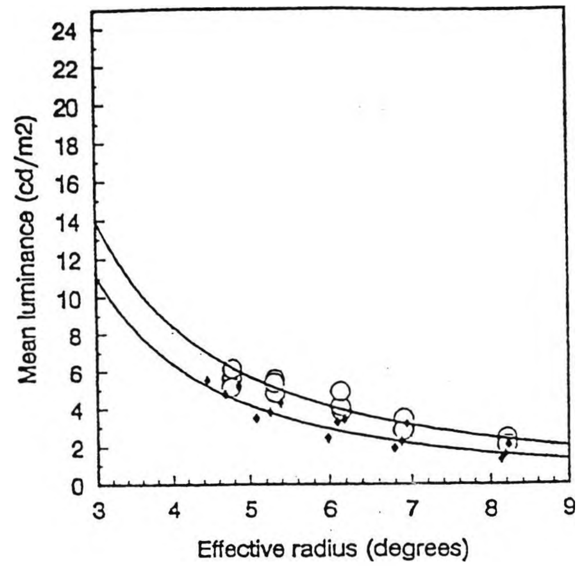
(a) Before insertion (O), after insertion (◆)



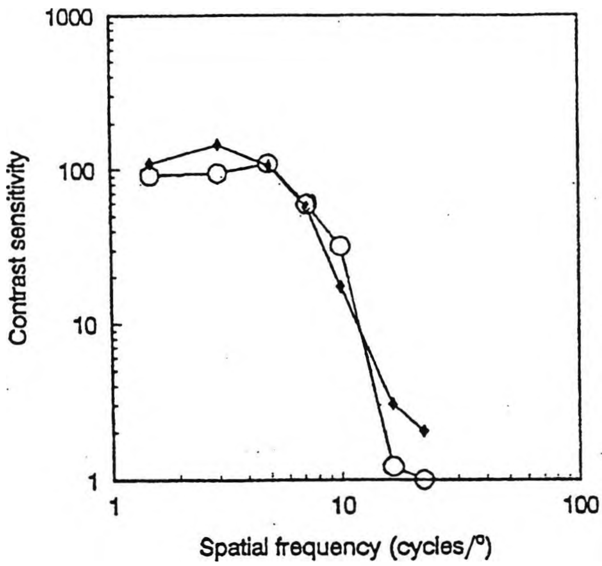
(b) Before insertion (O), after insertion (◆)

Three measurements were taken from a randomly chosen eye before and after hydrogel contact lens insertion.

Figure 9.37 *Change in (a) light scatter and (b) contrast sensitivity following insertion of a hydrogel contact lens for Subject PT*



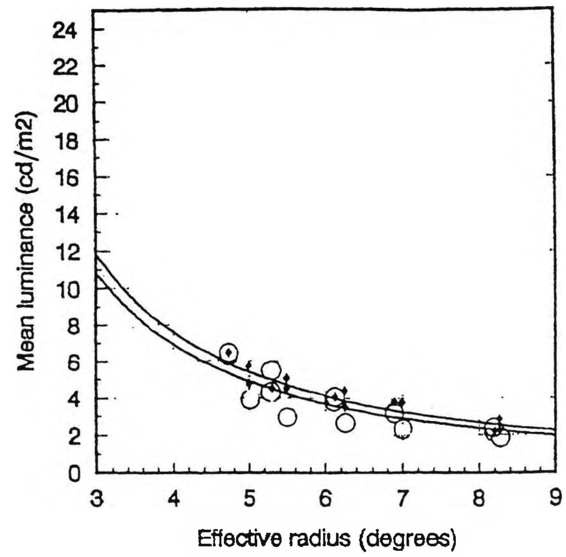
(a) Before insertion (O), after insertion (◆)



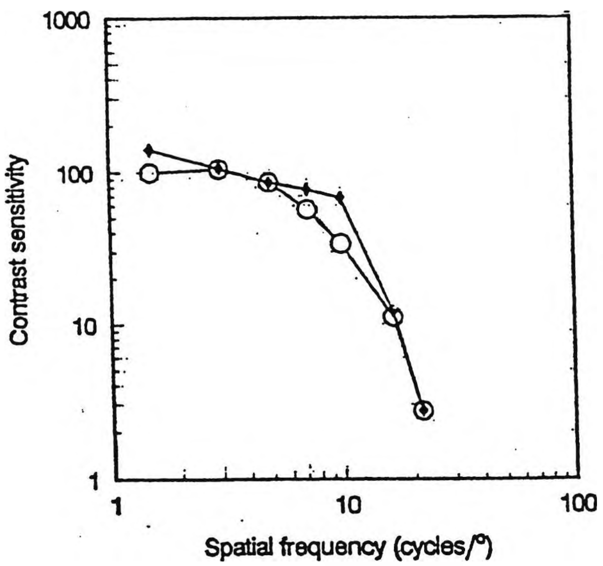
(b) Before insertion (O), after insertion (◆)

Three measurements were taken from a randomly chosen eye before and after hydrogel contact lens insertion.

Figure 9.38 *Change in (a) light scatter and (b) contrast sensitivity following insertion of a hydrogel contact lens for Subject KJ*



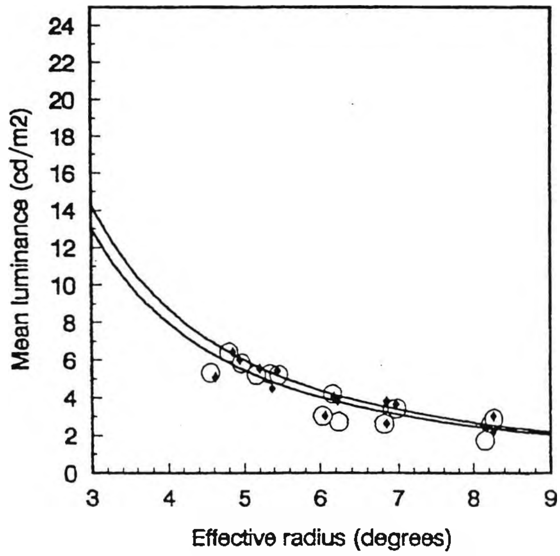
(a) Before insertion (O), after insertion (◆)



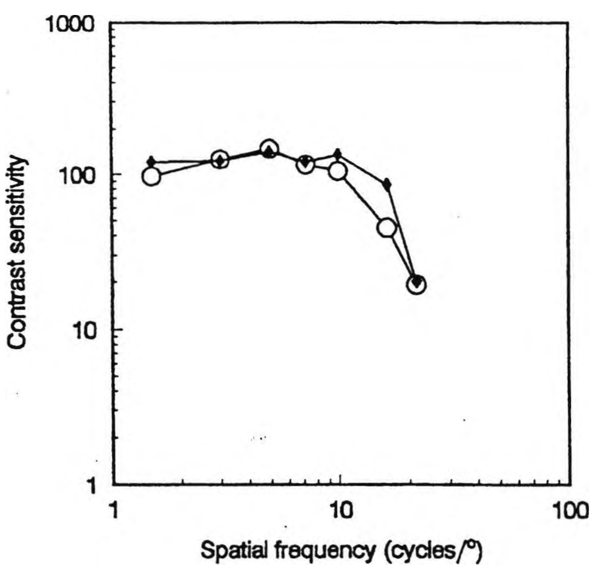
(b) Before insertion (O), after insertion (◆)

Three measurements were taken from a randomly chosen eye before and after hydrogel contact lens insertion.

Figure 9.39 *Change in (a) light scatter and (b) contrast sensitivity following insertion of a hydrogel contact lens for Subject TJ*



(a) Before insertion (O), after insertion (◆)



(b) Before insertion (O), after insertion (◆)

Three measurements were taken from a randomly chosen eye before and after hydrogel contact lens insertion.

standard deviations, which may be suggestive of experimental error. In fact, subjects PT and TJ show an approximate doubling of the standard deviation. This implies that these subjects, understandably, found the task of completing the test battery twice following a break of only 30 minutes arduous. In addition to fatigue, other possible causes of error include learning and an inadequate contact lens adaptation period. However, the change in light scatter observed as a consequence of hydrogel lens insertion appears to reflect the documented individual response to reduced oxygen levels (Holden et al 1984).

The CSF following insertion of a hydrogel contact lens was not adversely affected by the presence of the contact lens, with only subject AH revealing loss at 22 cpd, and subject PT revealing loss at 10 cpd. This finding is in contrast to Applegate and Massof (1975) and Grey (1986) who reported either CS loss at all or intermediate spatial frequencies following one or two hours of hydrogel lens wear in non-adapted wearers. However, Bernstein and Broderick (1981) and Nowozyckyj et al (1988) reported no difference between hydrogel lens wear and spectacles when measurements were taken after 0.5 and two hours after lens insertion. Following hydrogel lens insertion, there is an increase in sensitivity at 1.5 cpd in all subjects tested. Other increases in sensitivity are also evident but the spatial frequency at which the increase occurs varies between subjects. RT shows an increase at all spatial frequencies, TJ reveals increases in sensitivity at low, intermediate and high spatial frequencies, subjects SW and PT show increases at high and low spatial frequencies, AH and KJ show increases at intermediate and low, whilst subject MB reveals an increase at 1.5 cpd only. Therefore, hydrogel lens wear does not appear to have a detrimental effect on the CS. In fact, at certain spatial frequencies, sensitivity improves following insertion of a hydrogel lens. However, learning effects cannot be discounted.

9.9.3.2 RGP lens insertion

9.9.3.2.1 Results

Table 9.17 - Scatter results from seven non-adapted subjects before and after fitting with a RGP lens.

Subject	Age (years)	Gender	Time of measurement	*n*	s.d.	*k*	s.d.	*k'*	s.d.	2°- 1°
MN	20	Male	1°	2.13	0.10	18.55	2.33	6.82	0.57	0.22
			2°	1.98	0 .30	15.64	7.52	7.04	0.49	
RU	21	Male	1°	1.97	0.04	13.40	2.19	6.39	0.78	0.14
			2°	2.03	0.06	15.15	2.73	6.53	1.14	
KJ	32	Male	1°	1.75	0.06	12.82	1.22	9.48	0.50	-0.39
			2°	1.77	0.06	12.89	1.48	9.09	0.25	
JH	50	Male	1°	1.75	0.18	16.60	7.05	12.19	0.63	-0.23
			2°	1.99	0.13	25.70	3.91	11.96	0.56	
KH	48	Male	1°	1.77	0.15	17.35	2.76	11.94	1.84	1.19
			2°	1.76	0.30	18.37	8.49	13.13	2.65	
PH	50	Female	1°	2.13	0.14	34.48	9.54	12.31	0.82	3.08
			2°	1.77	0.41	23.96	18.28	15.39	1.68	
PT	59	Female	1°	1.87	0.39	29.07	19.58	15.55	0.60	-0.93
			2°	1.61	0.27	15.17	9.42	14.62	0.14	

Mean age = 40.29 years (15.73)

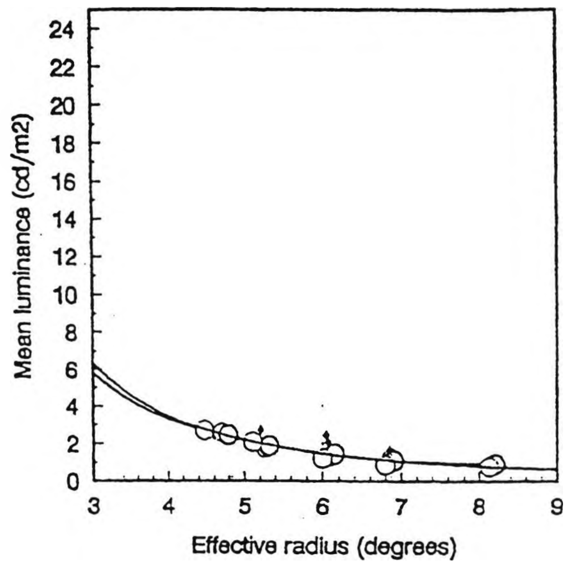
Mean *k'* 1° = 10.67 (3.29)

Mean *k'* 2° = 11.09 (3.58)

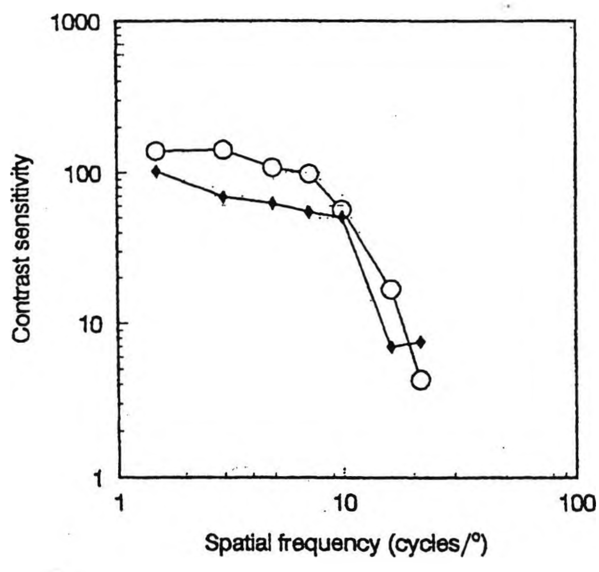
9.9.3.2.2 Discussion

For this small group of subjects, the presence of a RGP lens in the eye does not cause a statistically significantly change in intraocular light scatter (paired t-test, $p = 0.42$, $t = -0.87$). However, there was variability in the effects of lens wear on scattered light. The mean change in *k'* produced by RGP lens wear in this non lens-wearing population is +0.42 (3.9%). In the three youngest subjects (MN (figure 9.40)), RU (figure 9.41) and KJ (figure 9.42) clinically insignificant changes in scattered light occurred. Of the four older subjects, two showed increases in light scatter of 10.0% (KH (figure 9.44)), 25.0% (PH (figure 9.45)) and two showed a reduction in light scatter (1.9% - JH (figure 9.43), 6.4% - PT (figure 9.46)) following RGP lens insertion. Possible causes of error again include fatigue, learning and an inadequate contact lens adaptation period. There is less variability in the

Figure 9.40 *Change in (a) light scatter and (b) contrast sensitivity following insertion of a RGP contact lens for Subject MN*



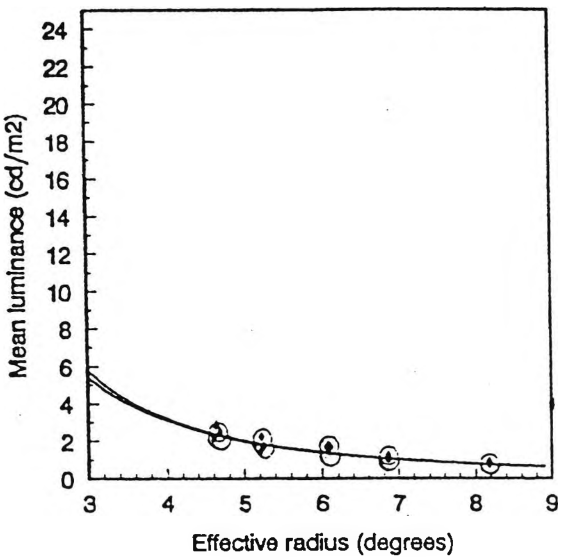
(a) Before insertion (O), after insertion (◆)



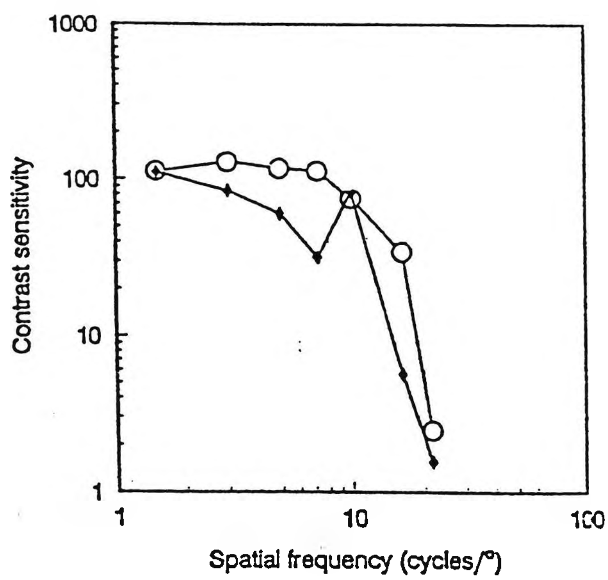
(b) Before insertion (O), after insertion (◆)

Three measurements were taken from a randomly chosen eye before and after RGP contact lens insertion.

Figure 9.41 *Change in (a) light scatter and (b) contrast sensitivity following insertion of a RGP contact lens for Subject RU*



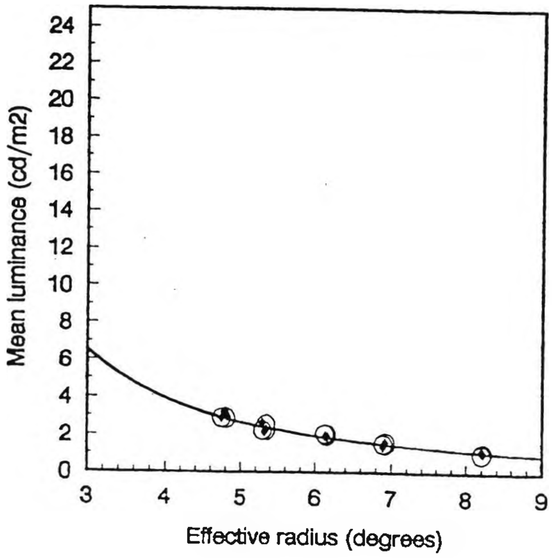
(a) Before insertion (O), after insertion (◆)



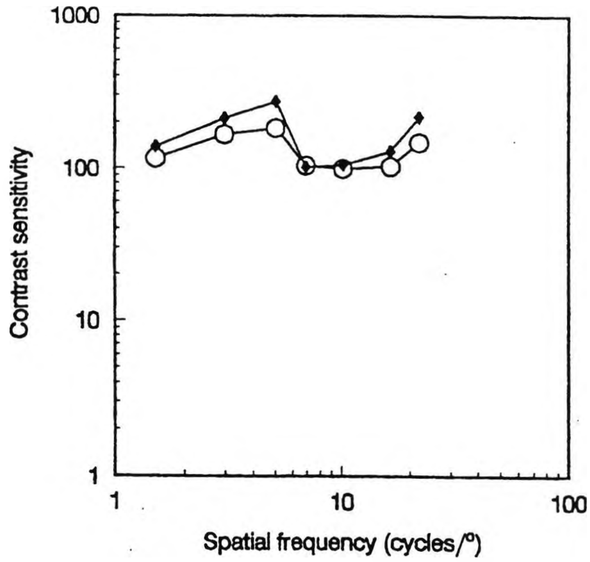
(b) Before insertion (O), after insertion (◆)

Three measurements were taken from a randomly chosen eye before and after RGP contact lens insertion.

Figure 9.42 *Change in (a) light scatter and (b) contrast sensitivity following insertion of a RGP contact lens for Subject KJ*



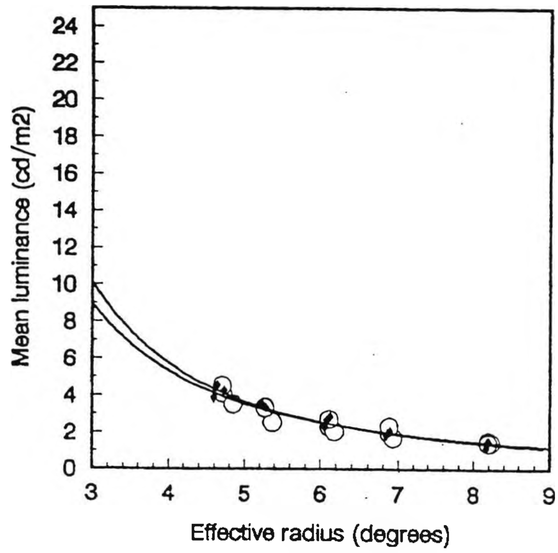
(a) Before insertion (O), after insertion (◆)



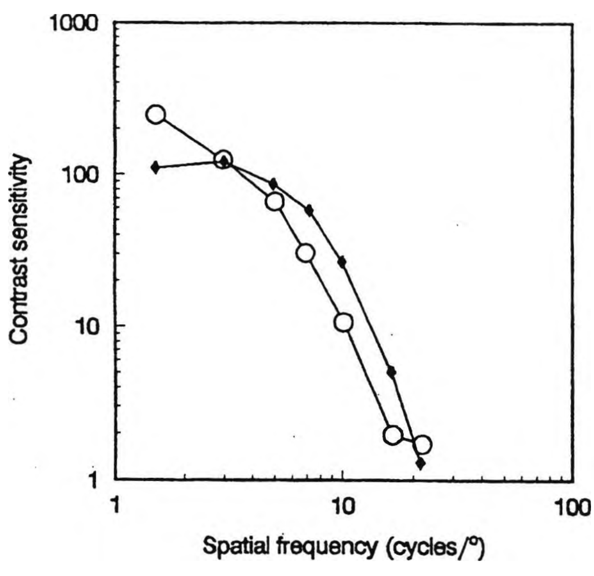
(b) Before insertion (O), after insertion (◆)

Three measurements were taken from a randomly chosen eye before and after RGP contact lens insertion.

Figure 9.43 *Change in (a) light scatter and (b) contrast sensitivity following insertion of a RGP contact lens for Subject JH*



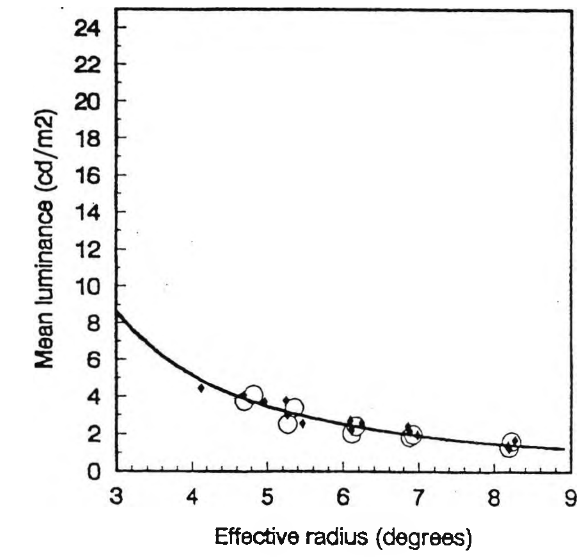
(a) Before insertion (O), after insertion (◆)



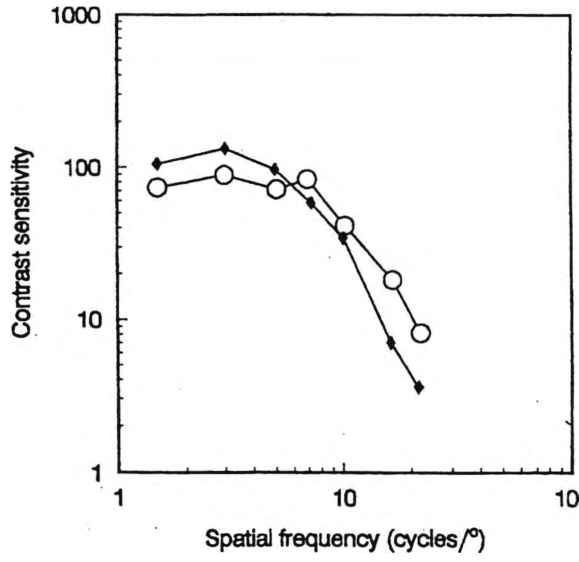
(b) Before insertion (O), after insertion (◆)

Three measurements were taken from a randomly chosen eye before and after RGP contact lens insertion.

Figure 9.44 *Change in (a) light scatter and (b) contrast sensitivity following insertion of a RGP contact lens for Subject KH*



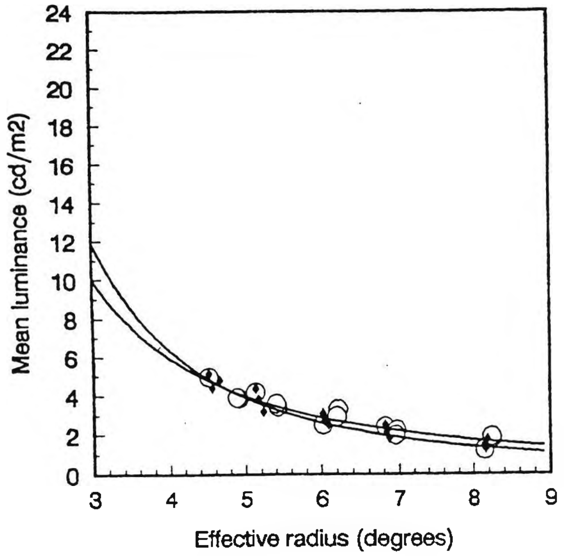
(a) Before insertion (O), after insertion (◆)



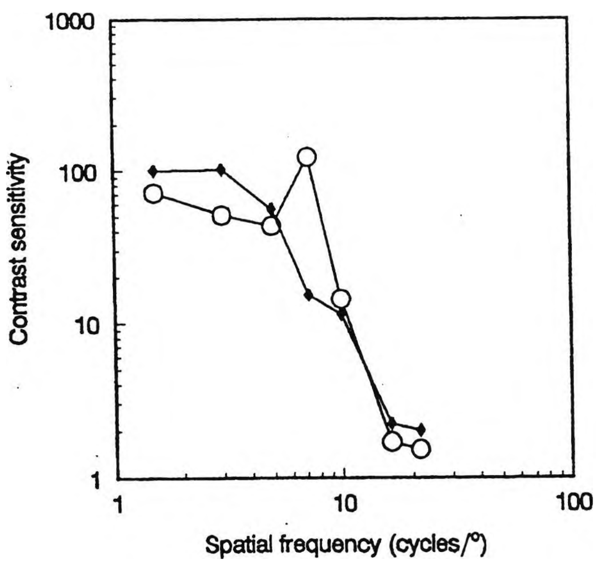
(b) Before insertion (O), after insertion (◆)

Three measurements were taken from a randomly chosen eye before and after RGP contact lens insertion.

Figure 9.45 *Change in (a) light scatter and (b) contrast sensitivity following insertion of a RGP contact lens for Subject PH*



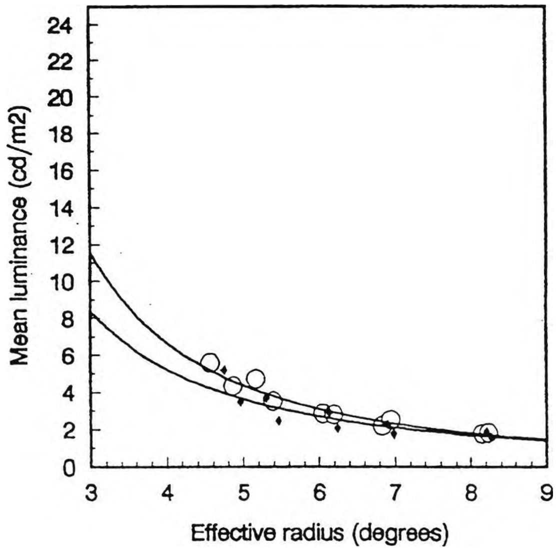
(a) Before insertion (O), after insertion (◆)



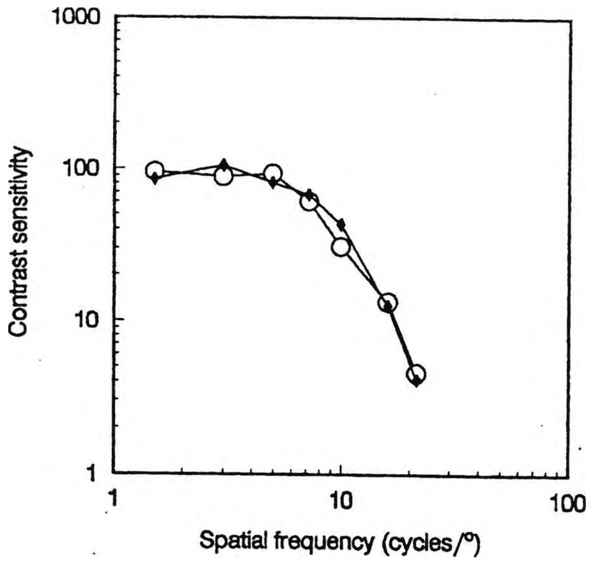
(b) Before insertion (O), after insertion (◆)

Three measurements were taken from a randomly chosen eye before and after RGP contact lens insertion.

Figure 9.46 *Change in (a) light scatter and (b) contrast sensitivity following insertion of a RGP contact lens for Subject PT*



(a) Before insertion (O), after insertion (◆)



(b) Before insertion (O), after insertion (◆)

Three measurements were taken from a randomly chosen eye before and after RGP contact lens insertion.

older age group when compared to the older hydrogel group (apart from subject KH). This may have been due to the fact that the hydrogel group contained older subjects than the RGP group or due to differences in lens design.

The effect of a RGP contact lens on the CSF is more variable both within and between subjects than for the hydrogel lens group. Following insertion of a RGP lens, two subjects reveal a loss of CS at most spatial frequencies (MN and RU), whilst two reveal an increase in sensitivity at most spatial frequencies (KJ and JH). Two subjects reveal CS loss at certain spatial frequencies and increases in sensitivity at others (PH and KH). The CSF for subject PT is unchanged by the presence of a RGP lens. Therefore, no definite trends in CS emerge from this group. In general, there is much greater variability between 2° and 1° measurements, when compared with the results obtained from the hydrogel group. It is difficult to compare these results with other studies investigating the effect of RGP lenses on the CSF, due to methodological differences. That said, CS losses have been recorded in non-adapted wearers wearing RGP lenses, although the length of time between insertion and testing was not stated (Guillon et al 1983).

The differences between the 2° - 1° k' values obtained from fitting non contact lens-wearing subjects with either a hydrogel or a RGP lens reveal no significant differences between the means (two sample t-test $p = 0.14$, $t = 1.73$).

9.10 Discussion of Chapter 9

Fitting non-adapted lens wearers with hydrogel or RGP lenses produced small increases or reductions in light scatter compared with those previously recorded in adapted wearers. When compared with age-matched controls the average increase in light scatter in the adapted contact lens-wearing group from Study 1 was 3.70 (3.99) whilst the average increase in the non-adapted wearers from Study 2 was 0.30 (2.65) when fitted with hydrogel lenses and 0.44 (1.33) when fitted with RGPs. Therefore, the presence of a contact lens in a non lens-wearing population did not cause a similar statistically or clinically significant increase in light scatter. Therefore, the elevated scatter observed in adapted lens-wearing subjects was unlikely to be due to the physical presence of the lens and is thus a physiological consequence of long-term lens-wear. However, it must be noted that different lenses were used than those worn by the adapted wearers and they were new plano lenses with less imperfections. Although the contact lens wearers included in Study 1 exhibited only minimal protein deposits, it is likely that frequently worn lenses had more deposits than recently inserted new lenses (as used in Study 2) (Randeri 1974; Randeri and Glicksir 1975; Leahy et al 1990; Lin et al 1991). That said, Elliott et al (1993) reported no significant correlation between lens deposits and increased forward light scatter. Therefore, lens deposits (if minimal) are unlikely to be responsible for the elevated scatter values observed in Study 1. In addition, the adapted group all had significant refractive error which required correction (i.e. contact lenses), whilst the non-adapted group contained only those with minimal refractive error. Due to the number of physiological changes that occur in association with refractive error (particularly myopia), it is possible that these changes may cause an increase in light scatter. However, Lohmann et al (1993) reported no significant correlation between the magnitude of myopic correction and increased forward light scatter in contact lens wearers.

Nine subjects in the non lens-wearing population exhibited an increase in light scatter following contact lens insertion (mean 1.33 (1.27)), whilst five exhibited a decrease (mean -1.35 (2.08)). The observed increase in light scatter is perhaps not suprising, due to the number of ocular changes that may occur as a result of contact lens adaptation (e.g. epithelial oedema, stromal oedema, endothelial blebs) and the intra-subject variability of the scatter data, especially with a test battery performed with only a 30 minute gap between sessions. In addition, changes in tear osmolarity and osmotic stress may each produce demonstrable effects in the ocular environment (Mandell and Harris 1968; Mandell and Polse 1970). Nevertheless, the differences between non-adapted and adapted wearers indicate that the effects on light scatter are due to the long-term impact of contact lenses on the eye, rather than the physical presence of the contact lens itself. The finding that long-term contact lens wear induces physiological corneal changes is in agreement with Hamano (1960), Morgonroth and Richman (1969), Millodot (1976, 1978), Schoessler and Woloschak (1981), Caldwell (1982), Hirst et al (1984), Millodot (1984), Holden (1985, 1988), Douthwaite (1986), Lydon (1986), MacRae et al (1986), Schoessler (1991), Nieuwedaal et al (1994), Sanaty and Temel (1998), and Setala et al (1998).

The most likely cause of elevated light scatter in long-term contact lens-wearing subjects is corneal hypoxia in response to the contact lens wear. Contact lenses provide a barrier to atmospheric oxygen which results in varying levels of corneal oedema (Smelser and Ozanics 1953; Smelser and Shen 1955; Korb and Exford 1968; Mandell et al 1970; Schauer et al 1973; O'Neal et al 1984). All commercially available contact lenses induce some degree of hypoxia (Mandell et al 1970; Schauer et al 1973). Several of the RGP lenses have Dk/L values low enough to cause some degree of oxygen deprivation (Sarver et al 1977; O'Neal and Polse 1984) and even mild hypoxia is thought to suppress aerobic epithelial metabolism, such that oedema results. The presence of oedema is classically evaluated using the slit lamp biomicroscope but this method only allows measurement of backward light scatter (section 1.2). As discussed in Chapter 6, epithelial oedema may cause an increase in forward light scatter without affecting backward light scatter. Furthermore, backward light scatter does not equal forward light scatter (Feuk and McQueen 1971). Therefore, although all wearers investigated in the present study were classified as clinically normal using the backscatter method, this does not preclude the presence of subclinical oedema (Elliott et al 1993). Epithelial oedema is well known to occur in response to contact lens wear (Finkelstein 1952; Mandell et al 1970; Kwon et al 1972; Schauer et al 1973; O'Neal et al 1984; Polse et al 1990). Scatter testing may thus aid diagnosis of otherwise unidentified sub-clinical levels of corneal oedema.

The corneal consequences of chronic hypoxia in response to contact lens wear are many and varied. Holden et al (1985) reported epithelial thinning as a result of contact lens wear and suggested that this was due to chronic hypoxia. Stromal thinning was also observed, and was attributed to stomal keratocytes undergoing morphological alterations in response to oedema (Kanai and Kaufman 1973). It has been well documented that stromal keratocytes produce the haze experienced by patients who have undergone refractive surgery (Lohmann et al 1991). Therefore it is possible that if there is a disruption to the stromal keratocytes, as a result of chronic hypoxia due to contact lens wear, then an increase in forward light scatter, despite no apparent changes in VA, scarring or other abnormalities on biomicroscopic examination, may be expected (Holden et al 1985).

In addition to the epithelial and stromal thinning that occurs in response to chronic corneal oedema, endothelial changes may also affect visual performance. Numerous researchers have reported endothelial cell loss, polymegethism and pleomorphism in response to long-term contact lens wear (e.g. Caldwell et al 1982; Caillard and Cochet 1983). The disruption of the normal hexagonal endothelium layer, as a result of contact lens wear, may in turn result in increased forward light scatter. It has been shown that long-term contact lens wear results in altered endothelial morphology and reduced corneal function (Polse et al 1990). Therefore, it is possible that such an alteration in endothelial cell morphology and function, as a consequence of long-term contact lens wear, causes the observed increase in light scatter.

Reductions in the CSF were evident in the adapted contact lens-wearing group but the spatial frequency at which the CS loss occurred varied markedly. Although classification is somewhat arbitrary, thirteen eyes revealed no CS loss, whilst 19 eyes showed loss at all spatial frequencies tested. Seven eyes revealed loss at high and intermediate frequencies, six at high and low spatial frequencies, five at low spatial frequencies only, and two at intermediate and low spatial frequencies. One eye revealed loss at intermediate spatial frequencies only and one eye revealed loss at high spatial frequencies only. Three eyes revealed no increase in light scatter but showed CS losses (subjects WR and AR). The reduction in CS may be due to optical aberrations caused by the contact lens (Mitra and Lamberts 1981; Guillon et al 1983) as measures of visual performance (such as CS) have been shown to be affected by optical aberrations in the absence of increased scattered light (Chisholm et al 2000; Maeda et al 2000). Thirteen eyes revealed an increase in light scatter but no reduction in CS (subjects PG, PC, AH, EL, TT, DE and CM). These subjects have worn a range of lens types for varying durations and it is, therefore, impossible to state clear causative factors. However, these subjects' results may simply reflect the known biological variability inherent in measures of CS. Therefore, in general, most contact lens wearers showed some degree of CS loss, compared to age-matched controls. In contrast, studies investigating the effect of contact lens wear on the CSF following long-term wear reported no CS loss (Grey 1987; Gundel et al 1988; Ziel et al 1990), although direct comparisons with the findings of other studies are difficult due to methodological differences.

The CSF following insertion of a contact lens in non-lens wearing subjects produced variable effects. A hydrogel contact lens did not adversely affect CS with only two subjects showing any loss of sensitivity (at only one spatial frequency). In fact, at certain spatial frequencies, sensitivity improved following insertion of a hydrogel lens. This finding is in contrast to Applegate and Massof (1975) and Grey (1986) who reported either CS loss at all or intermediate spatial frequencies following one or two hours of hydrogel lens wear in non-adapted wearers. However, Bernstein and Broderick (1981) and Nowozyckyj et al (1988) reported no difference between hydrogel lens wear and spectacles when measurements were taken after 0.5 and two hours after lens insertion. The effect of a RGP contact lens on the CSF appeared to vary between individuals and there was much greater variability between 2° and 1° measurements, when compared with the results obtained from the hydrogel group. CS losses have been recorded in non-adapted wearers wearing RGP lenses, although the length of time between insertion and testing was not stated (Guillon et al 1983). In conclusion, no clear pattern of CS loss was identified in the non-adapted contact lens-wearing group. This may have been to the physical impact of the lens on the eye, fatigue, learning, an inadequate adaptation time, or simple differences in lens design. In fact, only nine out of the 19 long-term contact lens-wearing subjects who revealed loss at all spatial frequencies were rigid lens wearers (PMMA or RGP) which indicates that rigid lens design is unlikely to have caused the observed reduction in CS in non-adapted and adapted wearers. However, differences in lens design cannot be ignored in reducing CS or increasing light scatter, in either the adapted or the unadapted group, as such variations have been identified as causing reduced VA. For hydrogel lenses, factors include strain induced with lathe-cut lenses during the manufacturing process (Mandell 1988) and hydrogel lens induced flexure (Gundel et al 1988). For RGP wearers, loss of VA is commonly the result of lens warpage (Henry et al 1987; Henry et al 1990) and/or poor surface wettability (Grohe and Caroline 1989). Although all subjects examined in the present study had a VA of at least 6/9, this does not preclude such changes causing the observed reduction in CS or indeed increased light scatter. However, given that 19 eyes of long-term contact lens wearers showed a reduction in sensitivity at all spatial frequencies tested and only two non-adapted wearers showed a similar pattern of loss (MN and RU), the observed reduction in the CSF in long-term wearers is most likely to be due to the same corneal changes that cause the increase in light scatter, such as corneal oedema, epithelial/stromal thinning and/or endothelial changes.

9.11 Conclusions

Long-term contact lens wear causes an increase in light scatter as measured by *k'*, the integrated straylight parameter. Forty eight out of 54 contact lens-wearing eyes were seen to have significantly greater levels of light scatter than non lens-wearing subjects of the same age (two sample t-test, $p < 0.001$, $t = 4.78$). Fitting non lens-wearing subjects with either a hydrogel or RGP contact lens had a variable effect on measures of light scatter - nine subjects showed an increase in k' whilst five revealed a decrease. The presence of a hydrogel or RGP lens in the eye did not cause a statistically significant change in intraocular light scatter (paired t-test, $p = 0.77$, $t = -0.30$, $p = 0.42$, $t = -0.87$, respectively). In all cases, the increases in light scatter found in the non lens-wearing population fitted with lenses were less than the average increase in k' found in adapted lens wearers.

The CSF was reduced in 41 of the 54 eyes of adapted contact lens wearers, compared to age-matched controls. The spatial frequencies at which the CS loss occurred varied between individuals. Fitting non lens-wearing subjects with either a hydrogel or RGP contact lens had a variable effect on measures of CSF - only two hydrogel lens subjects showed a reduced CS following insertion. CS was shown to be more variable following RGP lens insertion than following hydrogel lens insertion but no definite trend emerged from this group. Therefore, the increase in light scatter observed in the contact lens-wearing population is unlikely to be due to the physical presence of the contact lens, instead it is likely to be due to the number of physiological changes that are known to occur in response to contact lens wear. These changes include chronic corneal oedema resulting in epithelial and stromal thinning, and altered endothelial cell morphology and function.

CHAPTER 10

Conclusions and future work

10.1 Conclusions

This thesis is the first to investigate the full intraocular light scatter function in normal subjects, in those with anterior segment eye disease and in long-term contact lens wearers. Previous studies investigating forward light scatter have assumed that n (the scatter index, which describes the angular distribution of scattered light) has a constant value of two. In the present study, values of n were measured and varied between normal individuals. Also, n decreased with age, implying that light scatter becomes more widely distributed with age. In the studies presented in this thesis, the angular dependence of scatter is not assumed to be invariant, and k', the integral of the scatter function was determined. k' showed no significant change up to about 45 years of age. However, a rapid increase in scatter occurred above 45 years of age. For subjects less than 45 years of age, k' ranged from 4.85 to 8.13 (mean = 6.75, s.d. = 0.91). For older subjects, k' ranged from 10.69 to 19.71 (mean = 14.92, s.d. = 3.28). Older subjects had decreased sensitivity at all spatial frequencies apart from 22 cpd, when compared to younger subjects. The largest reduction in CS was found at low to medium spatial frequencies. As the subjects used in the present study had excellent VA, and apparently no pathology, this pattern of results is likely to be accounted for by advancing age. These changes may originate from any ocular structure, but the most likely cause is the crystalline lens. Even though all subjects were investigated using LOCS II, it has been demonstrated in the literature that backward light scatter (as seen with the slit lamp), does not equal forward light scatter. Measures of forward light scatter using the P_SCAN 100 apparatus reveal that, firstly it is incorrect to assume a constant value of n, and secondly that measures of backscatter do not adequately reflect measures of forward light scatter.

There have been no previous reports of a diurnal variation in light scatter. In the present study, the level of light scatter in the eye changed during the course of a day. Results from testing one subject revealed a diurnal variation in k', which showed an early morning peak. The value of k' then fell on each occasion to reach a steady value. When pachometry measurements were taken, CT increased following overnight sleep and also following patching. The level of corneal oedema produced by different subjects showed individual variations in corneal hydration control. Increases in k', and its subsequent reduction, may be related to changes in CT. This finding has important implications for future studies investigating light scatter.

When longitudinal measurements were taken at approximately the same time of day, female subjects revealed a greater fluctuation in light scatter compared to male subjects. Initially, results were obtained from one female, and a possible cyclical trend was noted during cycles 1 and 2, which was attributed to changes in response to the menstrual cycle. In cycle 1, k' was seen to fall from a maximal level on day 1 of the first cycle and then increase to day 17, whereupon there was a decrease from this second peak towards the end of the cycle. Cycle 2 revealed more variability than cycle 1, although a similar pattern was maintained. Testing a further two menstrual cycles (cycles 3 and 4) also revealed large variability in scatter, with little sign of a cyclical trend. These results may have been the consequence of hormonal effects resulting from concomitant corticosteroid administration.

A double-blind masked study on three subjects revealed that female subjects experience large variability in intraocular light scatter when measurements were taken longitudinally. Again, the most likely cause is the menstrual cycle. However, statistical analysis showed that precise cyclical trends were unclear, other than consistent falls in scatter levels during the first five days of menses. A variation in CCT and pupil diameter was also found during the menstrual cycle, however, this appeared to be unrelated to the changes in light scatter. The administration of acetylcysteine 5% reduced the amount of light scatter in one eye of one subject during menses, suggesting that changes in mucus levels in the tear film (possibly in response to reduced oestrogen levels) may be a contributory factor. Male subjects revealed less day-to-day variability in light scatter, with relatively constant values of k'. This may be due to the absence of hormone-related changes in ocular structures in these subjects. This finding should be taken into consideration in longitudinal studies involving pre-menopausal women. Furthermore, it is likely that any light scatter investigation taken with a study sample containing pre-menopausal women will be affected by such changes in light scatter.

Although studies have reported CS losses and increased glare susceptibility in subjects with keratoconus, the full intraocular scatter function in such subjects has not been measured. In the present study, subjects with keratoconus exhibited raised intraocular scatter compared to age-matched normals, which was associated with symptoms of glare and a reduction in the CSF at all spatial frequencies. The level of light scatter observed in this group of patients did not correlate with the backscatter grading of the condition. Subjects with corneal abnormalities revealed wide variability in the amount of scatter and similarly variable CS loss. The variability may be attributed to the diversity of the conditions examined. Extensive corneal involvement produced higher levels of light scatter.

Therefore, this method of directly assessing intraocular light scatter may provide clinicians with a useful means of quantifying a keratoconic's visual experience and the likely effects of the increased light scatter on visual function. In fact, in order to improve visual function degraded by light scatter, certain keratoconic subjects examined in this study subsequently received early surgical intervention as a direct result of ophthalmological review of their scatter results. These findings demonstrate the clinical value of testing forward light scatter using the P_SCAN 100 scatter apparatus.

To date, the effects of long-term contact lens wear (i.e. up to 30 years of lens wear) on measures of forward light scatter or CS have not been investigated. Nor has there been a comparison of the results of such measures from long-term wearers with non-lens wearers who have been fitted with contact lenses. The methodology employed in the present study enabled a comparison between the physiological effects of contact lens wear and those that are a consequence of the physical presence of the contact lens. The finding that long-term contact lens wear caused an increase in the amount of light scatter measured by the P_SCAN 100 scatter apparatus is of great clinical interest. Contact lens wearers had significantly greater levels of light scatter than non lens-wearing subjects of the same age and the CSF was also reduced in most adapted contact lens wearers, compared to age-matched controls. When 14 non lens-wearing subjects were fitted with either a hydrogel or RGP contact lens, neither lens type caused a statistically significant change in light scatter. In general, the increases in light scatter found in the non lens-wearing population fitted with lenses were less than those found in adapted lens wearers. Therefore, the increase in light scatter observed in the contact lens-wearing population is unlikely to be due to the physical presence of the contact lens and instead, is likely to be due to the number of physiological changes that are known to occur in response to contact lens wear. These changes include chronic corneal oedema resulting in epithelial and stromal thinning, and altered endothelial function.

10.2 Future work

Although the light scattering characteristics of the normal eye were determined in a wide range of age groups, it would be useful to expand the data set to include those above 60 years to determine whether, as predicted from studies investigating backscatter from the crystalline lens, forward light scatter continues to increase with age. However, it is acknowledged that it is difficult to separate biological changes due to old age, from those that are due to disease processes (Ludwig and Smoke 1980).

Increases in CT in this small subject sample were accompanied by increases in forward light scatter, as measured by the P_SCAN 100 apparatus. The level of corneal oedema produced by different subjects showed individual variations in corneal hydration control. Furthermore, the literature relating to diurnal and overnight variations in CT have proved controversial. A further study, using the P_SCAN 100 scatter apparatus, would allow further investigation of changes that occur throughout the day (e.g. with measurements taken every two hours over consecutive days) which would lead to a better understanding of the physiological changes that occur normally following overnight sleep and as a result of diurnal variations.

The results of the time-series analysis were indicative of a possible relationship between light scatter and the menstrual cycle. The lack of fluctuation in control (male) subjects supported this finding. However, larger subject groups are needed to confirm these findings, and these should be followed over several consecutive menstrual cycles. Of particular interest would be a major study on different subject groups, comprising a more representative sample of the female population. These subjects might include older menopausal and pregnant women. Other groups of women with different hormonal fluctuations, e.g. women taking hormone replacement therapies or those taking oral contraceptives, would also provide scope for further study. Future work in this area might also include direct measurement of hormone levels, not only to allow accurate detection of ovulation, but also to allow further research into the relationship between visual performance and hormonal fluctuations across the cycle. The results of acetylcysteine instillation in a single subject indicate that changing mucus levels at menses may be responsible for the increase in light scatter. This poses an interesting research question that could be investigated over several menstrual cycles. It may prove useful to take conjunctival smears and monitor tear changes to further characterise the hormone-sensitive structures.

Measurements taken with the P_SCAN 100 scatter apparatus showed that, in general, subjects with anterior segment eye disease exhibit high levels of scatter. In fact, in order to improve visual function degraded by light scatter, certain keratoconic subjects received early surgical intervention as a direct result of the findings of this study. Therefore, this method of directly assessing intraocular light scatter has provided the clinician with an improved appreciation of a keratoconic's visual experience and the likely effects of the increased light scatter on visual function. It would, therefore, be useful to investigate other ocular abnormalities that increase light scatter, such as cataract. Cataract has principally been investigated using CS. Measures of light scatter may be more appropriate than measures of CS, because of reduced subject variability with light scatter measurement.

Long-term contact lens wear was shown to increase light scatter in the eye. A further study documenting CT and endothelial cell morphology in established long-term wearers would be valuable to determine the cause of increase light scatter in long-term contact lens wearers. Ideally, a longitudinal study should measure baseline CT, endothelial cell morphology and light scatter measurements. This would enable the clinician to evaluate corneal changes due to contact lens wear at an earlier stage, thus avoiding detrimental physiological adaptations/alterations and the associated decline in visual performance.

References

Abrahamsson, M. and Sjostrand, J. (1986). Impairment of contrast sensitivity function (CSF) as a measure of disability glare. *Invest Ophthalmol Vis Sci* **27**: 1131-1136.

Abrahamsson, M., Frisen, M. and Sjostrand, J. (1988). Statistical evaluation of CSF in visual disorders - can diagnostic indices of CSF and acuity data be clinically useful? *Clin Vision Sci* **2**: 159-167.

Absolon, M.J. and Brown, C.A. (1968). Acetylcysteine in kerato-conjunctivitis sicca. *Br J Ophthalmol* **52**: 310-316.

Adamis, A., Filatov, V., Tripathi, B. and Tripathi, R. (1993). Fuchs' endothelial dystrophy of the cornea. *Surv Ophthalmol* **38**: 149-168.

Alexandridis, E., Leendertz, J.A. and Barbur, J.L. (1991). Methods for studying the behaviour of the pupil. *J Psychophysiol* **5**: 223-239.

Allansmith, M.R., Korb, D.R., Greiner, J.V., Henriquez, A.S ., Simon, M.A. and Finnemore, F.M. (1977). Giant papillary conjunctivitis in contact lens wearers. *Am J Ophthalmol* **83**: 697-708.

Allen, M.J. and Vos, J.J. (1967). Ocular scattered light and visual performance as a function of age. *Am J Optom Arch Am Acad Optom* **44**: 717-727.

Alsbirk, P. (1978a). Corneal thickness I: Age variation, sex difference and oculometric correlations. *Acta Ophthalmol* **56**: 95-103.

Alsbirk, P. (1978b). Corneal thickness II: Environmental and genetic factors. *Acta Ophthalmol* **56**: 105-113.

Andreassen, T.T., Simonsen, A.H. and Oxlund, H. (1980). Biomechanical properties of keratoconus and normal corneas. *Exp Eye Res* **31**: 435-441.

Ang, J.H.B. and Efron, N. (1990). Corneal hypoxia and hypercapnia during contact lens wear. *Am J Opt Physiol Opt* **67**: 512-521.

Applegate, R.A. and Jones, D.H. (1989). Disability glare and hydrogel lens wear revisited. *Am J Optom Physiol Opt* **66**: 756-759.

Applegate, R.A. and Massof, R.W. (1975). Changes in the contrast sensitivity function induced by contact lens wear. *Am J Optom Physiol Opt* **52**: 840-846.

Applegate, R.A. and Wolf, M. (1987). Disability glare increased by hydrogel lens wear revisited. *Am J Optom Physiol Opt* **64**: 309-312.

Aragona, P., Puzzolo, D., Micali, A., Ferreri, G. and Britti, D. (1998). Morphological and morphometric analysis on the rabbit conjunctival goblet cells in different hormonal conditions. *Exp Eye Res* **66**: 81-88.

Arden, G.B. (1978). The importance of measuring contrast sensitivity in cases of visual disturbance. *Br J Ophthalmol* **62**: 198-209.

Arden, G.B. (1988). Testing contrast sensitivity in clinical practice. *Clin Vision Sci* **2**: 213-224.

Arden, G.B. and Jacobson, J.J.A. (1978). Simple grating test for contrast sensitivity: Preliminary results indicate value in screening in glaucoma. *Invest Ophthalmol Vis Sci* **17**: 23-32.

Arnulf, A. and Dupuy, O. (1960). La transmission des contrasts par la systeme optique de l'oiel et les seuils des contrastes retiniens. *C R Acad Sci (Paris)* **250**: 2757-2759.

Arrowsmith, P.N. and Marks, R.G. (1987). Visual, refractive, and keratometric results of radial keratotomy - a 2-year follow-up. *Arch Ophthalmol* **105:** 76-80.

Arundale, K. (1978). An investigation into the variation of human contrast sensitivity with age and ocular pathology. *Br J Ophthalmol* **62**: 213-215.
Asso, D. and Braier, J. (1982). Changes with the menstrual cycle in psychophysiological and self-report measures of activation. *Biol Psychol* **15**: 95-107.
Atkin, A., Bodis-Wollner, I., Moss, A. and Podos, S. (1979). Abnormalities of central contrast sensitivity in glaucoma. *Am J Ophthalmol* **99**: 695-710.
Azen, S.P., Burg, K.A., Smith, R.E. and Margoen, E. (1979). A comparison of three methods for the measurement of corneal thickness. *Invest Ophthalmol Vis Sci* **18**: 535-538.
Bailey, I.L. (1971). Monochromatic aberration of the eye with contact lenses. *MSc Thesis in Physiological Optics, Indiaina University.*
Bailey, I.L. (1993). New procedures for detecting early vision losses in the elderly. *Optom Vis Sci* **70**: 299-305.
Bailey, I.L. and Bullimore, M.A. (1991). A new test for the evaluation of disability glare. *Optom Vis Sci.* **68**: 911-917.
Bailey, I.L. and Carney, L.G. (1973). Corneal changes from hydrophilic contact lenses. *Amer J Optom* **50**: 299-304.
Bando, M., Nakajima, A. and Satoh, K. (1975). Coloration of the human lens protein. *Exp Eye Res* **20**: 489-492.
Banks, M.S. and Salapatek, P. (1976). Contrast sensitivity function of the infant visual system. *Vision Res* **16**: 897-899.
Barbur, J. L. Harlow, A. J. and Williams, C. (1997). Light scattered in the eye and its effect on the measurement of the colour constancy index. In *Colour Vision Deficiencies XIII.* (Eds C.R. Cavonius) Dordrecht:Kluver Academic Publishers, London.
Barbur, J.L. (1991). The P_SCAN 100 system for simultaneous measurements of pupil size and eye movements. *J Psychophysiol* **5**: 231-235.
Barbur, J.L., de Cunha, D., Harlow, A. and Woodward, E.G. (1993). Methods for the measurement and analysis of light scattered in the human eye. In *Non-invasive Assessment of the Visual System (Technical Digest Series). J Opt Soc Am*, Washington D.C. **3**: 170-173.
Barbur, J.L., Edgar, D.F. and Woodward, E.G. (1995). Measurement of the scattering characteristics of the eye in relation to pupil size. In *Non-invasive Assessment of the Visual System (Technical Digest Series). J Opt Soc Am,* Washington D.C. **1**: 250-253.
Barbur, J.L., Hoban, B. and Thomson, D. (1986). A new photographic based system for the measurement of contrast sensitivity. *Ophthalmic Physiol Opt* **6**: 407-414.
Barris, M.C., Dawson, W.W. and Theiss, C.L. (1980). The visual sensitivity of women during the menstrual cycle. *Doc Ophthalmol* **49**: 293-301.
Baum, J. (1986). Clinical implications of basal tear flow. In *The Preocular Tear film in Health, Disease and Contact lens wear*, (Ed F.J. Holly) Dry Eye Institute, Lubbock, Texas.
Baur, G.T. (1979). Experimental study of the bending induced change of power and longitudinal spherical aberration of soft lenses. *J Opt Soc Am* **69**: 1447.
Becker, D., Creuzfeldt, O.D., Schwibbe, M. and Wuttke, W. (1982). Changes in physiological, EEG and psychological parameters in women during the spontaneous menstrual cycle and following oral contraceptives. *Psychoneuroendocrinology* **7**: 75-90.
Beckman, C., Abrahamsson, M. and Sjostrand, J. (1991). Evaluation of a clinical glare test based on estimation of intraocular light scatter. *Optom Vis Sci* **68**: 881-887.

Beems, E.M. and van Best, J.A. (1990). Light transmission of the cornea in whole human eyes. *Exp Eye Res* **50**: 393-395.
Bell, J.A. (1989). Danazol, pre-menstrual tension and uveitis. *Arch Ophthalmol* **107**: 796.
Benedek, G.B. (1971). Theory of the transparency of the eye. *Appl Optics* **10**: 459-473.
Bennett, A.G. and Rabbetts, R.B. (Ed) (1998). The eye's optical system. In *Clinical Visual Optics*, Butterworth-Heineman, Oxford.
Bennett, E.S., Henry, V.A. and Davis, L.J. (1989). Comparing empirical and diagnostic fitting of daily wear flouro-silicone/acrylate contact lenses. *Contact Lens Forum* **14**: 38-44.
Ben-Sira, I., Weinberger, D., Bo-Deinheimer, J. and Yassur, Y. (1980). Clinical method for measurement of light backscattering from the in vivo human lens. *Invest Ophthalmol Vis Sci* **19**: 435-437.
Bergenske, P.D. and Polse, K.A. (1988). The effect of rigid gas permeable lenses on corneal sensitivity. *J Am Optom Assoc* **58**: 212-215.
Bergin, D.A. (1952). Relation of refractive findings to menses. *Am J Optom Arch Am Acad Optom* **29**: 129-134.
Bernstein, I.H. and Broderick, J. (1981). Contrast sensitivities through spectacles and soft contact lenses. *Am J Optom Phsyiol Opt* **58**: 309-313.
Bettelheim, F.A. (1985). Physical basis of lens transparency. In *The ocular lens.* (Ed H. Maisle), Marcel Dekker, New York, USA.
Bettelheim, F.A. and Vinciguerra, M.J. (1971). Laser diffraction patterns of highly ordered superstructures in the lenses of bovine eyes. *Ann NY Acad Sci* **172**: 429-439.
Billings, E.J. and Westmore, A. (Ed) (1980). *The Billings method.* A. O'Donovan Ptg Ltd, Melbourne.
Billings, E.J., Billings, J.S., Brown, J.B. and Burger, H.G. (1972). Symptoms and hormonal changes accompanying ovulation. *Lancet* **1**: 282-284.
Binder, P., Kohler, J. and Rorabaugh, D. (1977). Evaluation of an electronic corneal pachometer. *Invest Ophthalmol Vis Sci* **16**: 855-859.
Birren, J.E. and Schock, N.W. (1950). Age changes in rate and level of visual dark adaptation. *J Appl Physiol* **2**: 407-410.
Blakemore, C. and Campbell, F.W. (1969). On the existence of neurones in the human visual system selectively sensitive to orientation and size of retinal images. *J Physiol* **203**: 237-260.
Bleeker, J.C., Van Best, J.A., Vrij, L., Vandervelde, E.A. and Oosterhuis, J.A. (1986). Autofluorescence of the lens in diabetic and healthy subjects by fluorophotometry. *Invest Ophthalmol Vis Sci* **27**: 791-794.
Blix, M. (1880). Oftalmometriska studier. *Acta Soc Med Upsal* **15**: 349-421.
Block, M. G. and Rosenblum, W. (1987). MTF measurements of the human lens. *J Opt Soc Am Acad* **4**: 7-9.
Bluthner, K., Seitz, B., Muller, E.E., Langenbucher, A. and Naumann, G.O.H. (1996). Reliability of automated endothelial cell analysis in cornea guttata. *Invest Ophthalmol Vis Sci* **37**: 3210.
Bodis-Wollner, I. (1980). Detection of visual defects using contrast sensitivity function. *Int Ophthalmol Clin* **20**: 135-153.
Bodis-Wollner, I. and Diamond, S.P. (1976). The measurement of spatial contrast sensitivity in cases of blurred vision associated with cerebral lesions. *Brain* **99**: 695-710.

Bodis-Wollner, I., Hendley, C.D., Mylin, L.H. and Thornton, J. (1979). Visual evoked potentials and the visuogram in multiple sclerosis. *Ann Neurol* **5**: 40-47.
Boettner, E.A. and Wolter, J.R. (1962). Transmission of the ocular media. *Invest Ophthalmol Vis Sci* **1**: 776-783.
Bondy, P. K. (1985). Disorders of the adrenal cortex. In *Williams' Textbook of Endocrinology*, (Eds J.D. Wilson, D.W. Foster), 7th Edition, Saunders, Philadelphia.
Bonnano, J.A. and Polse, K.A. (1987). Measurement of in vivo human corneal stromal pH: open and closed eyes. *Invest Ophthalmol Vis Sci* **28**: 522-530.
Bonnet, R. (1964). *La Topagraphie Corneene et L'adaptations des Lentilles de Cornee.* Desroches, Paris.
Botwinick, J. (1978). *Aging and behaviour: a comprehensive integration of research findings,* Springer, New York.
Bourne, W.M. (1983). Morphologic and functional evaluation of the endothelium of transplanted corneas. *Trans Am Ophthalmol Soc* **81**: 403-450.
Boynton, R.M. and Clarke, F.J.J. (1964). Sources of entoptic scatter in the human eye. *J Opt Soc Am* **54**: 110-119.
Boynton, R.M., Enoch, J.M. and Bush, W.R. (1954). Physical measures of straylight in excised eyes. *J Opt Soc Am* **44**: 879-886.
Braier, J.R. and Asso, D. (1980). Two-flash fusion as a measure of changes in cortical activation with the menstrual cycle. *Biol Psychol* **11**: 153-156.
Brennan, N.A., Efron, N. and Holden, B.A. (1986). Methodology for determining the intrinsic oxygen permeability of contact lens materials. *Clin Exp Optom* **70**: 42-45.
Bron, A.J. (1988). Keratoconus. *Cornea* **7**: 163-169.
Bron, A.J. (1990). The corneal dystrophies. *Current Opinion in Ophthalmology* **1**: 333-346.
Bron, A.J., Lobascher, D.J., Dixon, W.S., Das, S.N. and Ruben, M. (1975). Fibrillary lines of the cornea. A clincial sign of keratoconus. *Br J Ophthalmol* **59**: 139-140.
Bron, A.J., Ross, J.E. and Clarke, D. (1984). Contrast sensitivity and other measures of visual function in chronic simple glaucoma. *Ophthalmic Res* **16**: 202.
Bron, A.J., Sparrow, J., Brown, N.A.P., Harding, J.J. and Blakytny, R. (1993). The lens in diabetes. *Eye* **7**: 260-275.
Bron, A.J., Vrensen, G.F.J.M., Koretz, J., Maraini, G. and Harding, J.J. (2000). The Ageing lens. *Ophthalmologica* **214**: 86-104.
Bron, A.M., Creuzot-Garcher, C.P., Boutillon, S., Morales, C. and Lewden, O. (1997). Corneal thickness and intraocular pressure. *Invest Ophthalmol Vis Sci* **38**: 4929.
Brown, N. (1976). Dating the onset of cataract. *Trans Ophthalmol Soc UK* **96**:18-23.
Brown, N.A., Sparrow, J.M. and Bron, A.J. (1988). Central compaction in the process of lens growth as indicated by lamellar cataract. *Br J Ophthalmol* **72**: 538-544.
Buckley, R.J. (1998). Chronic corneal abnormalites. *Optom Today* **38**: 28-33.
Caillaud, S. and Cochet, P. (1983). Corneal endothelium and contact lenses. *Contactolog* **5**: 32-43.
Caldwell, D.R., Kastl, P.R., Dabezies, O.H., Miller, K.R. and Hawk, T.J. (1982). The effect of long-term hard lens wear on the corneal endothelium. *Contact Intraocular Lens Med J* **8**: 87-91.
Campbell, F.W. and Green, D.G. (1965). Optical and retinal factors affecting visual resolution. *J Physiol* **181**: 576-593.
Campbell, F.W. and Gubisch, R.W. (1966). Optical quality of the human eye. *J Physiol* **186**: 558-578.

Campbell, F.W. and Maffei, L. (1974). Contrast and spatial frequency. *Sci Am* **231**: 106-114.
Campbell, F.W. and Maffei, L. (1981). The influence of spatial frequency and contrast on the perception of moving patterns. *Vision Res* **21**: 713-721.
Campbell, F.W. and Robson, J.G. (1968). Application of fourier analysis to the visibility of gratings. *J Physiol* **197**: 551-566.
Campbell, F.W., Carpenter, R.H. and Levinson, J.C. (1969). Visibility of a periodic pattern compared with that of sinusoidal gratings. *J Physiol* **204**: 283-298.
Candela, V., Castagna, L., Aragona, P., Midolo, S. and Panama, S. (1989). Modificazioni dela secrezione mucosa congiuntivale in gravidanza e nella contraccezione farmacologica. *Boll Ocul* **68**: 19-23.
Capella, J.A. (1971). The pathology of the corneal endothelium. *Ann Ophthalmol* **3**: 397-400.
Capilla, P., Felipe, A., Pons, A. and Artigas, J.M. (1993). Effect of colour on contrast sensitivity with two different accommodative stimuli. *Optom Vis Sci* **70**: 24-29.
Carlson, K.H., Bourne, W.M., McClaren, J.W. and Brubaker, R.F. (1988). Variations in human corneal endothelial cell morphology and permeability to fluorescein with age. *Exp Eye Res* **47**: 27-41.
Carney, L.G. (1974). Corneal topography changes during contact lens wear. *Contact Lens J* **3**: 5-16.
Carney, L.G. (1982a). Contact lens correction of visual loss in keratoconus. *Acta Ophthalmol* **60**: 795-802.
Carney, L.G. (1982b). Visual loss in keratoconus. *Arch Ophthalmol* **100**: 1282-1285.
Carney, L.G. (1990). Is the quality of vision with contact lenses adequate? Not only adequate but often superior. *Cornea* **9** : S16-19; discussion S23-24.
Carney, L.G. and Jacobs, R.J. (1984). Mechanisms of visual loss in corneal oedema. *Arch Ophthalmol* **102**: 1068-1071.
Carney, L.G. and Kelley, C.G. (1991). Visual losses after myopic epikeratoplasty. *Arch Ophthalmol* **109**: 499-502.
Carney, L.G. and Lembach, R.G. (1991). Management of keratoconus: comparative visual assessments. *CLAO J* **17**: 52-58.
Carson, T.E., Daane, T.A., Lee, P.A., Tredway, D.R. and Wallin, J.D. (1977). Effect of intramuscular triamcinolone acetonide on the human ovulatory cycle. *Cutis* **19**: 633-637.
Caspersson, T and Engstrom, A. (1946). The transparency of corneal tissue. *Nord Med* **30**: 1279-82.
Cavonius, C.R. and Hilz, R. (1973). Invariance of visual receptive-field size and visual acuity with viewing distance. *J Opt Soc Am* **63**: 929-933.
Charman, W.N. and Heron, G. (1979). Spatial frequency and the dynamics of the accommodative response. *Optica Acta* **26**: 217-228.
Chatfield, C. (Ed) (1994). Autocorrelation. In *The Analysis of Time Series, An Introduction*. 4th Edition, Chapman and Hall, London.
Chilton, B.S., Deeb, E.A. and Dalley, B.K. (1991). Progesterone regulates epidermal growth factor receptor on mucous secreting cells in the rabbit endocervix. *Endocrinology* **129**: 2094-2100.
Chisholm, C.M., Barbur, J.L., Edgar D.F. and Thomson, W.D. (2000). The effect of excimer laser refractive surgery on visual performance. *Invest Ophthalmol Vis Sci* **41**: 462.

Christopoulos, V. and Garner, A. (1993). Emergence of corneal guttata in donor tissue: a cause of late graft failure. *Eye* **7**: 772-774.
Chylack, L.T.Jr., Leske, C., McCarthy, D., Khu, P., Kashiwagi, T. and Sperduto, R. (1989). Lens Opacity Classification system II (LOCS II). *Arch Ophthalmol* **107**: 991-997.
Ciuffreda, K.J. (1991). The Glenn A. Fry invited lecture. Accommodation to gratings and more naturalistic stimuli. *Optom Vis Sci* **68**: 243-260.
Clare, G., Tong, J.E., Lyon, R.G. and Leigh, G. (1976). Menstrual cycle and ethanol effects on temporal discrimination. *Percept Mot Skills* **42**: 1085-1086.
Clark, B.A.J. (1974). Mean topography of normal corneas. *Aust J Optom* **57**: 107-114.
Cobb, P.W. (1911). The influence of illumination of the eye on visual acuity. *Am J Physiol* **29**: 76-99.
Cogan, D.G. (1965). Do oral contraceptives have neuro-ophthalmic complications? *Arch Ophthalmol* **73**: 461-462.
Cogan, D.G. and Kinsey, E.K. (1972). The cornea v physiologic aspects. *Arch Ophthalmol* **28**: 661-669.
Cohen, R.W., Carlson, C.R. and Cody, G.O. (1976). Image description for displays. Technical report to the office of naval research. Contract no. N00014-74-0184.
Cook, C. and Langham, M.E. (1953). Corneal thickness in interstitial keratitis *Br J Ophthalmol* **37**: 301-304.
Cooper, G.F. and Robson, J.G. (1969). The yellow colour of the lens of man and other primates. *J Physiol* **203**: 411-417.
Coren, S. and Girgus, J.S. (1972). Density of human lens pigmentation: in vivo measurements over an extended age range. *Vision Res* **12**: 343-346.
Cornsweet, T.N. (1962). The staircase method in pyschophysics. *Am J Psychol* **75**: 485-491.
Cornsweet, T.N. (1970). Cones and cone pigment. In *Visual perception*. Academic Press, London.
Corwin, T.R. and Richman, J.E. (1986). Three clinical tests of the spatial contrast sensitivity function: A comparison. *Am J Psychol* **75**: 485-491.
Costagliola, C., Uliano, G., Rinaldi, E., Trapanese, A., Russo, V., Camera, A. and Scibelli, G. (1989). In vivo measurement of human lens ageing using the lens opacity meter. *Ophthalmology* **199**: 158-161.
Coulombre, J.L. and Coulombre, A.J. (1975). Corneal development. V. Treatment of five day old embryos of domestic fowl with 6-diazo-5-oxo-l-norleucine, (DON). *Dev Biol* **45**: 291-303.
Coupland, S.G. and Kirkham, T.H. (1981). Improved contrast sensitivity with antireflective coated lenses in the presence of glare. *Can J Ophthalmol* **16**: 136-140.
Cox, I. and Holden, B.A. (1990). Can vision loss be used as a quantitative assessment of corneal oedema? *Int Contact Lens Clin* **17**: 176-179.
Cox, I.G. (1986). Vision with soft lenses. *PhD thesis, UNSW, Sydney, Australia.*
Craig, A.S., Robertson, J.G. and Parry, D.A.D. (1987). Preservation of corneal collagen structure using low-temperature procedures for electron microscopy. *J Ultrastruct Mol Struct Res* **96**: 172-175.
Crook, T.G. (1979). Fluorescein as an aid in pachometry. *Am J Optom Physiol Opt* **56**: 124-127.
Cuiffreda, K.J., Rosenfield, M., Rosen, J., Azimi, A. and Ong, E. (1990). Accommodative responses to naturalistic stimuli. *Ophthalmic Physiol Opt* **10**: 168-174.

Cunningham, G.R., Goldzieher, J.W., de la Pena, A. and Oliver, M. (1978). The mechanism of ovulation inhibition by triamcinolone acetonide. *J Clin Endocrinol Metab* **46**: 8-14.
Curico, C.A., Millican, C.L., Allen, K.A. and Kalina, R.E. (1993). Ageing of the human photoreceptor mosaic: Evidence for selective vulnerability of rods in central retina. *Invest Ophthalmol Vis Sci* **34**: 3278-3296.
Dalton, K. (1967). Influence of menstruation on glaucoma. *Br J Ophthalmol* **51**: 692-695.
Daniel, M. and Whitteridge, D. (1961). The representation of the visual field on the cerebral cortex in monkeys. *J Physiol* **159**: 203-221.
Davidson, S.L. (1971). Reported adverse effects of oral contraceptives on the eye. *Trans Ophthalmol Soc UK* **91**: 561-574.
Davis, L., Barr, J. and Vanotteren, D. (1993). Transient rigid lens induced striae in keratoconus. *Optom Vis Sci* **70**: 216-219.
Davson, H. (1955). The hydration of the cornea. *Biochem J* **59**: 24-28.
Daxer, A. and Fratzl, P. (1997). Collagen fibril orientation in the human corneal stroma and its implications in keratoconus. *Invest Ophthalmol Vis Sci* **38**: 121-129.
De Palma, J.J. and Lowry, E.M. (1962). Sine wave response of the visual system II. Sine wave and square contrast sensitivity *J Opt Soc Am* **52**: 328-335.
de Waard, P.W., Ijspeert, J.K., van den Berg, T.J. and de Jong, P.T. (1992). Intraocular light scattering in age-related cataracts. *Invest Ophthalmol Vis Sci* **33**: 618-625.
Delaye, M. and Tardieu, A. (1983). Short range order of crystallin lens proteins accounts for eye lens transparency. *Nature* **302**: 415-417.
DeMarchi, G.W. and Tong, J.E. (1972). Menstrual, diurnal and activation effects on resolution of temporally paired flashes. *Psychophysiol* **9**: 362-367.
DeMott, D.W. and Boynton, R.M. (1954). Retinal distribution of entoptic straylight. *J Opt Soc Am* **48**: 120-125.
DeMott, D.W. and Boynton, R.M. (1958). Sources of entoptic straylight. *J Opt Soc Am* **48**: 120-124.
DeNatale, R., Flammer, J., Zulauf, M. and Bebie, T. (1988). Influence of age on the transparency of the lens in normals - a population study with help of the lens opacity meter. *Ophthalmologica* **197**: 14-18.
Derefeldt, G., Lennerstrand, G. and Lundh, B. (1979). Age variation in normal human contrast sensitivity. *Acta Ophthalmol* **57**: 679-689.
DeValois, K.K. (1977). Spatial frequency adaptation can enhance contrast sensitivity. *Vision Res* **17**: 1057-65.
DeValois, R.L. (1978). Spatial processing of luminance and colour information. *Invest Ophthalmol Vis Sci* **17**: 834-835.
DeValois, R.L., Morgan H. and Snodderly, D.M. (1974). Psychophysical studies of monkey vision III. Spatial luminance contrast sensitivity tests of macaque and human observers. *Vision Res* **14**: 75-81.
Devaney, K.O. and Johnson, H.A. (1980). Neuron loss in the ageing visual cortex of man. *J Gerontol* **35**: 836-841.
DeWaard. P.W.T., Ijspeert,J.K, van den Berg, T.J.T.P. and de Jong, P.T.V.M. (1992). Intraocular light scattering in age-related cataract. *Invest Ophthmol Vis Sci* **33** 618-625.
Diamond, A.L. (1955). Foveal simultaneous brightness contrast as a function of inducing field area. *J Exp Psychol.* **50**: 144-152.

Diamond, M., Diamond, A.L. and Mast, M. (1972). Visual sensitivity and sexual arousal levels during the menstrual cycle. *J Nerv Ment Dis* **155**: 170-176.
Diczfalusy, E. and Landgren, B.M. (1977). Hormonal changes in the menstrual cycle. In *Regulation of Human Fertility.* (Ed D. Diczfalusy), Scriptor, Copenhagen.
Dikstein, S. and Maurice, D.M. (1972). The metabolic basis to the fluid pump in the cornea. *J Physiol* **221**: 29-41.
Dilley, K.J. and Pirie, A. (1974). Changes to the proteins of the human lens nucleus. In *The ocular lens.* (Ed H. Maisle), Marcel Dekker, New York, USA.
Ding, G. and Bertelsen, T. (1992). Epikeratophakia for keratoconus - long-term results using fresh, free-hand made lamellar grafts. *Hov Acta Ophthalmologica* **70**: 461-469.
Doane, M.G., Timberlake, G.T. and Bertera, J.M. (1990). Low contrast visual acuity loss associated with in-vivo contact lens drying. *Inv Ophthalmol Vis Sci* **321**: 407.
Donaldson, D. (1966). A new instrument for the measurement of corneal thickness. *Arch Ophthalmol* **76**: 25-31.
Doughty, M.J. (1990). The ambiguous coefficient of variation: Polymegathism of the corneal endothelium and central corneal thickness. *Int Contact Lens Clin* **17**: 240-247.
Doughty, M.J. and Dilts, D.M. (1994). Identification of topographical variations in the sizes of cells in a monolayer - Application to corneal endothelium. *Tissue Cell* **26**: 621-636.
Doughty, M.J. and Maurice, D. (1988). Bicarbonate sensitivity of rabbit corneal endothelium fluid pump in vitro. *Invest Ophthalmol Vis Sci* **29**: 216-223.
Douthwaite, W.A. and Connelly, A.T. (1986). The effect of hard and gas permeable contact lenses on refractive error, corneal curvature, thickness and sensitivity. *J Br Contact Lens Assoc* **9**: 14-20.
Downie, W.W., Dixon, J.S., Lowe, J.R., Rhind, V.M., Leatham, P.A. and Pickup, M.E. (1978). Adrenocortical suppression by synthetic corticosteroid drugs: a comparative study of prednisolone and betamethasone. *Br J Clin Pharmacol* **6**: 397-399.
Dressler, M. and Rossow, B. (1981). Neural contrast sensitivity with a laser interference system for clinical screening application. *Invest Ophthalmol Vis Sci* **21**: 737-744.
Duke-Elder, S. (Ed) (1932) The absorption of radiant energy by the ocular tissues. *In Textbook of ophthalmology: Vol. I. Biological optics,* Henry Kimpton, London.
Duke-Elder, S. and Leigh, A.G. (1965). Disease of the outer eye. In *System of Ophthalmology,* (Ed S. Duke-Elder), Vol 8, Henry Kimpton, London.
Dunn, C. and Ross, H. (1985). Gender, the menstrual cycle and visual contrast sensitivity. *J Physiol* **267**: 19P, (abstract in Proceedings of the Physiological Society).
Durand, L., Monnot, J.P., Burillon, A. and Assi, A. (1992). Complications of radial keratotomy: eyes with keratoconus and late wound dehiscence. *Refract Corneal Surg* **8**: 311-314.
Dye, L. (1989). Variation in CFFT during the menstrual cycle: The effect of benzodiazepines. *Unpublished PhD thesis, Leeds University, UK.*
Dye, L. (1991). Visual information processing and the menstrual cycle. In *Cognition and the Menstrual cycle,* (Ed J.T.E. Richardson), Springer-Verlag, NewYork.
Dye, L. and Hindmarsh, I. (1991). The effects of Clobazam on critical flicker fusion threshold and symptomatology during the menstrual cycle. *Human Psychopharmacol* **6**: 129-137.
Edgar, D.F., Hennelly, M.L. and Barbur, J.L. (2000). Factors affecting the accuracy of light scatter measurements in human vision. *Invest Ophthalmol Vis Sci* **41**: 3.

Edmund, C. (1985). The central-peripheral radius of the normal corneal curvature. A photokeratoscopic study. *Acta Ophthalmol* **63**: 670-677.
Edmund, C. (1987). Determination of the corneal thickness profile by optical pachometry. *Acta Ophthalmol* **65**: 147-152.
Edmund, C. and la Cour, M. (1986). Some components affecting the precision of corneal thickness measurement performed by optical pachometry. *Acta Ophthalmol* **64**: 499-503.
Edrington, T.B., Barr, J.T., Zadnik, K., Fink, B.A., Nichols, J.J. and Gordon, M.O. (1999). Correlation of corneal scarring with clinical measures and patient outcomes at baseline in the Collaborative Longitudinal Evaluation of Keratoconus (CLEK) Study. *Invest Ophthalmol Vis Sci* **40**: 4607.
Efron, N. and Carney, L.G. (1979). Oxygen levels beneath the closed eyelid. *Optom Vis Sci* **18**: 93-95.
Eggink, F.A.G.J., Pinckers, A.J.L.G, and De Graff, R. (1990). Visual acuity and contrast sensitivity with Diffrax contact lenses. *Contact Lens J* **18**: 37-39.
Ehlers, N. and Kruse Hansen, F. (1971). On the optical measurement of corneal thickness. *Acta Ophthalmol* **49**: 65-81.
Ehlers, N., Kruse Hansen, F. and Aasved, H. (1975). Biometric correlations of corneal thickness. *Acta Ophthalmol* **53**: 652-659.
Ehlers, N., Sorenson, T., Bramsen, T. and Poulsen, E.H. (1976). Central corneal thickness in newborns and children. *Acta Ophthalmol* **54**: 285-290.
Einstein, A. (1910). Theory of the opalescence of homogenous liquids and liquid in mixtures in the neighbourhood of the critical. *Ann Phys* **33**: 1275-1298.
Eisner, A., Fleming, A., Klein, M.L. and Mauldin, M.W. (1987). Sensitivites in older eyes with good acuity: cross sectional norms. *Invest Ophthalmol Vis Sci* **28**: 1824-1831.
El-Hage, S.G. and Beauline, C. (1973). Changes in central and peripheral corneal thickness with menstrual cycle. *Am J Optom Arch Am Acad Optom* **50**: 863-870.
Elliazy, A.R., Wang, R.H. and Dillon, J. (1994). Model studies on the photochemical production of lenticular fluorophores. *Photochem Photobiol* **59**: 479-484.
Elliott, D.B. (1987). Contrast sensitivity decline with ageing: A neural or optical phenomenon? *Ophthalmic Physiol Opt* **7**: 415-419.
Elliott, D.B. and Bullimore, M.A. (1993). Assessing the reliability, discriminative ability and validity of disability glare tests. *Invest Ophthalmol Vis Sci* **34**: 108-119.
Elliott, D.B. and Whitaker, D. (1992a). How useful are contrast sensitivity charts in optometric practice? Case reports. *Optom Vis Sci* **69**: 378-385.
Elliott, D.B. and Whitaker, D. (1992b). Clinical contrast sensitivity chart evaluation. *Ophthalmic Physiol Opt* **12**: 275-280.
Elliott, D.B., Fonn, D., Flanagan, J. and Doughty, M. (1993a). Relative sensitivity of clinical tests to hydrophilic lens-induced corneal thickness changes. *Optom Vis Sci* **70**: 1044-1048.
Elliott, D.B., Mitchell, S. and Whitaker, D. (1991). Factors affecting light scatter in contact lens wearers. *Optom Vis Sci* **68**: 629-633.
Elliott, D.B., Yang, K.C.H., Dumbleton, K. and Cullen, A.P. (1993b). Ultraviolet induced lenticular fluorescence – intraocular straylight affecting visual function. *Vision Res* **33**: 1827-1833.
Elnashar, N.F. and Larke, J.R. (1986). Wave-front aberration in the hydrogel lens-wearing eye. *Amer J Optom Physiol Optics* **63**: 409-412.

Enoch, J.M. and Fry, G.A. (1958). Characteristics of a modal retinal receptor studied at microwave frequencies. *J Opt Soc Am* **48**: 899-911.
Enoch, J.M., Yamade, S. and Namba, A. (1979). Contrast (modulation) sensitivity functions measured in patients with high refractive error with emphasis on aphakia: II. Determinations on patients. *Doc Ophthalmol* **47**: 147-162.
Eppstein, J.A., Kratz, B.J., Callahan, K.M., Wasinger, F., Wang, O. and Bursell, S.E. (1995). Screening for diabetes-mellitus using lens scattering and fluorescence. *Invest Ophthalmol Vis Sci* **36**: 819.
Evans, D.W. and Ginsburg, A.P. (1985). Contrast sensitivity predicts age-related differences in high sine discriminability. *Human Factors* **27**: 637-642.
Farrell, R.A. and McCally, R.L. (1975). On corneal transparency and its loss with swelling. *J Opt Soc Am* **66**: 524-530.
Farrell, R.A., McCally, R.L. and Tathman, P.E.R. (1973). Wavelength dependencies of light scattering in normal and cold swollen rabbit corneas and their structural implications. *J Physiol* **233**: 589-612.
Fatt, I. and Beiber, M.T. (1968). The steady-state distribution of oxygen and carbon dioxide in the in vivo cornea I: The open eye in air and the closed eye. *Exp Eye Res* **7**: 103-112.
Fatt, I. and Harris, M.G. (1973). Refractive index of the cornea as a function of its thickness. *Am J Optom Arch Am Acad Optom* **50**: 383-386.
Fatt, I. and St. Helen, R. (1971). Oxygen tension under an oxygen-permeable contact lens. *Am J Optom* **48**: 545-555.
Feldman, F., Bain, J. and Matuk, A.R. (1978). Daily assessment of ocular and hormonal variables throughout the menstrual cycle. *Arch Ophthalmol* **96**: 1835-1838.
Feldman, G.L., Flannary, L.M., Brucehert, R.W. and Sampson, W.G. (1969). New concepts in corneal adaptation to contact lenses. *Contact Lens Med Bull* **2**: 8-10.
Ferris, R.L., Rakahashi, G.H. and Donne, A. (1965). Oxygen flux across the in vivo rabbit cornea. *Arch Ophthalmol* **74**: 679.
Feuk, T. (1970). On the transparency of the corneal stroma in the mammalian cornea. *IEEE Trans Biomed Eng* **17**: 186-190.
Feuk, T. (1971). The wavelength dependence of scattered light intensity in rabbit corneas. *IEEE Trans Biomed Eng* **18**: 92-96.
Feuk, T. and McQueen, D. (1971). The angular dependence of light scattered from rabbit corneas. *Invest Ophthalmol* **10**: 294-299.
Fincham, E.F. citing Koby, F.E. (1930). A propos de l'epaisseur de la cornee vivante *Rev Gen Ophthal* **44**: 222-225.
Finkelstein, I.S. (1952). The biophysics of corneal light scatter and diffraction of light induced by contact lenses, Part 1. *Am J Optom Arch Am Acad Optom* **29**: 185-208.
Finkelstein, I.O. (1987). On sensory disorders in diseases and on changes of the fields of cision in menstruation. *Ophthalmic Review* **6**: 323-326.
Fiorentini, A. and Mahhei, L. (1976). Spatial contrast sensitivity of myopic subjects. *Vision Res* **16**: 437-438.
Fisher, A.J. and Christie, A.W. (1965). A note on disability glare. *Vision Res* **5**: 565-571.
Flynn, M.A. and Esterly, D.B. (1966). Ocular manifestations after envoid. *Am J Ophthalmol* **61**: 907-910.
Ford, M. (1974) Paper read to the International contact lens conference. Montreux.

Forsius, H., Luukka, H. and Eriksson, A.W. (1971). Ophthalmogenetic studies on the Skolt Lapps. *Acta Ophthalmol* **49**: 498-502.
Forsius, H., Luukka, H., Fellman, J. and Erifsson, A.W. (1967). Corneal thickness and its heredity in the population in North Finland. *Bull Eur Soc Hum Genet* **1**: 81-83.
Fowler, S.A. and Allansmith, M.R. (1980). Evolution of soft contact lens coatings. *Arch Ophthalmol* **98**: 95-99.
Fowler, S.A., Korb, D.R., Finnemore, V.M. and Allansmith, M.R. (1984). Surface deposits on worn hard contact lenses *Arch Ophthalmol* **102**: 757-759.
Fowler, S.A., Korb, D.R., Finnemore, V.M., Ross, R.N. and Allansmith, M.R. (1987). Coatings on the surface of siloxane gas permeable lenses worn by keratoconic patients. A scanning electron microscope study. *CLAO* **13**: 207-210.
Frampton, P., Da Rin, D. and Brown, B. (1987). Diurnal variation of intraocular pressure and the overriding effects of sleep. *Am J Optom Physiol Opt 64*: 54-61.
Franceschetti, A. (1965). Keratoconus. In *The cornea.* (Eds J.H. King and J.W. McTigue), World Congress, Butterworths, Washington.
Franklin, S.L., Flammer, J., Dentale, R. and Rutishuser, C. (1990). The transparency of the lens - a comparison between diabetic and non-diabetic patients. *Int J Ophthalmol* **14**: 73-76.
Franz, W.B. (1988). Basic review: Endocrinology of the normal menstrual cycle. *Prim Care* **15**: 607-617.
Fratzl, P. and Daxer, A. (1993). Structural transformation of collagen fibrils in corneal stroma during drying. An X-ray scattering study. *Biophys J* **64**: 1210-1214.
Fraunfelder, F.T., Wright, P. and Tripathi, R.C. (1977). Corneal mucus plaques. *Am J Ophthalmol* **83**: 191-197.
Freeman, M.H. (Ed) (1990). Photometry and detectors. In *Optics,* 10th Edition, Butterworths, London.
Freeman, R.D. (1972). Oxygen consumption by the component layers of the cornea. *J Physiol* **225**: 15-32.
Friedman, J. and Meares, R.A. (1978). Comparison of spontaneous and contraceptive menstrual cycles on a visual discrimination task. *Aust N Z J Psychiatry* **12**: 233-239.
Frisen, L. and Frisen, M. (1981). How good is normal visual acuity? A study of letter acuity thresholds as a function of age. *Albrecht von Graefe's Arch Klin Exp Ophthalmol* **215**: 149-157.
Fry, G.A. (1965). Distribution of focused and straylight on the retina produced by a point source. *J Opt Soc Am* **55**: 333-334.
Fry, G.A. and Alpern, M. (1953). The effect of a peripheral glare source upon the apparent brightness of an object. *J Opt Soc Am* **43**: 189-195.
Fujita, S. (1980). Diurnal variation in human corneal thickness. *Jap J Ophthalmol* **24**: 444-456.
Fukuchi, T., Yue, B.Y., Sugar, J. and Lam, S. (1994). Lysosomal enzyme activites in conjunctival tissues of patients with keratoconus. *Arch Ophthalmol* **112**: 1368-1374.
Furchner, C.S., Thomas, J.P. and Campbell, F.W. (1977). Detection and discrimination of simple and complex patterns at low spatial frequencies. *Vision Res* **17**: 827-836.
Gambrell, R.D.Jr., Maier, R.C. and Sanders, B.I. (1983). Decreased incidence of breast cancer in postmenopausal oestrogen-progesterone users. *Obstet Gynecol* **62**: 435-443.
Gannon, L. (1981). Evidence for a psychological aetiology of menstrual disorders: a critical review. *Psychol Rep* **48**: 287-294.

Garner, B., Vazquez, S, Griffith, R., Lindner, R.A., Carver, J.A. and Truscott, R.J.W. (1999). Identification of glulathionyl-3-hydroxykynurenine glucoside as a novel flourophore associated with ageing of the human lens. *J Biol Chem* **274**: 20847-20854.
Gartner, S. and Henkind, P. (1981). Ageing and degeneration of the human macula. I. Outer nuclear layer and photoreceptors. *Br J Ophthalmol* **65**: 23-28.
Gellatly, K.W., Brennan, N.A. and Efron, N. (1988). Visual decrement with deposit accumulation on HEMA contact lenses. *Am J Optom Physiol Opt* **65**: 937-941.
Gertsman, D.R. (1972). The biomicroscope and Vickers image splitting eyepiece applied to the diurnal variation in human central corneal thickness. *J Microsc* **96**: 385-388.
Gharagozloo, N.Z. and Brubaker, R.F. (1991). The correlation between serum progesterone and aqueous dynamics during the menstrual cycle. *Acta Ophthalmol* **69**: 791-795.
Giasson, C. and Forthomme, D. (1992). Comparison of central corneal thickness measurements between optical and ultrasound pachometers. *Optom Vis Sci* **69**: 236-241.
Gibbons, R.A. and Mattner, P.E. (1971). The chemical and physical characteristics of the cervical secretion and its role in reproductive physiology. In *Pathways to conception.* (Ed A.I. Sherman), C.C. Thomas, Illinois.
Ginsburg, A.P. (1978). Visual information processing based on spatial filters constrained by biological data. *Aerospace Med Res Lab Rep*/AMRL-TR-78 129 Vols 1 and 2.
Ginsburg, A.P. (1980). Specifying relevant spatial information for image evaluation and display design: An explanation of how we see certain objects. *Proc Soc Inform Display* **21**: 219-227.
Ginsburg, A.P. (1981a). Proposed new vision standards for the 1980's and beyond: CS. In *The effect of long-term therapeutics, prophylaxsis and screening techniques on aircrew* (Ed C.E. Simpson), Medical Standards Advisory Group for Aerospace Research and Development NATO AGARD-CP, 310.
Ginsburg, A.P. (1981b). Spatial filtering and vision: Implications for normal and abnormal vision. In *Clinical applications of visual psychophysics.* (Eds L.M. Prenza, J.M. Enoch and A. Jampolskt), Cambridge University Press, New York.
Ginsburg, A.P. (1982). Contrast sensitivity predicts pilots' performance in aircarft stimulators. *Am J Optom Physiol Opt* **59**: 105-109.
Ginsburg, A.P. (1984). A new contrast sensitivity vision test chart. *Am J Optom Physiol Opt* **61**: 403-407.
Ginsburg, A.P. and Cannon, M.W. (1983). Comparison of three methods for rapid determination of threshold contrast sensitivity. *Invest Ophthalmol Vis Sci* **24**: 798-802.
Ginsburg, A.P., Evans, D.W., Cannon, M.W. and Fullenkamp, S. (1980). Individual differences in contrast sensitivity and the visibility of complex objects. Presented at the Topical Meeting on Recent Advances in Vision. *Opt Soc Am* paper WA-11.
Ginsburg, A.P., Evans, D.W., Cannon, M.W., Owsley, C. and Mulvanny, P. (1984). Large sample norms for contrast sensitivity. *Am J Optom Physiol Opt* **61**: 80-84.
Ginsburg, A.P., Evans, D.W., Sekuler, R. and Harp S.A. (1982). Contrast sensitivity predicts pilots performance in aircraft simulators. *Am J Optom Physiol Opt* **59**: 105-109.
Ginsburg, A.P., Osher, R.P., Blauvelt, K. and Blosser, E. (1987). The assessment of contrast and glare sensitivity in patients having cataracts. *Invest Ophthalmol Vis Sci* **28**: 397.

Goldman, J.N. and Benedek, G.B. (1967). The relationship between morphology and transparency in the non-swelling corneal stroma of the shark. *Invest Ophthalmol* **6**: 574-581.
Goldman, J.N. and Kuwabara, T. (1968). Histopathology of corneal oedema. *Invest Ophthalmol Clin* **8**: 561-579.
Goldman, J.N., Benedek, G.B., Dohlman, C.H. and Kravitt, B. (1968). Structural alterations affecting transparency in swollen human corneas. *Invest Ophthalmol* **7**: 501-579.
Goosey, J.G, Prager, T.C. and Goosey, C.D. (1991). A comparison of penetrating keratoplasty to epikeratoplasty in the surgical management of keratoconus. *Am J Ophthalmol* **112**: 145-151.
Goran, S.B. (1967). Retinal oedema secondary to oral contraceptives. *Am J Ophthalmol* **64**: 447-449.
Gordon, H. (1976). Corneal geometry: an alternative explanation of the effect of 6-diazo-5-oxo-l-norleucine on the development of the chick cornea. *Dev Biol* **53**: 303-305.
Gould, H. and Inglima, R. (1964). Corneal contact lens solutions. *Eye Ear Nose Throat Monthly* **43**: 39-49.
Graham, N. and Nachmias, J. (1971). Detection of grating patterns containing two spatial frequencies: A comparison of single-channel and multiple channel models. *Vision Res* **11**: 251-259.
Gray, L.S. and Barrett, B.T. (1999). The effect of disability glare in keratoconus. *Invest Ophthalmol Vis Sci* **40**: 8611.
Green, D.M. and Swets, J.A. (Eds) (1966). Basic experiments: separation of sensory and decision processes. In *Signal detection theory and psychophysics*, R.E. Kreiger, New York.
Green, K., Cullen, P.M. and Phillips, C.I. (1984). Aqueous humour turnover and intraocular pressure during menstruation. *Br J Ophthalmol* **68**: 736-740.
Grey, C.P. (1986). Changes in contrast sensitivity during the first hour of soft lens wear. *Am J Optom Physiol Opt* **63**: 702-707.
Grey, C.P. (1987). Changes in contrast sensitivity during the first six months of soft lens wear. *Am J Optom Physiol Opt* **64**: 768-774.
Grohe, R.M. and Caroline, P.J. (1989). RGP non-wetting lens syndrome. *Contact Lens Spectrum* **4**: 32-44.
Gromacki, S. and Barr, J. (1994). Central and peripheral corneal thickness in keratoconus and normal patient groups. *Optom Vis Sci* **71**: 437-441.
Guilford, J.P. (Ed) (1954). The constant methods. In *Psychometric Methods,* 2nd Edition, McGraw-Hill, New York.
Guillon, M. and Sayer, G.S (1988). Critical assessment of visual performance in contact lens practice. *Contax* (May) 9-13.
Guillon, M. and Schock, S.E. (1991). Soft contact lens visual performance: a multicentre study. *Optom Vis Sci* **68**: 96-103.
Guillon, M., Guillon, J.P. and Osborn, G. (1993). Visual performance stability of disposable contact lenses. *Int Contact Lens Clin* **20**: 7-17.
Guillon, M., Lydon, D.P.M. and Wilson, C. (1983) Variations in contrast sensitivity function with spectacles and contact lenses. *J Br Contact Lens Assoc* **6**: 120-122.

Gullstrand, A. (1924). I. The cornea. Appendix to part 1 of Helmholtz's Treatise on physiological optics. (Ed J.P.C. Southall), Menasha, Wis: *Optical Society of America* **1**: p327.
Gundel, R.E., Kirshen, S.A. and DiVergilio, D. (1988). Changes in contrast sensitivity induced by spherical hydrogel lenses on low astigmats. *J Am Optom Assoc* **59**: 636-640.
Gunker, R.D. and Gouras, P. (1963). Changes in scotopic visibility thresholds with age. *Arch Ophthalmol* **69**: 4-9.
Guth, S.L. (1973). On neural inhibition, contrast effects and visual sensitivity. *Vision Res* **11**: 251-259.
Guttridge, N. M. (1994). Changes in ocular and visual variables during the menstrual cycle. *Ophthalmol Physiol Opt* **14**: 38-48.
Hamano, H. (1960). Topical and systemic influences of wearing contact lenses. *Contacto* **4**: 41-48.
Harding, J. (1997). Cited by Bron, A.J. and Caird, F.I. (1997). Loss of vision in the ageing eye. Research into Ageing Workshop, London, 10 May 1995. *Age and ageing* **26**: 159-162.
Harper, C.L., Boulton, M.E., Bennett, D., Marcynik, B., Jarvis-Evans, J.H. and Tullo, A.B. (1996). Diurnal variations in human corneal thickness. *Br J Ophthalmol* **80**: 1068-1072.
Harper, R.A. and Halliday, B.L. (1989). Glare and contrast sensitivity in contact lens corrected aphakia, epikeratophakia, and pseudophakia. *Eye* **3**: 561-570.
Harris, J.E. (1962). Symposium on the cornea. Introduction: Factors influencing corneal hydration. *Invest Ophthalmol* **1**: 151-157.
Harrison, J.M., Tennant, T.B., Gwin, M.C., Applegate, R.A., Tennent, J.L., van den Berg, T.J.T.P. and Lohmannn, C.P. (1995). Forward light scatter at one month after photorefractive keratectomy. *J Refract Surg* **11**: 83-88.
Harrison, R. and Wolf, E. (1964). Ocular studies with special reference to glaucoma in a group of 107 elderly males. *Am J Ophthalmol* **57**: 235-241.
Hart, G.W. (1982). Corneal protoglycans. In *Cell biology of the eye*, (Ed D.S. McDevitt), Academic Press, New York.
Hart, R.W. and Farrell, R.A. (1969). Light scattering in the cornea. *J Opt Soc Am* **59**: 766-774.
Haut, J, Labrune, P. Ullern, M. and Chermet, M. (1977). New trial for the treatment of dry eye with acetylcysteine eye drops. *Bulletin de Societe Ophthalmologies de France.* **77**: 165-167.
Hedbys, B. and Mishima, S. (1966). The thickness-hydration relationship of the cornea. *Exp Eye Res* **5**: 221-228.
Helve, J. and Nieminen, H. (1976). Autofluorescence of the human diabetic lens in vivo. *Am J Ophthalmol* **81**: 493-494.
Hemenger, R.P. (1984). Intraocular light scatter in normal vision loss with age. *Appl Optics* **23**: 1972-1974.
Hemenger, R.P. (1990). Light scatter in cataractous lenses. *Ophthalmic Physiol Opt* **10**: 394-396.
Hemenger, R.P. (1992). Sources of intraocular light scatter from inversion of an empirical glare function. *Appl Optics* **31**: 3687-3693.
Hemenger, R.P. (1996). Dependence on angle and wavelength of light scattered by the lens. *Ophthalmic Physiol Opt* **16**: 237-238.

Hemenger, R.P., Occhipinti, J.R. and Mosier, M.A. (1989). Ageing parameters of the ocular lens by scanning fluorophotometry. *Ophthalmic Physiol Opt* **9**: 191-197.
Henker, O. (1924). In *Introduction to the theory of spectacles Jena*: Jena School of Optics.
Henkind, P. and Walsh, J.B. (1981). Diurnal variations in intraocular pressure. Chronic open angle glaucoma. Preliminary report. *Trans Ophthalmol Soc NZ* **33**: 18-20.
Henkind, P., Leitman, M. and Weitzman, E. (1973). The diurnal curve in man: new observations. *Invest Ophthalmol* **12**: 705-707.
Hennelly, M.L., Barbur, J.L., Edgar, D.F. and Woodward, E.G. (1997). Factors affecting the integrate straylight parameter in the normal human eye. *Invest Ophthalmol Vis Sci* **38**: 1014.
Hennessy, R.T. and Richards, W. (1975). Contrast sensitivity and viewing distance. *J Opt Soc Am* **65**: 97-98.
Henry, V.A., Bennett, E.S. and Forrest, J.F. (1987). Clinical investigation of the rigid gas-permeable contact lens. *Am J Optom Phys Optics* **64**: 313-320.
Henry, V.A., Bennett, E.S., and Sevigny, J. (1990). Rigid contact lens wear problem solving. *Int Contact Lens Clin* **17**: 121-133.
Herman, J.P. (1983). Flexure of rigid contact lenses on toric corneas as a function of base curve fitting relationship. *J Am Optom Assoc* **54**: 209-213.
Hernandez, C., Domemech, B., Segui, M.M. and Illuiece, C. (1996). The effect of pupil and observation distance on the contrast sensitivity function. *Ophthalmic Physiol Opt* **16**: 336-341.
Herse, P. and Yao, W. (1993). Variation of corneal thickness with age in young New Zealanders. *Acta Ophthalmol* **71**: 360-364.
Hess, R.F. (1979). Contrast sensitivity assessment of functional amblyopia in humans. *Trans Ophthalmol Soc UK* **99**: 391-397.
Hess, R.F. and Carney, L.G. (1979). Vision through an abnormal cornea: a pilot study of the relationship between visual loss from corneal distortion, corneal oedema, keratoconus and some allied corneal pathology. *Invest Ophthalmol Vis Sci* **18**: 476-483.
Hess, R.F. and Garner, L.F. (1977). The effect of corneal oedema on visual function. *Invest Ophthalmol Vis Sci* **16**: 5-13.
Hess, R.F. and Woo, G. (1978). Vision through cataracts. *Invest Ophthalmol Vis Sci* **17**: 428-435.
Higgins, K.E., Jaffe, M.J., Caruso, R.C. and de Monasterio, F.M. (1988). Spatial contrast sensitivity: Effects of age, test-retest and psychophysical method. *J Opt Soc Am (A)* **5**: 2173-2180.
Higgins, K.E., Jaffe, M.J., Coletta, N.J., Caruso, R.C. and de Monasterio, F.M. (1984). Spatial contrast sensitivity: Importance of controlling the patient's visibility criterion. *Arch Ophthalmol* **102**: 1035-1041.
Hill, R.M., Rengsdorf, R.H. and Petrali, J.P. (1974). Critical oxygen requirement of the corneal epithelium as indicated by succinic dehydrogenase. *Am J Optom* **51**: 331-335.
Hirji, N.K. and Larke, J.R. (1978). Thickness of human cornea measured by topographic pachometer. *Am J Optom Physiol Opt* **55**: 97-100.
Hirsch, R.P., Nadler, P. and Miller, D. (1984a). Glare measurement as a predictor of outdoor vision among cataract patients. *Ann Ophthalmol* **16**: 965-968.
Hirsch, R.P., Nadler, P. and Miller, D. (1984b). Clinical performance of a disability glare tester. *Arch Ophthalmol* **102**: 1633-1636.

Hirst, L.W., Auer, C., Cohn, J., Tseng, S.C.G. and Khodadoust, A.A. (1984). Specular microscopy of hard contact lens wearers. *Ophthalmol* **91**: 1147-1153.
Hirvela, H., Koskela, P. and Laatikainen, L. (1995). Visual acuity and contrast sensitivity in the elderly. *Acta Ophthalmol Scand* **73**: 111-115.
Hitzenberger, C., Baumgartner, A., Wolfgang, D. and Fercher, A. (1994). Interferometric measurement of corneal thickness with micrometer precision. *Am J Ophthalmol* **118**: 468-476.
Ho, A. and Bilton, S.A. (1986). Low contrast charts effectively differentiate between types of blur. *Am J Optom Physiol Opt* **63**: 202-208.
Hodson, S. and Miller, F. (1976). The bicarbonate ion pump in the endothelium which regulates the hydration of rabbit cornea. *J Physiol* **263**: 563-577.
Hoekstra, J., van der Groot, D.P.A., van der Brink, G. and Bilsen, F.A. (1974). The influence of the number of cycles upon the visual contrast threshold for spatial sine wave patterns. *Vision Res* **14**: 365-368.
Hofstetter, H. (1959). A keratoscopic survey of 13,395 eyes. *Am J Acad Optom* **36**: 3-11.
Hogan, M.J., Alvarado, J.A. and Weddell, J.E. (Eds) (1971). Descemet's membrane. In *Histology of the human eye: an atlas and textbook.* Saunders, London.
Hogan, R. (1985). The effect of menstruation on the longitudinal stability of TA and TV. *PhD thesis*, Aston University, Birmingham.
Holden, B.A. (1990). Perspectives on the future of contact lens wear: summary. *Cornea* **9:** 569-571.
Holden, B.A. and Mertz, G.W. (1984). Critical oxygen levels to avoid corneal oedema for daily and extended wear contact lenses. *Invest Ophthalmol Vis Sci* **25**: 1161-1167.
Holden, B.A., Mertz, G.W. and McNally, J.J. (1983). Corneal swelling response to contact lenses worn under extended wear conditions. *Invest Ophthalmol Vis Sci* **24**: 218-226.
Holden, B.A., Swarbrick, H.A., Sweeney, D.F., Ho, A., Efron, N., Vannas, A. and Nilsson, K.T. (1987). Strategies for minimizing the ocular effects of extended contact-lens wear - a statistical analysis. *Am J Optom Physiol Optics* **64**: 781-789.
Holden, B.A., Sweeney, D.F. and Sanderson, G. (1984). The minimum precorneal oxygen tension to avoid corneal oedema. *Invest Ophthalmol Vis Sci* **25**: 476-480.
Holden, B.A., Sweeney, D.F., Efron, N. Vanna, A. and Nilsson, K.T. (1988). Contact lenses can induce stromal thinning. *Clin Exp Optom* **71**: 109-113.
Holden, B.A., Sweeney, D.F., Vanna, A., Nilsson, K.T. and Efron, N. (1985). Effects of long-term extended contact lens wear on the human cornea. *Invest Ophthalmol Vis Sci* **26**: 1489-1501.
Holladay, J.T., Trujillo, J., Prager, T.C. and Rui, R.S. (1987). Brightness acuity test and outdoor visual acuity in cataract patients. *J Cataract Refract Surg* **13**: 67-69.
Holladay, L.L. (1926). The fundamentals of glare and visibility. *J Opt Soc Am* **12**: 271-319.
Holladay, L.L. (1927). Action of a light source in the field of view in lowering visibility. *J Opt Soc Am Rev Sci Instr* **14**: 1-15.
Holly, F.J. and Lemp, M.A. (1977). Wettability and wetting of corneal epithelium. *Exp Eye Res* **11**: 239-250.
Horie, T. and Kitazawa, Y. (1979). The clinical significance of diurnal pressure variation in primary open-angle glaucoma. *Jpn J Ophthalmol* **23**: 310-333.

Hovding G. and Bertelsen, T. (1992). Epikeratophakia for keratoconus – Long-term results using fresh, free-hand made lamellar grafts. *Acta Ophthalmol* **70**: 461-469.
Howell, E.R. and Hess, R.F. (1978). The functional area for summation to threshold for sinusoidal gratings. *Vision Res* **18**: 369-374.
Huggert, A. (1946). The thickness of the cortex of the crystalline lens in different ages. *Acta Ophthalmol (Kbh)* **24**: 43-62.
Ihalainen, A., Salo, T., Forsius, H. and Pertonen, L. (1986). Increase in type I and type IV collagenolytic activity in primary cultures of keratoconus cornea. *Eur J Clin Invest.* **16**: 78-84.
Ijspeert, J.K., de Waard, P.W.T., van den Berg, T.J.T.P. and de Jong, P.T.V.M. (1990). The intraocular straylight function in 129 healthy volunteers: Dependence on angle, age and pigmentation. *Vision Res* **30**: 699-707.
Ijspeert, J.K., van den Berg, T.J.T.P. and Spekreijse, H. (1993). An improved mathematical description of the foveal visual point spread function with parameters for age, pupil size and pigmentation. *Vision Res* **33**: 15-20.
Insler, V., Bernstein, D., Glezerman, M. and Misgav, N. (1979). Correlation of seminal fluid analysis with mucus penetrating ability of spermatozoa. *Fertil Steril* **32**: 316-319.
Ivanoff, A. (1947). Contribution a l'etude de la composante inhibitive de l'eblouissement. *Rev Opt* **26:** 241-266.
Ivanoff, A. (1956). About spherical aberration of the eye. *J Opt Soc Amer* **46**: 901-903.
Jaegur, W. (1952). Tiefenmessug der menschlichen Vorderkammer mit planparallelen platten (Zusuyzgerat zur Spaltlampe). *Graefe Arch Ophthal* **153**: 120-131.
Jakus, M.A. (1961). The fine structure of the human cornea. In *The Structure of the Eye*. (Ed: G.K. Smelser), Academic Press, New York.
Jani, S. (1966). The age factor in stereopsis screening. *Am J Optom* **43**: 653.
Jenkins, T.C.A. (1963). Aberrations of the eye and their effects on vision. *Br J Physiol Opt* **20**: 161-201.
Johnson, C.A. (1976). Effects of luminance and stimulus distance on accommodation and visual resolution. *J Opt Soc Am* **66**: 138-142.
Johnson, G., Minassian, D. and Franken, S. (1989). Alterations of the anterior lens capsule associated with climatic keratopathy. *Br J Ophthalmol* **73**: 229-234.
Johnson, M.A. and Choy, D. (1987). On the definition of age-related norms for visual function testing. *Appl Optics* **26**: 1449-1454.
Johnson, N. and Petersik, J.T. (1987). Preliminary findings suggesting cyclic changes in visual contrast sensitivity during the menstrual cycle. *Percept Mot Skills* **64**: 587-594.
Jordon, G. and Jaschinski-Kruza, W. (1986). Dark focus and visual acuity in relation to the menstrual cycle. *Perception* **15**: A20.
Judd, H.L., Cleary, R.E. and Creasman, W.T. (1981). Estrogen replacement therapy. *Obstet Gynecol* **58**: 267-275.
Juillerat, J. and Koby, F.E. (1928). Determination de l'epaisser de la cornee sur le vivant aumoyen de la lampe a fente. *Rev Gen Ophtal* **42**: 203-227.
Kanai, A. and Kaufman, H. (1973). Electron microscope studies of swollen corneal stroma. *Ann Ophthalmol* **5**: 178-190.
Kanski J. J. (Ed) (1989). The cornea and sclera. In *Clinical Ophthalmology: A systematic approach*, 2nd Edition, Butterworths, London.
Kao, W.W.Y., Vergnes, J-P., Ebert, J., Sundar-Raj, C.V. and Brown, S.I. (1982). Increased collagenase and gelatinase in keratoconus. *Biochem Biophys Res Commun* **107**: 929-936.

Karbissi, M., Chylack, L.T., Wolfe, J.M. and Mangione, C.M. (1993). Correlation between subjective and objective measures of glare disability in preoperative elderly patients with cataract. *Invest Ophthalmol Vis Sci* **34**: 1224.
Kato, T, Nakayasu, K., Kanai, A. and Hayashi, T. (1997). Heterogeneity in type IV collagen localisation in normal and keratoconus cornea. *Invest Ophthalmol Vis Sci* **38**: 1085.
Kaufman, H.E. (1980). The correction of aphakia. *Am J Ophthalmol* **89:** 1-10.
Kaushansen, M. (1993). The histopathological changes of keratoconus. *Acta Ophthalmol* **71**: 411-414.
Kay, C.D. and Morrison, J.D. (1987). A quantitative investigation into the effects of pupil diameter and defocus on contrast sensitivity for an extended range of spatial frequencies in natural and homatropinised eyes. *Ophthalmol Physiol Opt* 7: 21-30.
Kayazawa, F., Yamamoto, T. and Itoi, M. (1981). Clinical measurement of contrast sensitivity function using laser generated sinusoidal grating. *Jap J Ophthal* **25**: 229-236.
Kelly, D.H. (1972). Adaptation effects on spatio-temporal sine-wave thresholds. *Vision Res* **12**: 89-101.
Kelly, D.H. (1977). Visual contrast sensitivity. *Optica Acta* **24**: 107-129.
Kelly, D.H. and Savoie, R.E. (1973). A study of sine-wave contrast sensitivity by two psychophysical methods. *Percept Psychophys* **14**: 313-318.
Kendall, K. (1986). *The Society for Menstrual Cycle Research*, Newsletter, 3(1) Summer.
Kennedy, R.H., Bourne, W.M. and Dyer, J.A. (1986). A 48-year clinical and epidemiologic study of keratoconus. *Am J Ophthalmol* **101**: 267-273.
Khodadoust, A.A. and Hirst, L.W. (1984). Diurnal variation in corneal endothelial morphology. *Ophthalmology* **91**: 1125-1128.
Khong, A.M., Mannis, M.J, Plotnick, R.D. and Johnson, C.A. (1993). Computerized topographic analysis of the healing graft after penetrating keratoplasty for keratoconus. *Am J Ophthalmol* **115**: 209-215.
Kiely, P., Carney, L.G. and Smith, G. (1982). Diurnal variations of corneal topography and thickness. *Am J Optom Physiol Opt* **59**: 976-982.
Kiely, P., Carney, L.G. and Smith, G. (1983). Menstrual cycle variations of corneal thickness. *Am J Optom Physiol Opt* **60**: 822-829.
Kikkawa, Y. (1960). Light scattering studies of the rabbit cornea. *Jap J Physiol* **10**: 292-301.
Kikkawa, Y. (1973). Diurnal variation in corneal thickness. *Exp Eye Res* **15**: 1-9.
Kikkawa, Y. (1974). Effects of the light and dark cycle and a corticosteroid on the diurnal variation in corneal thickness. *Exp Eye Res* **18**: 157-161.
Kilbride, P.E., Hutman, P., Fishman, M. and Read, J.S. (1986). Foveal cone pigment density difference in the ageing human eye. *Vision Res* **26**: 321-325.
King, J.E., Augsburger, A. and Hill, R.M. (1971). Quantifying the distribution of lactic acid dehydrogenase in the corneal epithelium with oxygen deprivation. *Am J Optom* **48**: 1016-1020.
Kitazawa, Y. and Horie, T. (1975). Diurnal variation in intraocular pressure in primary open-angle glaucoma. *Am J Ophthalmol* **79**: 557-566.
Kleist, F.D. (1979). Appearance and nature of hydrophilic contact lens deposits – Part 1: protein and other organic deposits. *Int Contact Lens Clin* **6**: 120-130.

Kline, D.W. (1987). Ageing and the spatiotemporal discrimination performance of the visual system. *Eye* **1**: 323-329.
Kline, D.W. and Schieber, F. (1985). Vision and ageing. In *Handbook of the psychology of ageing*, (Eds J.E. Birren and K.W. Schaie), 2nd Edition, Van Nostrand Reinhold, New York.
Klyce, S.D. (1981). Stromal lactate accumulation can account for corneal oedema osmotically following epithelial hypoxia in the rabbit. *J Physiol* **321**: 49-64.
Klyce, S.D. and Beuerman, R.W. (1987). Structure and function of the cornea. In *The cornea,* (Eds H.E. Kaufman, B.A. Barron, M.B. McDonald and S.R. Waltman), Churchill Livingstone, New York.
Klyce, S.D. and McCarey, B.E. (1986). Physiology of the cornea. In *Contact lenses: CLAO Guide to Basic Science and Clinical Practice*, Vol 1, Grune & Stratton, Philadelphia.
Klyce, S.D. and Russell, S.R. (1979). Numerical solution of coupled transport equations applied to corneal hydration dynamics. *J Physiol* **292**: 107-134.
Knoblauch, K., Barbur, J. and Vitaldurand, F. (1995). Development and ageing of chromatic sensitivity. *Invest Ophthalmol Vis Sci* **360** :910.
Koch, D.D. and Liu, J.F. (1990). Survey of the clinical use of glare and contrast sensitivity testing. *J Cataract Refract Surg* **16**: 707-711.
Koch, D.D., Emery, J. and Jardeleza, T. (1986). Glare following posterior chamber lens implantation. *J Cataract Refract Surg* **12**: 480-484.
Koch, D.D., Samuelson, S.W., Haft, E.A. and Merin, L.M. (1991). Pupillary size and responsiveness. *Ophthalmol.* **98**: 1030-1035.
Komai,Y. and Ushiki, T. (1991). A three-dimensional organisation of collagen fibrils in the human cornea and sclera. *Invest Ophthalmol Vis Sci* **32**: 2244-2258.
Kopell, B.S., Lunde, D.T., Cayton, R.B. and Moos, R.H. (1969). Variations in some measures of arousal during the menstrual cycle. *J Nerv Ment Dis* **148**: 180-187.
Korb, D.R. and Exford, J.M. (1968). The phenomenon of central circular clouding. *J Am Optom Assoc* **39**: 223-230.
Kornzweig, A.L. (1954). Physiological effects of age on the visual processes. *Sight Sav Rev* **24**: 130-138.
Krachmer, J.H., Feder, R.S. and Belin, M.W. (1984). Keratoconus and related non-inflammatory corneal thinning disorders. *Surv Ophthalmol* **28**: 293-322.
Kramer, P., Lubkin, V., Potter, W., Jacobs, M., Labay, G. and Silverman, P. (1990). Cyclic changes in conjunctival smears from menstruating females. *Ophthalmology* **97**: 303-307.
Kremer, F., Waltom, P. and Gensheimer, G. (1985). Determination of corneal thickness using ultrasonic pachometry. *Ann Ophthalmol* **17**: 506-507.
Krug, R., Pietrowsky, R., Fehm, H.L. and Born, J. (1994). Selective influence of menstrual cycle on perception of stimuli with reproductive significance. *Psychosom Med* **56**: 410-417.
Kruse Hansen, F. (1971). A clinical study of the normal human central corneal thickness. *Acta Ophthalmol* **49**: 82-89.
Kulikowski, J.J. (1971). Some stimulus parameters affecting spatial and temporal resolution of human vision. *Vision Res* **11**: 83-93.
Kwon, M., Nibikoski, J. and Hunt, T.K. (1972). In vivo measurement of oxygen tension in the cornea: aqueous humour and anterior lens of the open eye. *Invest Ophthalmol Vis Sci* **11**: 108-114.

Labhart, A. and Martz, G. (1986). Fundamentals of hormone treatment of nonendocrine disorders. In *Clinical Endocrinology* (Ed A. Labhart), Ch. XX, Springer, Berlin-Heidelberg-New York.

Lachenmayr, B.J., Kojetinsky, S., Ostermaier, N., Angstwurm, K., Vivell, P.M.O. and Schaumberger, M. (1994). The different effects of ageing on normal sensitivity in flicker and light-sense perimetry. *Invest Ophthalmol Vis Sci* **35**: 2741-2748.

Laing, R.A., Neubauer, L., Leibowitz, H.M., and Oak, S.S. (1983). Coalescence of endothelial cells in the traumatised cornea II. Clinical observations. *Arch Ophthalmol* **101**: 1712-1715.

Laing, R.A., Neubauer, L., Oak, S.S., Kayne, H.L. and Leibowitz, H.M. (1984). Evidence for mitosis in the adult corneal endothelium. *Ophthalmology* **91**: 1129-1134.

Laing, R.A., Sandstrom, M.M. and Leibowitz, H.M. (1979a). Clinical specular microscopy II. Qualitative evaluation of corneal endothelial photomicrographs. *Arch Ophthalmol* **97**: 1720-1725.

Laing, R.A., Sandstrom, M.M. and Leibowitz, H.M. (1979b). The human corneal endothelium in keratoconus. A specular microscopic study. *Arch Ophthalmol* **97**: 1867-1869.

Laing, R.A., Sandstrom, M.M., Berrospi, A.R. and Leibowitz, H.M. (1976). Changes in the corneal endothelium as a function of age. *Exp Eye Res* **22**: 587-594.

Lambert, S. and Klyce, S. (1981). The origins of Sattler's veil. *Am J Ophthalmol* **91**: 51-56.

Lancon, M. and Miller, D. (1973). Corneal hydration, visual acuity and glare sensitivity. *Arch Ophthalmol* **90**: 227-230.

Lanfair, K.M. and Smith, L.A. (1974). A review of menstruation on accident involvemnt size, of visual field and color perception. In *Proceedings of the 18th meeting of the Human Factors Society*, Huntsville, Alabama, USA.

Langham, N. (1952). Utilisation of oxygen by the component layers of the living cornea. *J Physiol* **117**: 461.

Larke, J. R., Parish, S.T. and Wigham, C.G. (1981). Apparent human corneal oxygen uptake rate. *Am J Optom Physiol Opt* **58**: 803-805.

Larke, J.R. and Hirji, N.K. (1979). Some clinically observed phenomena in extended contact lens wear. *Br J Ophthalmol* **63**: 475-477.

Larsen, M. (1993). Fluorometric assessment of equivalent healthy lens age for people with diabetes. *Invest Ophthalmol Vis Sci* **34**: 2607.

Larsen, M., Kjer, B., Bendtson, I, Dalgaard, P., Lund-Andersen, H. (1989). Lens flourscence in relation to metabolic control of insulin dependent diabetes mellitus. *Arch Ophthalmol* **107**: 59-62.

Latham, K. (1998). Who uses contrast sensitivity in optometric practice? *Ophthalmic Physiol Opt* **18**: S2-13.

Lavergne, G. and Kelecom, J. (1962). Applications cliniques de la mesure de l'epaisseur de la cornee. *Bull Soc Belge Ophthal* **131**: 323-333.

Le Claire, J., Nadler, P., Weiss, S. and Miller, D. (1982). A new glare tester for clinical testing. *Arch Ophthalmol* **100**: 153-158.

Le Grand, Y. (1937). Recherces sur la diffusion de la lumiere dans l'oiel humain. *Rev Opt* **16**: 241-266.

Leach, N.E., Wallis, N.E., Lothringer, L.L. and Olsen, J.A. (1971). Corneal hydration changes during the menstrual cycle - a preliminary study. *J Reprod Med* **6**: 201-205.

Leahy, C.D., Mandell, R.B. and Lin, S.T. (1990). Initial in vivo tear protein deposition on individual hydrogel contact lenses. *Optom Vis Sci* **67**: 504-511.
Lebow, K.A. and Pishka, K. (1980). Ocular changes associated with extended wear contact lenses. *Int Contact Lens Clinic* **7**: 49-51.
Lederman, S. (1982). Direct and photosensitised UV-radiation and the eye - experimental and clinical observations. *Metab Ped System Ophthalmol* **6**: 27-32.
Lehtonen, J., Hyyppa, M.T., Kaihola, H-L., Kangasniemi, O. and Lang, A.H. (1979). Visual evoked potentials in menstrual migraine. *Headache* **19**: 63-70.
Leibowitz, H., Post, R. and Ginsburg, A.P. (1980). Role of fine detail in visually controlled behaviour. *Invest Ophthalmol Vis Sci* **19**: 846.
Lerman, S. (1980a). Human ultraviolet radiation cataracts. *Ophthalmic Res* **8**: 335-353.
Lerman, S. (1980b). Radiant energy and the eye. In *Functional Ophthalmology series*. Macmillan, New York.
Lerman, S. (1983). An experimental and clinical evaluation of lens transparency and ageing. *J Gerontol* **38**: 293-301.
Lerman, S. (1984). Biophysical aspects of corneal and lenticular transparency. *Curr Eye Res* **3**: 3-14.
Lerman, S. and Borkman, R.F. (1976). Spectroscopic evaluation and classification of the normal ageing and cataractous lens. *Ophthalmic Res* **8**: 335-353.
Lerman, S., Hockwin, O. and Dragomirescu, V. (1981). In vivo lens fluorescence photography. *Ophthalmic Res* **13**: 224-228.
Lerman, S., Kuck, J.F., Borkam, R. and Saker, E. (1976). Induction, acceleration and prevention (in vitro) of an ageing parameter in the ocular lens. *Ophthalmic Res* **8**: 213-226.
Lerman, S., Moran, M. and Matthews, N. (1989). Photographic and spectroscopic correlations of human cataracts. *Ophthalmic Res* **21**: 18-26.
Lerman, S., Tan, T.T., Louis, D. and Hollander, M. (1970). Anomalous absorptivity of lens proteins due to a fluorogen. *Ophthalmic Res* **1**: 338-343.
Leske, M.C. (1983). The epidemiology of open angle glaucoma: a review. *Am J Epidemiol* **118**: 166-191.
Liang, J.M. (1991). Photoxidation of the non-enzymatic browning products in calf lens alpha-crystallin. *Ophthalmic Res* **23**: 259-264.
Lin, S.L., Mandell, R.B., Leahy C.D. and Newell, J.O. (1991). Protein accumulation on disposable extended wear lenses. *CLAO J* **17:** 44 –50.
Lindstrom, J.I., Feuk, T. and Tengroth, B. (1973). The distribution of light scattered from the rabbit's cornea. *Acta Ophthalmol* **51**: 656-669.
Loewenfeld, I.E. (1979). Pupillary changes related to age. In *Topics in Neuro-Ophthalmology,* (Eds H. S. Thompson, R. Daroff, L. Frisen, J.S. Glaser and M.D. Sanders), Williams and Wilkins, Baltimore.
Logothetis, J., Harnes, R., Morrell, F. and Torres, F. (1959). The role of estrogens in catamenial exacerbation of epilepsy. *Neurology* **9**: 352-360.
Lohmann, C., Gartry, D., Muir, M.K., Timberlake, G., Fitzke, F. and Marshall, J. (1991). Haze and photorefractive kerectomy. Its origins and consequences. *Lasers Ophthalmol* **4:** 15-19.
Lohmann, C., Timberlake, G., Fitzke, F. Gartry, D., Muir, M.K., and Marshall, J. (1992). Corneal light scattering after excimer laser photorefractive keratectomy. The objective measurements of haze. *Refract Corneal Surg* **8:** 114-117.

Lohmann, C.P., Fitzke, F., O'Brart, D., Muir, M.K., Timberlake, G. and Marshall, J. (1993). Corneal light scattering and visual performance in myopic individuals with spectacles, contact lenses, or excimer laser photorefractive keratectomy. *Am J Ophthalmol* **115**: 444-453.
Long, G.M. and Penn, D.L. (1987). Normative contrast sensitivity functions: The problem of comparison. *Am J Optom Physiol Opt* **64**: 131-135.
Long, G.M. and Tuck, J.P. (1988.) Reliabilities of alternate measures of contrast sensitivity functions. *Am J Optom Physiol Opt* **65**: 37-48.
Lovasik, J.V. (1983). An electrophysical investigation of the macular photostress test. *Invest Ophthalmol Vis Sci* **24**: 437-441.
Lovasik, J.V. and Remole, A. (1983). An instrument for mapping corneal light scattering characteristics. *Ophthalmol Physiol Opt* **3**: 247-254.
Lowe, R.F. (1969). Central corneal thickness. Ocular correlations in normal eyes and those with primary angle-closure glaucoma. *Br J Ophthalmol* **53**: 824-826.
Ludvigh, E. and McCarthy, E.F. (1938). Absorption of visible light by the refractive media of the human eye. *Arch Ophthalmol* **20**: 37-51.
Ludwig, F. and Smoke, M.E. (1979). The measurement of physiological age. In *Topics in Neuro-Ophthalmogy,* (Eds H. S. Thompson, R. Daroff, L. Frisen, J.S. Glaser and M.D. Sanders), Williams and Wilkins, Baltimore.
Lydon, D.P.M. (1986). Effects of rigid contact lens materials on the cornea and tear film of the eye. *Submitted doctoral thesis, UNSW, Sydney, Australia.*
MacRae, S.M.M., Matsuda, M., Shellans, S. and Rich, L.F. (1986). The effects of hard and soft contact lenses on the corneal endothelium. *Am J Ophthalmol* **102**: 50-57
Macsai, M.S., Varley, G.A. and Krachmer, J.H. (1990). Development of keratoconus after contact lens wear. Patient characteristics. *Arch Ophthalmol* **108**: 534-538.
Maeda, N., Mihashi, T., Kuroda, K., Usui, S., Fujikado, T. and Tano, Y. (2000). Relationship between corneal wavefront aberrations and visual functions in the patients with keratoconus. *Invest Ophthalmol Vis Sci* **41**: 105
Malik, N.S., Moss, S.J., Ahmed, N., Furth, A.J., Wall, R.S. and Meek, K.M. (1992). Ageing of the human corneal stroma - structural and biochemical changes. *Biochim Biophys Acta* **1138**: 222-228.
Maltzman, B.A., Horan, C. and Rengel, A. (1988). Penlight test for glare disability of cataracts. *Ophthalmic Surg* **19**: 356-358.
Manchester, P.J. (1970). Hydration of the cornea. *Trans Am Ophthalmol Soc* **68**: 425-461.
Mandel, K. and Lerman, S. (1993). Stability of normal and ageing lens gamma-crystallins. *Ophthalmic Res* **25**: 295-301.
Mandell, R. and Polse, K. (1969). Keratoconus: Spatial variation of corneal thickness as a diagnostic test. *Arch Ophthalmol* **82**: 182-188.
Mandell, R.B. (Ed) (1965). Corneal topography. In *Contact Lens Practice: Basic and Advanced*, 3rd Edition, C. C. Thomas, Illinois.
Mandell, R.B. and Farrell, R. (1980). Corneal swelling at low atmospheric oxygen pressures. *Invest Ophthalmol Vis Sci* **19**: 697-702.
Mandell, R.B. and Fatt, I. (1965). Thinning of the human cornea on awakening. *Nature* **208**: 292-293.
Mandell, R.B. and Kong, L. (1988). Rigid contact-lens area and corneal oxygenation. *Am J Optom Physiol Optics* **65**: 387-394.

Mandell, R.B. and Polse, K.A. (1971). Corneal thickness changes accompanying central corneal clouding. *Am J Optom Arch Amer Acad Optom* ***48***: 129-132.
Mandell, R.B. and St Helen, R. (1969). Position and curvature of the corneal apex. *Am J Optom Arch Amer Acad Optom* **46**: 25-29.
Mandell, R.B., Polse, K.A. and Fatt, I. (1970). Corneal swelling caused by contact lens wear. *Arch Ophthalmol* **83**: 3-7.
Mannier, V.M. and Cerami, A. (1982). Non-enzymatic glycosylation and browning of proteins in diabetes. *Clin Endocrin Metab* **11**: 431-452.
Mannis, M.J., Zadnik, K. and Johnson, C.A. (1984). The effect of penetrating keratoplasty on contrast sensitivity in keratoconus. *Arch Ophthalmol* **102**: 1513-1516.
Mannis, M.J., Zadnik, K., Johnson, C.A. and Adams, C. (1987). Contrast sensitivity after penetrating keratoplasty. *Arch Ophthalmol* **105**: 1220-1223.
Marieb, E.N. (1989). In *Human Anatomy and Physiology*, Benjamin/Cummings, USA.
Marshall, J. (1987). The ageing retina: Physiology or pathology. *Eye* **1**: 282-295.
Marshall, J. (1997). Cited by Bron, A.J. and Caird, F.I. (1997). Loss of vision in the ageing eye. Research into Ageing Workshop, London, 10 May 1995. *Age and ageing* **26**: 159-162.
Martola, E. and Baum, J.L. (1968). Central and peripheral corneal thickness. *Arch Ophthalmol* **79**: 28-30.
Maurice, D.M. (1957). The structure and transparency of the cornea. *J Physiol* **136**: 263-286.
Maurice, D.M. (1962). Distribution and movement of plasma proteins in the cornea. *J Physiol* **162**: 2P.
Maurice, D.M. (1967). The use of fluorescein in ophthalmological research. *Invest Ophthalmol* **6**: 464-477.
Maurice, D.M. (1969). The cornea and sclera. In *The Eye, Vol 1*, 2nd Edition (Ed H. Davson), Academic Press, New York.
Maurice, D.M. (1972). The location of the fluid pump in the cornea. *J Physiol* **221**: 43-54.
Maurice, D.M. (1984). The cornea and the sclera. In *The Eye* (Ed H. Davson), Vol 1, 3rd Edition, Academic Press, New York.
Maurice, D.M. and Giardini, A.A. (1951). A simple optical apparatus for measuring the corneal thickness of the human cornea. *Br J Ophthalmol* **35**: 169-177.
Maurice, D.M. and Watson, P.G. (1965). The distribution and movement of serum albumin in the cornea. *Exp Eye Res* **4**: 355-359.
McCally, R.L. and Farrell, R.A. (1976). The depth dependence of light scattering from the normal rabbit cornea. *Exp Eye Res* **23**: 69-81.
McCally, R.L. and Farrell, R.A. (1982). Structural implications of small light angle scattering from the cornea. *Exp Eye Res* **34**: 99-113.
McClure, D.A., Ohota, S. and Eriksen, S.P. (1977). The effect on measured acuity of protein deposition and removal of soft contact lenses. *Contacto* **21**: 8-12.
McFarland, R.A. and Fisher, M.B. (1955). Adaptation of dark adaptation as a function of age. *Geront* **10**: 424-428.
McGrath, C. and Morrison, J.D. (1981). The effects of age on spatial frequency perception in human subjects. *Q J Exp Physiol* **66**: 253-261.
McLaren, J.W. and Bourne, W.M. (1999). A new video pachometer. *Invest Ophthalmol Vis Sci* **40**: 1593-1598.

McMonnies, C.W. (1989). After-care symptoms, signs and management. In *Contact lenses*, 3rd Edition, (Eds A.J. Phillips and J. Stone), Butterworths, London.

McTigue, J.W. (1967). The human cornea, a light and electron microscopic study of the normal cornea and its alterations in various dystrophies. *Trans Am Ophthalmol Soc* **65**: 591-660.

Meek, K.M., Blamires, T., Elliott, G.F., Gyi, T.J. and Nave, C. (1987). The organisation of collagen fibrils in human corneal stroma: A synchrotron X-ray diffraction study. *Curr Eye Res* **6**: 841-846.

Mellerio, J. (1971). Light absorption and scatter in the human lens. *Vision Res* **11**: 129-141.

Mellerio, J. and Palmer, D.A. (1972). Entoptic halos and glare. *Vision Res* **12**: 141-143.

Mertz, G.W. (1980). Overnight swelling of the living human cornea. *J Am Optom Assoc* **51**: 211-213.

Mie, G. (1908). Optics of turbid media. *Ann Phys* **25**: 377-445.

Miller, D, and Wolf, E. (1969). A model for comparing the optical properties of different sized corneal grafts. *Am J Ophthalmol* **67**: 724-730.

Miller, D. and Benedek, G. (Eds) (1973). *Intraocular light scattering*. C.C. Thomas, Illinois.

Miller, D. and Lazenby, G.W. (1977). Glare sensitivity in corrected aphakes. *Ophthalmic Surg* **8**: 54-57.

Miller, D. and Wolf, E. (1969). A model for comparing the optical properties of different sized corneal grafts. *Am J Ophthalmol* **67**: 724-728.

Miller, D., Jernigan, M.S., Molnar, M.S., Wolf, E. and Newman, J. (1972). Laboratory evaluation of a clinical glare tester. *Arch Ophthalmol* **87**: 324-332.

Miller, D., Wolf, E., Geer, S. and Vasallo, V. (1967). Glare sensitivity related to the use of contact lenses. *Arch Ophthalmol* **78**: 448-450.

Millodot, M. (1976). Effect of the length of wear of contact lenses on corneal sensitivity. *Acta Ophthalmol* **54**: 721-730.

Millodot, M. (1978). Effect of long-term hard lens wear on corneal sensitivity. *Arch Ophthalmol* **96**: 1225-1227.

Millodot, M. (1984). Clinical evaluation of an extended wear lens. *Int Contact lens Clin* **11**: 16-23.

Millodot, M. (1991). Corneal anesthesia following contact lens wear. In *Glare and Contrast Sensitivity for clinicians,* (Eds M.P. Nadler, D. Miller and D.J. Nadler), Springer-Verlag, New York.

Millodot, M. and Lamont, A. (1974). Influence of menstruation on corneal sensitivity. *Br J Ophthalmol* **58**: 752-756.

Mishima, S. (1965). Some physiological aspects of the precorneal tear film. *Arch Ophthalmol* **73**: 233-241.

Mishima, S. and Hedbys, B.O. (1968). Measurement of corneal thickness with the Haag Streit Pachometer. *Arch Ophthalmol* **80**: 710-713.

Mishima, S. and Maurice, D.M. (1961). The effect of normal evaporation on the eye. *Exp Eye Res* **1**: 46-52.

Mitchell, S. and Elliott, D.B. (1991). Light scatter changes due to corneal oedema and contact lens wear. *J Br Contact Lens Assoc* **14**: 183-187.

Mitra, S. and Lamberts, D.W. (1981) Contrast sensitivity in soft lens wearers. *Contact lens* 7: 315-322.

Molinari, J.F. and Bonds, T. (1983). Pachometry: A comparison between touch and overlap measurement method. *Am J Optom Physiol Opt* **60**: 61-66.

Moreland, L. (1978). Temporal variation in anomaloscope equations. *Mod Probl Ophthalmol* **19**: 167-172.

Morganroth, J. and Richman, L. (1969). Changes in the corneal reflex in patients wearing contact lenses. *J Pediatr Ophthalmol* **6**: 207-208.

Morrison, J.D. and McGrath, C. (1985). Assessment of the optical contributions to age related deterioration in vision. *Q J Exp Physiol* **70**: 249-269.

Mosier, M.A., Occhipinti, J.R. and Burstein, N.L. (1986). Autofluorescence of the crystalline lens in diabetes. *Arch Ophthalmol* **104**: 1340-1343.

Mota, M.C., Carvalho, P., Ramoolho, J.S., Cardoso, E., Gaspar, A.M. and Abren, G. (1994). Protein glycation and in-vivo distribution of human lens fluorescence. *Int Ophthalmol* **18**: 187-193.

Mota, M.C., Ramalo, J.S., Carvelho, P., Quadrado, T. and Daltar, A.S. (1992). Monitoring in-vivo lens changes - A comparative study with biochemical analysis of protein aggregation. *Doc Ophthalmol* **82**: 287-296.

Nadler, D.J. (1984). Glare disability in eyes with intraocular lenses. *Am J Ophthalmol* **97**: 43-47.

Nash, I.S., Greene, P.R. and Foster, C.S. (1982). Comparison of mechanical properties of keratoconus and normal corneas. *Exp Eye Res* **35**: 413-424.

Navarro, R., Losada, M.A. and Peres, M. (1990). CSF test: un sistema informatizado para le medida de la funcion de sensibilidad al contraste. *Integracion* **4**: 4-10.

Neumann, A.C., McCarty, G.R., Locke, J. and Cobb, B. (1988a). Glare disability devices for cataractous eyes: A consumer guide. *J Cataract Refract Surgery* **14**: 212-216.

Neumann, A.C., McCarty, G.R., Steedle, T.O., Sanders, D.R. and Raanan, M.G. (1988b). The relationship between cataract type and glare disability as measured by the Miller Nadler glare tester. *J Cataract Refract Surgery* **14**: 40-45

Niesel, P., Krauchi, H. and Bachman, E. (1976). The disjunction zone in the slit image photograph of the human ageing lens. *Albrecht Von Graefes Arch Klin Exp Ophthalmol* **199**: 11-20.

Nieuwendaal, C.P., Pdenthal, M.T.P., Kok, J.H.C., Venema, H.W., Oosting, J., Riemslag, F.C.C. and Kilstra, A. (1994). Morphology and function of the corneal endothelium after long-term contact lens wear. *Invest Ophthalmol Vis Sci* **35**: 3071-3077.

Novak, A.E., Lindstrom, R.I., Williams, P.A. and Everson, M. (1985). Corneal pachometry prior to radial keratotomy: A comparison of techniques. *J Refract Surg* **1**: 151-153.

Nowozyckyj, A., Carney, L.G. and Efron, N. (1988). Effect of hydrogel lens wear on contrast sensitivity. *Am J Optom Physiol Opt* **65**: 263-271.

Nyquist, G.W. (1968). Stress induced birefringence of the cornea. *Am J Ophthalmol* **65**: 398-404.

O'Neal, M., Polse, K.A. and Sarver, M. (1984). Corneal response to rigid and hydrogel lenses worn during eye closure. *Invest Ophthalmol Vis Sci* **25**: 837-836.

O'Brian, B. (1951). Vision and resolution in the central retina. *J Opt Soc Am* **41**: 882-894.

Occhipinti, J.R., Mosier, M.A., and Burstein, N.L. (1986). Autofluorescence and light transmission in the ageing crystalline lens. *Ophthalmologica* **192**: 203-209.

O'Leary, D.J., Wilson, G. and Henson, D.B. (1981). The effect of anoxia on the human corneal epithelium. *Am J Optom Physiol Opt* **58**: 472-476.
Oliver, K.M., Walsh, G., Tomlinson, A., McFadyen, A. and Hemenger, R.P. (1996). Effect of the menstrual cycle on corneal curvature. *Ophthalmol Physiol Opt* **16**: 467-473.
Olsen, T. (1982). Light scattering from the human cornea. *Invest Ophthalmol Vis Sci* **23**: 81-86.
Olsen, T. (1993). On the Stiles-Crawford effect and ocular imagery. *Acta Ophthalmol* **71**: 85-88.
Olsen, T. and Ehlers, N. (1984). The thickness of the human cornea as determined by a specular method. *Acta Ophthalmol* **62**: 859-871.
Olsen, T., Nielson, C.B. and Ehlers, N. (1980). On the optical measurement of corneal thickness. I. Optical principles and sources of errors. *Acta Ophthalmol* **58**: 760-766.
Olzat, L.A. and Thomas, J.P. (1981). Gratings: why frequency discrimination is sometimes better than detection. *J Opt Soc Am* **71**: 64-70.
O'Neal, M.R. and Polse, K.A. (1985). In vivo measurement of mechanisms controlling corneal hydration. *Invest Ophthalmol Vis Sci* **26**: 849-855.
Owsley C., Gardner T, Sekuler, R. and Leiberman H. (1985). Role of crystalline lens in the spatial vision loss in the elderly. *Vision Res* **26**: 1165-1170.
Owsley, C., Sekuler R. and Boldt, C. (1981). Ageing and low-contrast vision. *Invest Ophthalmol Vis Sci* **21**: 362-365.
Owsley, C., Sekuler, R. and Siemsen, D. (1983). Contrast sensitivity throughout adulthood. *Vision Res* **23**: 689-699.
Oxlund, H. and Simonsen, A.H. (1985). Biochemical studies of normal and keratoconus corneas. *Acta Ophthalmol (Copenh)* **63**: 66-69.
Parlee, M.B. (1983). Menstrual rhythms in sensory processes: A review of fluctuations in vision, olfaction, audition, taste and touch. *Psychol Bull* **93**: 539-548.
Parmley, V., Ng, J., Gee, B., Rotkis, W. and Mader, T. (1995). Penetrating keratoplasty after radial keratotomy. *Ophthalmol* **102**: 947-950.
Patel, S., Marshall, J. and Fitzke, F.W. (1995). Refractive index of the human corneal epithelium and stroma. *J Refract Surg* **11**: 100-105.
Paterson, G.D. and Miller, S.J.H. (1963). Hormonal influence in simple glaucoma. *Br J Ophthalmol* **47**: 129-137.
Pau, H., Degen, J. and Hans-Herbert, S. (1993). Different regional changes of fluorescence spectra of clear human lenses and nuclear cataracts. *Graefe's Arch Clin Exp Ophthalmol* **231**: 656-661.
Pau, M. (1955). Die doppelbrechung van sklera und cornea. *Klin Monatsbl Augenheilkd* **131**: 610-615.
Paulsson, L.E. and Sjostrand, J. (1980). Contrast sensitivity in the presence of glare light. Theoretical concepts and preliminary clinical studies. *Invest Ophthalmol Vis Sci* **19**: 401-406.
Pearson, A., Sarvananthan, N., Soneji, B. and Sandford Smith, J.H. (1999). Does ethnic origin influence the incidence or severity of keratoconus? *Invest Ophthalmol Vis Sci* **40**: 7610.
Pelli, D.G., Robson, J.G. and Wilkins, A.J. (1988). The design of a new letter chart for measuring contrast sensitivity. *Clin Vision Sci* **2**: 187-199.
Peterson, J. (1968). Corneal thickness. *Contacto* **12**: 41-44.

Phelps, C.D., Woolson, R.F., Kolker, A.E. and Becker, B. (1974). Diurnal variation in intraocular pressure. *Am J Ophthalmol* **77**: 367-377.

Philipson, B. (1973). Changes in the lens related to the reduction of transparency. *Exp Eye Res* **16**: 9-39.

Pinckers, A., Eggink, F., Aandekerk, A.L., van't Pad Bosch A. (1987). Contact lens-induced pseudo-dystrophy of the cornea. *Doc Ophthalmol* **65**: 433-437.

Pirie, A. (1968). Colour and solubility of the proteins of human cataracts. *Invest Ophthalmol Vis Sci* **7**: 634-650.

Pitts, D.G. (1982). The effects of ageing on selected visual functions; dark adaptation, visual acuity, stereopsis, and brightness contrast. In *Ageing and Human Visual Function,* (Eds R. Sekuler, D. Kline and K. Dismukes), AR Liss, New York.

Pokorny J., Smith, V.C and Lutze, M. (1987). Aging of the human lens. *Appl Optics* **26**: 1437-1441.

Polse, K.A. and Mandell, R.B. (1970). Critical oxygen tension at the corneal surface. *Arch Ophthalmol* **84**: 505-508.

Polse, K.A., Brand, R., Mandell, R., Vastine, D., Dermartini, D. and Flam, R. (1989). Age differences in corneal hydration control. *Invest Ophthalmol Vis Sci* **30**: 392-399.

Polse, K.A., Brand, R.J., Cohen, S.R. and Guillon, M. (1990). Hypoxic effects on corneal morphology and function. *Invest Ophthalmol Vis Sci* **31**: 1542-1544.

Polse, K.A., Sarver, M.D. and Harris, M.G (1975). Corneal oedema and vertical striae accompanying the wearing of hydrogel lenses. *Am J Optom Physiol Opt* **52**: 185-191.

Poon, W.W. and McCoshen, R.W. (1985). Variances in mucous architecture as a cause of cervical factor infertility. *Fertil Steril* **44**: 361-365.

Potts, A.M. (1962). Some aspects of interrelation between corneal hydration and corneal transparency. *Invest Ophthalmol Vis Sci* **1**: 163-169.

Potts, A.M. and Friedman, B.C. (1959). Studies on corneal transparency. *Am J Ophthalmol* **48**: 480.

Prasad, A., Asbell, P. and Senie, R. (1991). Evaluation of glare in normal and pseudophakic subjects. *Ann Ophthalmol* **23**: 268-272.

Probst, L., Geddes, D. and Heathcote, J. (1996). The ultrastructure of Descemet's membrane in keratoconus. *Invest Ophthalmol Vis Sci* **37**: 4772.

Quinn, T.G. and Schoessler, J.P. (1984). Human corneal epithelial oxygen demand - population characteristics. *Am J Optom Physiol Opt* **61**: 386-388.

Rabinowitz, Y.S. (1998). Keratoconus. *Surv Ophthalmol* **42**: 297-319.

Radner, W., Zehetmayer, M., Skorpik, C. and Mallinger, R. (1996). Altered arrangement of collagen lamellae in keratoconus. *Invest Ophthalmol Vis Sci* **37**: 4680.

Randeri, K. (1974). Development and efficacy aspects of a new soft lens cleaner. *Aust J Optom* **57**: 392-398.

Randeri, K. and Glicksir, B.A. (1975). A survey of the incidence of visible deposits on soft lenses. Allergan report series No 121.

Reeves, B.C., Hill, A.R. and Ross, J.E. (1988). Test-retest reliability of the Arden grating test: Inter-tester reliability. *Ophthalmol Physiol Opt* **8**: 128-138.

Reeves, B.C., Wood, J.M. and Hill, A.R. (1991). Vistech VCTS 6500 charts - within- and between-session reliability. *Optom Vis Sci* **68**: 718-737.

Regan, D. (1988). Low contrast visual acuity test for paediatric use. *Can J Ophthalmol* **23**: 224-227.

Regan, D. and Neima, D. (1983). Low contrast letter charts as a test of visual function. *Ophthalmology* **90**: 1192-1200.

Regan, D., Silver, R. and Murray, R. (1977). Visual acuity and contrast sensitivity in multiple sclerosis - hidden visual loss. *Brain* **100**: 563-79.
Rehany, U., Lahav, M. and Shoshan, S. (1982). Collagenolytic activity in keratoconus. *Ann Ophthalmol* **14**: 751-754.
Reinke, A.R. (1975). Keratoconus - a review of research and current fitting techniques. *Int Contact Lens Clin* **2**: 70-92.
Remeijer, L., Vanrij, G., Beekhuis, W.H., Polak, B.C.P. and Vannes, J. (1990). Deep corneal stromal opacities in long-term contact-lens wear. *Ophthalmology* **97**: 281-285.
Remole, A. (1977). Border enhancement as an index of contact lens performance. *Am J Optom Physiol Opt* **54**: 153-159.
Remole, A. (1981). Effect of saline solution immersion on corneal scattering characteristics. *Am J Optom Physiol Opt* **58**: 435-444.
Richards, O.W. (1977). Effects of luminance and contrast on visual acuity ages 16 to 90 years. *Am J Optom Physiol Opt* **54**: 178-184.
Riley, M.V. (1969). Glucose and oxygen utilisation by the rabbit cornea. *Exp Eye Res* **8**: 193-200.
Riss, B., Binder, S., Riss P. and Kemeter, P. (1982). Corneal sensitivity during the menstrual cycle. *Br J Ophthalmol* **66**: 123-126.
Rohde, M.D. and Huff, J.W. (1986). Contact lens-induced oedema in vitro - amelioration by lactate-dehydrogenase inhibitors. *Curr Eye Res* **5**: 751-758.
Rojansky, N., Halbreich, V. and Collins, D.C. (1990). Daily monitoring of gonadal glucoronides in urine studies of menstrually related change. *J Psychosom Obstet Gynaecol* **11**: 137-146.
Rosenfield, M., Ciufredda K.J., Hung, G.K. and Gilmartin, B. (1993). Tonic accommodation: A review I. Basic aspects. *Ophthalmol Physiol Opt* **13**: 266-284.
Ross, J.E., Bron, A.J. and Clarke, D. (1984). Contrast sensitivity and visual disability in chronic simple glaucoma. *Br J Ophthalmol* **68**: 821-827.
Ross, J.E., Bron, A.J., Reeves, B. and Gardner, I. (1987). Contrast sensitivity to detect visual pathway damage in ocular hypertension. *Ophthalmic Res* **19**: 10.
Ross, J.E., Clarke, D.D. and Bron, A.J. (1985). Effect of age on contrast sensitivity function uniocular and binocular findings. *Br J Ophthalmol* **69**: 51-56.
Roth, H.W. (1978). The etiology of ocular irritation in soft lens wearers: distribution in a large clinical sample. *Contact Intraocular Lens Med* **4**: 38-49.
Rovamo, J. and Raninen, A. (1988). Critical flicker frequency as a function of stimulus area and luminance at various eccentricities in human cone vision - A revision of Granit-Harper and Ferry-Porter laws. *Vision Res* **28**: 785-790.
Rovamo, J. and Virsu, V. (1979). An estimation and application of the human cortical magnification factor. *Exp Brain Res* **37**: 495-510.
Rovamo, J., Virsu, V. and Nasanen, R. (1978). Cortical magnification factor predicts the photopic contrast sensitivity of peripheral vision. *Nature* **271**: 54-56.
Ruben, M. (1966). Contact lenses and oral contraceptives. *BMJ* **1**: 1110.
Rubinow, D.R. and Roy-Byrne, P.R. (1984). Pre-menstrual syndromes: Overview from a methodologic perspective. *Am J Psychiatry* **141**: 163-172.
Rushton, W.A. and Gubisch, R.W. (1966). Glare: Its measurement by cone thresholds and by the bleaching of cone pigments. *J Opt Soc Am* **56**: 104-110.
Sachs, M.B., Nachimias, J. and Robson, J.G. (1971). Spatial frequency in human vision. *J Opt Soc Am* **61**: 1176-1186.

Said, F.S. and Sawires, W.S. (1972). Age dependence of changes in pupil diameter in the dark. *Optica Acta* **19**: 359-361.
Said, F.S. and Weale, R.A. (1959). The variation with age of the spectral transmisitivity of the living crystalline lens. *Gerontologia* **3**: 213-231.
Salvati, A. (1923). L'influence de la menstruation sur la tension oculaire. *Ann Ocul* **160**: 568-569.
Sample, P.A., Esterson, F.D., Weinreb, R.N. and Boynton, R.M. (1988). The ageing lens: In vivo assessment in 84 human eyes. *Invest Ophthalmol Vis Sci* **29**: 1306-1311.
Sanaty, M. and Temel, A. (1998). Corneal sensitivity changes in long-term wearing of hard polymethylmethacrylate contact lenses. *Ophthalmologica* **212**: 328-330.
Sanders, B. and Larsen, M. (1994). Photochemical bleaching of fluorescence glycosylation products. *Int Ophthalmol* **18**: 195-198.
Satoh, K., Brando, M. and Nakajima, A. (1973). Fluorescence in human lens. *Exp Eye Res* **16**: 167-172.
Savage, G.L. and Banks, M.S. (1992). Scotopic visual efficiency - constraints by optics, receptor properties, and rod pooling. *Vision Res* **32**: 645-656.
Savage, G.L., Haegerstrom-Portney, G., Adams, A.J. and Hewlett, S.E. (1993). Age changes in the optical density of human ocular media. *Clin Vision Sci* **8**: 97-108.
Savoy, R.L. and McCann, J.J. (1975). Visibility of low spatial frequency sine wave targets. Dependence on number of cycles. *J Opt Soc Am* **65**: 343-350.
Sawaguchi, S., Yue, B.Y., Sugar, J. and Gilboy, J.E. (1989). Lysosomal enzyme abnormalites in keratoconus. *Arch Ophthalmol* 107: 1507-1510.
Sayers, Z., Elliott, G.F., Meek, K.M., Whitburn, S.B. and Koch, M.J.H. (1982). A synchrotron X-ray diffraction study of the structure of the corneal stroma. *J Mol Biol* **160**: 593-607.
Schade, O.H. (1948). Electro-optical characteristics of television systems I. Characteristics of vision and visual systems. *RCA Review* **9**: 54-37.
Schauer, K.R., Hughes, C.C. and Jarrell, R.L. (1973). Corneal thickness change associated with hard and soft contact lens wear. *Optometric Weekly* **5**: 644-649.
Scher, D., Pionk, M. and Purcell, D.G. (1981). Visual sensitivity fluctuations during the menstrual cycle under dark and light adaptation. *Bull Psychonomic Soc* **18**: 159-160.
Scher, D., Purcell, D.G. and Caputo, S.J. (1985). Visual acuity at two phases of the menstrual cycle. *Bull Psychonomic Soc* **23**: 119-121.
Scher, R.K. (1964). Triamcinolone acetonide intramuscularly: effective long acting steroid therapy in dermatologic disorders. *J Am Geriatr Soc* **12**: 328-336.
Schimmelpfennig, B. (1984). Topography of age related changes in corneal endothelial cell size: Some preliminary microscopic observations. *Kiln Monatsbl Augenheilkd* **184**: 353-356.
Schmidt, S.Y. and Peisch, R.D. (1986). Melanin concentration in normal human retinal pigment epithelium. Regional variation and age related reduction. *Invest Ophthalmol Vis Sci* **27**: 1063-1067.
Schober, H.A.W. and Hilz, R. (1965). Contrast sensitivity of the human eye for square wave gratings. *J Opt Soc Am* **55**: 1086-1091.
Schoessler J.P. (1991) Hypoxic changes in corneal endothelium. In *Complications of contact lens wear*, (Ed A. Tomlinson), Mosby-Year Book, St Louis.
Schoessler, J.P. and Barr, J.T. (1980). Corneal thickness changes with extended contact lens wear. *Am J Optom Physiol Opt* **57**: 729-733.

Schoessler, J.P. and Woloschak, M.J. (1981). Corneal endothelium in veteran PMMA contact lens wearers. *Int Contact Lens Clinic* **8**: 19-25.
Sekuler, R., Hutman, L.P. and Owsley, C. (1980). Human aging and spatial vision. *Science* **209**: 1255-1256.
Sekuler, R., Owsley, C. and Hutman, L.P. (1982). Assessing spatial vision of older people. *Am J Optom Vis Sci* **59**: 961-968.
Sen, A.C., Veno, N. and Chakrabarti, B. (1992). Studies on human lenses. 1. Origin and development of fluorescent pigments. *Photochem Photobiol* **55**: 753-764.
sensitivity in extended wear of the Boston IV lens. *CLAO* 16: 276-278
Serup, J. and Serup, J. (1985). Increased central corneal thickness in localised scleroderma. *Metab Pediatr Syst Ophthalmol* **8**: 11-14.
Setala, K., Vasara, K., Vesti, E. and Ruusuvaara, P. (1998). Effects of long-term wear on the corneal endothelium. *Acta Ophthalmologica Scandinavica* **76**: 299-303.
Sheridan, M. (1989). Keratometry and slit lamp biomicroscopy In *Contact lenses: A textbook for practitioner and student,* (Eds A.J. Phillips and J. Stone), Butterworths, London.
Sherrard, E.S., Novakovic, P. and Speedwell, L. (1987). Age-related changes of the corneal endothelium and stroma as seen in vitro by specular microcscopy. *Eye* **1**: 197-203.
Sherwood, H., Epstein, J., Maurer, M.L., Blau, S., Kanof, N.B., Zucker, A. and Chemris, W. (1967). Intramuscular triamcinolone acetonide injections in the treatment of allergic and cutaneous diseases. *Curr Ther Res Clin Exp* **9**: 114-130.
Siew, S., Troen, P. and Nankin, H. (1981). Ultrastructural investigation of human orchiectomy tissue in the older age group. *J Androl* **2**: 27.
Sigelman, J., Trokel, S.L. and Spector, A. (1974). Quantitative biomicroscopy of lens light back scatter: Changes in ageing and opacification. *Arch Ophthalmol* **92**: 437-442.
Siik, S., Airaksinen, P.J. and Tuulonen, A. (1992). Light scatter in ageing and cataractous human lens. *Acta Ophthalmol* **70**: 383-388.
Simpson, G.C. (1953). Ocular haloes and corneas. *Br J Ophthalmol* **37**: 450-486.
Sjostrand, J. (1979). Contrast sensitivity in macular disease using a small-field and a large-field TV-system. *Acta Ophthalmol* **57**: 832-846.
Sjostrand, J. and Frison, L. (1977). Contrast sensitivity in macular disease. A preliminary report. *Acta Ophthalmol* **55**: 507-514.
Skalka, H.W. (1980). Effect of age on Arden grating acuity. *Br J Ophthalmol* **64**: 21-23.
Slataper, F.J. (1949). Age norms of refraction and vision. *Arch Ophthalmol* **2**: 466-481.
Sloane, M. E., Owsley C. and Jackson, C.A. (1988a). Ageing and luminance adaptation effects in spatial contrast sensitivity. *J Opt Soc Am* **5**: 2181-2190.
Sloane, M.E., Owsley, C. and Alverez, S.L. (1988b). Ageing, senile miosis and spatial contrast sensitivity at low luminances. *Vision Res.* **28**: 1235-1246.
Smelser, G.K. and Ozanics, V. (1953). Structural changes of corneas of guinea pigs after wearing contact lenses. *Am J Ophthalmol* **88**: 543-548
Smelser, G.K. and Shen, D. (1955). Physiological changes in the cornea induced by contact lens. *Arch Ophthalmol* **53**: 676-680
Smiddy, W.E., Hamburg, T.R., Kracher, G.P. and Stark, W.J. (1988). Keratoconus. Contact lens or keratoplasty? *Ophthalmology* **95**: 487-492.
Smith, G.T.H., Brown, N.A.P. and Shun-Shin, G.A. (1990). Light scatter from the central cornea. *Eye* **4**: 584-588.

Smith, G.T.H., Smith, R.C., Brown, N.A.P., Bron, A.J. and Harris, M.L. (1992). Changes in light scatter and width measurements from the human lens cortex with age. *Eye* **6**: 55 -59.

Smith, P., Pratzer, K., Webster, N. and Miller, D. (1987). A clinical comparison of two methods of glare testing. *Ophthalmic Surg* **18**: 680-682.

Smith, V.C., Pokernu, J. and Diddle, K.R. (1988). Colour matching and the Stiles-Crawford effect in observers with early age related macular changes. *J Opt Soc Am (A)* **5**: 2113-2121.

Sobanski, J. (1934). Klin. Oczna 12, 317. Cited by von Bahr (1948).

Sokol, S., Domor, A. and Moskowitz, A. (1980). Utility of Arden grating test in glaucoma screening: high false positive rate in normals over 50 years of age. *Invest Ophthalmol Vis Sci* **19**: 1529-1533.

Soni, P.S. (1980). Effects of oral contraceptive steroids on the thickness of the cornea. *Am J Optom Physiol Opt* **57**: 825-834.

Soni, P.S. and Borish, I.M. (1979). A report on central and peripheral corneal thickness. *Int Cont Lens Clinic* **16**: 196-200.

Sparrow, J.M., Bron, A.J., Brown, N.A.P. and Neil, H.A.W. (1992). Autofluorescence of the crystalline lens in early and late onset diabetes. *Br J Ophthalmol* **76**: 25-31.

Sparrow, J.M., Bron, A.J., Brown, N.A.P., Ayliffe, W. and Hill, A.R. (1986). The Oxford clinical cataract classification and grading system. *Int Ophthalmol* **9**: 207-225.

Sparrow, J.M., Brown, N.A. and Bron, A.J. (1993). Estimation of the thickness of the crystalline lens from on axis and off axis Scheimpflug photographs. *Ophthalmic Physiol Opt* **13**: 291-294.

Spector, A., Roy, D. and Stauffer, J. (1975). Isolation and characterisation of an age-dependant polypeptide from human lens with non-tryptophan fluorescence. *Exp Eye Res* **21**: 9-24.

Sperduto, R.D. and Hiller, R. (1984). The prevalence of nuclear, cortical and posterior sub-capsular lens opacities in a general-population sample. *Ophthalmology* **91**: 815-818.

Srinivasan, B.D., Jakobiec, F.A. and Iwamoto, T. (1982). Conjunctiva. In *Ocular anatomy, embryology, and teratology*, (Ed F.A. Jakobiec), Harper and Row, Philadelphia.

Stafford, M. (1990). The crystalline lens. *Optician* **5459**: 20-25.

Stallard, H.B. (1973). The conjunctiva, cornea, and sclera. In *Eye surgery,* John Wright and Sons Ltd. Stonebridge Press, Bristol.

Stangos, N., Voutas, S., Topouzis, F. and Karampatakis, V. (1995). Contrast sensitivity evaluation in eyes pre-disposed to age-related macular degeneration and presenting normal visual acuity. *Ophthalmologica* **209**: 194-198.

Steen, R. (1994). Age related effects of glare on luminance and colour contrast sensitivity. *Optom Vis Sci* **71**: 792-796.

Stefansson, A., Muller, O. and Sundmacher, R. (1982). Non-contact specular microsocopy of the normal corneal endothelium: A statistical evaluation of morphometric parameters. *Graefes Arch Clin Exp Ophthalmol* **218**: 200-205.

Steinert, R.F. and Wagoner, M.D. (1988). Long-term comparison of epikeratoplasty and penetrating keratoplasty for keratoconus. *Arch Ophthalmol* **106**: 493-496.

Stevenson, R., Vaja, N. and Jackson, J. (1983). Corneal transparency changes resulting from osmotic stress. *Ophthalmol Physiol Opt* **3**: 33-39.

Stiles, W.S. (1929). The scattering theory of the effect of glare on the brightness difference threshold. *Pros Royal Soc* **104 B**: 322-355.
Stiles, W.S. and Crawford, B.H. (1937). The effect of a glaring light source on extrafoveal vision. *Proc Royal Soc* **122 *B***: 255-280.
Stone, J. (1974). The measurement of corneal thickness. *Contact Lens* J **5**: 14-19
Storch, R.L. and Bodis-Wollner, I. (1990). Overview of contrast sensitivity and neuro-ophthalmic disease. In *Glare and Contrast Sensitivity for Clinicians*, (Eds M.P. Nadler, D. Miller and D.J. Nadler) Springer-Verlag, New York.
Strauss, B. and Appelt, H. (1983). Psychological concomitants of the menstrual cycle: A prospective approach. *J Psychosom Obstet Gynaecol* **24**: 215-220.
Sturbaum, C.W. and Peiffer, R.L.Jr. (1996). Pathology of corneal endothelium in keratoconus. *Ophthalmologica* **206**: 192-208.
Suda, T. (1984). Mosaic pattern changes in human corneal endothelium with age. *Jpn J Ophthalmol* **28**: 331-338.
Tardibuono, L., Nelson, J. and Bennett, E.S. (1987). A comparison of spherical versus aspheric flouro-silicone/acrylate lens design based on contrast sensitivity function, disability glare and overall performance. *Poster presented at the American academy of Optometry*, Denver, December.
Taylor, M.M., Forbes, S.M. and Creelman, C.D. (1983). PEST reduces bias in forced choice psychophysics. *J Acoust Soc Am* **74**: 1367-1374.
Teitelbaum, B.A., Kelly, S.A. and Gemoules, G. (1985). Contrast sensitivity through spectacles and hydrogel lenses of different polymers. *Int Contact Lens Clinic* **12**: 162-166.
Timberlake, G., Doane, M. and Bertera, J. (1992). Short-term, low-contrast visual acuity reduction associated with in vivo contact lens drying. *Optom Vis Sci* **69**: 755-759.
Toates, F.M. (1972). Accommodation function of the human eye. *Physiol Rev* **52**: 828-863.
Tomlinson, A. (1972). A clinical study of the central and peripheral thickness and curvature of the human cornea. *Acta Ophthalmol* **50**: 73-82.
Tomlinson, A. (Ed) (1992). Oxygen requirements of the cornea. In *Complications of contact lens wear,* Mosby-Year Book, St Louis.
Tomlinson, A. and Cedarstaff, T.H. (1992). Diurnal variation in tear film evaporation. *J Br Contact Lens Assoc* **13**: 77-79.
Tomlinson, A. and Mann, G. (1985). An analysis of visual performance with contact lenses and spectacle correction. *Ophthalmic Physiol Opt* **5**: 53-57.
Tomlinson, A. and Schwartz, C. (1979). The position of the corneal apex in the normal eye. *Am J Optom Physiol Opt* **56**: 236-240.
Toole G.and Toole S. (Eds) (1989). Sexual cycles. In *Understanding Biology for Advanced Level*, Hutchinson, London.
Travers, M.J. (1990). Structural correlates of shape changes in the primate crystalline lens. *PhD thesis, City University, London.*
Travis, D.S. and Thompson, P.G. (1989). 'Good' and 'bad' eyes in multiple sclerosis: it depends on the test used. *Clin Vis Sci* **4**: 211-219.
Treffers, W.F. (1982). Human corneal endothelial wound repair – in vitro and in vivo. *Ophthalmology* **89**: 605-613.
Trokel, S. (1962). The physical basis for the transparency of the crystalline lens. *Invest Ophthalmol* **1**: 493-501.

Tseng, C.C. (1962). Fine structure of the human cornea: epithelium and stroma. *Am J Ophthalmol* **54**: 969-1002.
Tseng, C.C. (1963). Electron microscopic study of the pathology of keratoconus. Part 1. *Am J Ophthalmol* **55**: 18-47.
Tunnacliffe, A.H. (Ed) (1993). Ocular aspects of vision. In *Introduction to visual optics,* 2nd Edition, Association of Dispensing Opticians, London.
Twersky, V. (1975). Transparency of pair correlated random distributions of small scatterers, with applications to the cornea. *J Opt Soc Am* **65**: 524-530.
Ussher, J.M. and Wilding, J.M. (1991). Performance and state changes during the menstrual cycle, conceptualised in a broad band testing framework. *Soc Sci Med* **32**: 525-534.
Vaegan and Halliday B.L. (1982). A forced choice test improves clinical contrast sensitivity testing. *Br J Ophthalmol* **66**: 477-491.
van den Berg, T.J.T.P. (1986). Importance of pathological intraocular light scatter for visual disability. *Doc Ophthalmol* **57**: 679-689.
van den Berg, T.J.T.P. (1988). Relation between media disturbances and the visual field. *Doc Ophthalmol* **49**: 33-38.
van den Berg, T.J.T.P. (1991). On the relation between glare and straylight. *Doc Ophthalmol* **78**: 177-181.
van den Berg, T.J.T.P. (1994). On the relation between intraocular straylight and visual function parameters. *Invest Ophthalmol Vis Sci* **35**: 2659-2661.
van den Berg, T.J.T.P. (1995a). Age related changes in the clarity of the ocular media In *Proceedings of the 3rd Int. Symposium Lighting for ageing vision and health,* Lighting Res Inst, New York.
van den Berg, T.J.T.P. (1995b). Analysis of intraocular straylight, especially in relation to age. *Optom Vis Sci* **72**: 52-59.
van den berg, T.J.T.P. and Boltjes, B. (1988). The point spread function of the eye from 0 degrees to 100 degrees and the pattern electroretinogram. *Doc Ophthalmol* **67**: 347-354.
van den Berg, T.J.T.P. and Ijspeert, J.K. (1991). The Straylight meter. *Non-invasive Assessment of the Visual System (Technical Digest Series). J Opt Soc Am,* Washington D.C. **1**: 256-259.
van den Berg, T.J.T.P. and Ijspeert, J.K. (1992). Clinical assessment of intraocular straylight. *Appl Optics* **31**: 3694-3696.
van den Berg, T.J.T.P. and Ijspeert, J.K. (1995). Light scattering in donor lenses. *Vision Res* **35**: 169-177.
van den Berg, T.J.T.P. and Spekreijse, H. (1987). Measurement of the straylight function of the eye in cataract and other optical disturbances by means of a direct compensation method. *Invest Ophthalmol Vis Sci* **28**: 397.
van den Berg, T.J.T.P. and Spekreijse, H. (1997). Light scattering by donor lenses as a function of depth and wavelength. *Invest Ophthalmol Vis Sci* **38**: 4753.
van den Berg, T.J.T.P. and Tan, K.E. (1994). Light transmittence of the human cornea from 320 to 700nm for different ages. *Vision Res* **34**: 1453-1456.
van den Berg, T.J.T.P., de Waard, P.W.T., Ijspeert, J.K. and de Jong, P.T.V.M. (1989). Intraocular light scattering assessed quantitatively in age related cataract. *Invest Ophthalmol Vis Sci* **30**: 499.

van den Berg, T.J.T.P., Ijspeert, J.K. and de Waard, P.W.T. (1991). Dependence of intraocular straylight on pigmentation and light transmission through the ocular wall. *Vision Res* **31**: 1361-1367.

van den Berg, T.J.T.P., Ijspeert, J.K., de Waard, P.W.T. and Meire, F. (1990). Functional quantification of diaphany. *Doc Ophthalmol* **75**: 239-246.

van der Heijde, G.L., Weber, J. and Boukes, R. (1985). Effects of straylight on visual acuity in pseudophakia. *Doc Ophthalmol* **59**: 81-84.

Vavilis, D., Maloutas, S., Natioutziki, M., Boni, E. and Bontis, J. (1995). Conjunctiva is an oestrogen sensitive epithelium. *Acta Obstet Gynecol Scand* **74**: 799-802.

Verriest, G. (1963). Further studies on acquired deficiency of colour discrimination. *J Opt Soc Am* **53**: 185-193.

Verriest, G. and Uvuils, A. (1989). Disability glare in normal and diseased eyes. *Clin Vision Sci* **4**: 253-256.

Vinciguerra, M.J. and Bettelheim, F.A. (1971). Packing and orientation of fibre cells. *Exp Eye Res* **11**: 214-219.

Virsu, V. and Rovamo, J. (1979). Visual resolution, contrast sensitivity and the cortical magnification factor. *Exp Brain Res* **37**: 475-494.

Virsu, V., Lathio, P.K. and Nyman, G. (1975). Contrast sensitivity as a measure of visual performance. 3rd Nordac meeting on medical and biological engineering *Tampere* **16**: 1-5.

Von Bahr, G. (1948). Measurements of the thickness of the cornea. *Acta Ophthalmol* **26**: 247-266.

Vos, J.J. (1962). On mechanisms of glare. Institute for perception RVO-TNO, Soesterberg, Netherlands.

Vos, J.J. (1963). Contribution of the fundus oculi to entoptic scatter. Letters to the Editor, *Appl Optics* **31**: 1449.

Vos, J.J. (1965). On mechanisms of glare. *Thesis, Soesterberg, The Netherlands.*

Vos, J.J. (1984). Disability glare - A state of the art report. *Commission International de l'Eclairage* **3**: 39-53.

Vos, J.J. and Boogaard, J. (1963). Contribution of the cornea to entoptic scatter. *J Opt Soc Am* **53**: 869-873.

Vos, J.J. and Bouman, M. (1964). Contribution of the retina to entoptic scatter. *J Opt Soc Am* **54**: 95-100.

Vos, J.J., Walraven, J. and van Meeteren, A. (1976). A light profile of the foveal image of a point source. *Vision Res* **16**: 215-219.

Wald, G. (1952). Alleged effects of the near ultraviolet on human vision. *J Opt Soc Am* **42**: 171-177.

Walker, J. (1988). A clinical and laboratory comparison of the deposition characteristics of both silicone/acrylate and flouro-silicone/acrylate lenses. *Trans Br Contact Lens Assoc* **11:** 83-86.

Waller, S.G., Steinart, R.F. and Wagnor, M.D. (1995). Long-term effects of epikeratoplasty for keratoconus. *Cornea* **14:** 84-88.

Walls, G.L. and Judd, H.D. (1933). Intraocular colour filters of vertebrates. *Br J Ophthalmol* **17**: 641-705.

Walraven, J. (1973). Spatial characteristics of chromatic induction: the segregation of lateral effects from straylight artefacts. *Vision Res* **13**: 1739-1753.

Walsh, D.A. (1976). Age differences in central perceptual processing. A dichoptic backward masking investigation. *J Gerontol* **31**: 178-185.

Ward, M.M., Stone, S.C. and Sandman, C.A. (1978). Visual perception in women during the menstrual cycle. *Physiol Behav* **20**: 239-243.

Waring, G.O., Lynn, M.J., Culbertson, W., Laibson, P.R., Lindstrom, R.D., McDonald, M.B., Myers, W.D., Obstbaum, S.A., Rowsey, J.J. and Schanzlin, D.J. (1987). 3-year results of the prospective evaluation of radial keratotomy (PERK) study. *Ophthalmology* **94**: 1339-1354.

Waring, G.O., Lynn, M.J., Nizam, A., Kutner, M.H., Cowden, J.W., Culbertson, W., Laibson, P.R., McDonald, M.B., Nelson, J.D. and Obstbaum, S.A. (1991). Results of the prospective evaluation of radial keratotomy (PERK) study five years after surgery. The Perk study group. *Ophthalmology* **98**: 1164-1176.

Watson, A.B. and Robson, J.G. (1981). Discrimination at threshold: Labelled detectors in human vision. *Vision Res* **15**: 115-1122.

Weale, R. (1980). A note on a possible relation between refraction and a disposition for senile nuclear cataract. *Br J Ophthalmol* **64**: 311-314.

Weale, R.A. (1975). Senile changes in visual acuity. *Trans Ophthalmol* **95**: 36-38.

Weale, R.A. (1986). Real light scatter in the human crystalline lens. *Graefes Arch Clin Exp Ophthalmol* **224**: 463-466.

Weale, R.A. (1987). Senescent vision: is it all the fault of the lens? *Eye* **1**: 217-221.

Weale, R.A. (1988). Age and the transmittance of the human crystalline lens. *J Physiol* **395**: 577-587.

Weale, R.A. (Ed) (1963). The lens. In *The Ageing Eye*, H.K. Lewis, London.

Wechsler, S. (1978). Visual acuity in hard and soft contact lens wearers: A comparison. *Contact Lenses* **49**: 251-256.

Werner, J.S., Donnelly, S.K. and Klegl, R. (1987). Ageing and human macular pigmentation; appended with translations from the work of Mac Schultze and Edward Hering. *Vis Res* **27**: 257-268.

Wesemann, W. (1987). Incoherent image formation in the presence of scattering eye media. *J Opt Soc Am (A)* **4**: 1439-1447.

Westheimer, G. (1960). Modulation thresholds for sinusoidal light distribution on the retina. *J Physiol* **152**: 67-74.

Westhiemer, G. (1961). Aberrations of contact lenses. *J Optom Arch Am Acad Optom* **38**: 445-448.

Weymouth, F. (1960). Effect of age on visual acuity. In *Vision of the ageing patient,* (Eds Quinn and Borden), New Jersey.

Whitaker, D., Steen, R. and Elliott, D.B. (1993). Light scatter in the normal young, elderly and cataractous eye demonstrates little wavelength dependency. *Optom Vis Sci* **70**: 963-968.

Wicker, D., Sanislo, S. and Green, D.G. (1992). Effect of contact-lens correction on sine wave contrast sensitivity in keratoconus patients after penetrating keratoplasty. *Optom Vision Sci* **69**: 342-346.

Wigham, C.G. and Hodson, S.A. (1987). Physiological changes in the cornea of the eye. *Eye* **1**: 190-196.

Wilkins, A.J., Della Sala, S., Somazzi, L. and Nimmo-Smith, I. (1988). Age-related norms for the Cambridge low contrast gratings including details concerning their design and use. *Clin Vision Sci* **2**: 201-212.

Willey, R.F., Fergusson, R.J., Godden, D.J., Crompton, G.K. and Grant, I.W. (1984). Comparison of oral prednisolone and intramuscular depot triamcinolone in patients with severe chronic asthma. *Thorax* **39**: 340-344.

Williamson, J, Doig, W.M., Forrester, J.V., Tham, M.H., Wilson, T., Whaley, K. and Dick, W.C. (1975). Management of the dry eye in Sjogren's syndrome. *Br J Ophthalmol* **58**: 798-805

Wilson, G. and Fatt, I. (1980). Thickness of the corneal epithelium during anoxia. *Am J Optom Physiol Opt* **57**: 409-415.

Wilson, G., Fatt, I. and Freeman, R.D. (1981). Thickness changes in the epithelium of the excised rabbit cornea. *Am J Optom Arch Am Acad Optom* **51**: 75-83.

Wilson, S.E., He, Y.G., Weng, J., Li, Q., McDowall, A.W., Vital, M. and Chwang, E.L. (1996). Epithelial injury induces keratocyte apoptosis: hypothesised role for the interleukin-1 system in the modulation of corneal tissue organisation and wound healing. *Exp Eye Res* **62**: 325-327.

Winn, B., Whitaker, D., Elliott, D.B. and Phillips, N.J. (1994). Factors affecting light-adapted pupil size in normal subjects. *Invest Ophthalmol Vis Sci* **35**: 1132-1137.

Wolf, E. (1960). Glare and age. *Arch Ophthalmol* **64**: 502-514.

Wolf, E. and Gardiner, J.S. (1965). Studies on the scatter of light in the dioptric media of the eye as a basis of visual glare. *Arch Ophthalmol* **74**: 338-345.

Wolfe, J.M. (1990). An introduction to contrast sensitivity testing. In *Glare and Contrast Sensitivity for Clinicians,* (Eds M.P. Nadler, D. Miller and D.J. Nadler), Springer-Verlag, New York.

Wong, S. and Tong, J.E. (1974). Menstrual cycle and contraceptive hormonal effects on temporal discrimination. *Percept Mot Skills* **39**: 103-108.

Woo, G. and Hess, R. (1979). Contrast sensitivity function and soft contact lenses. *Int Contact Lens Clinic* **4**: 37-42.

Woodhouse, J.M. (1975). The effect of pupil size on grating detection at various contrast levels. *Vision Res* **15**: 645-648.

Woods, R.L. (1993). Reliability of visual performance measurement under optical degradation. *Ophthalmic Physiol Opt* **13**: 143-150.

Woods, R.L. and Thomson, W.D. (1993). A comparison of psychometric methods for measuring the contrast sensitivity of experienced observers. *Clin Vision Sci* **8**: 401-415.

Woods, R.L., Saunders, J.E. and Port, M.J.A. (1993). Optical performance of decentered bifocal contact lenses. *Optom Vis Sci* **70**: 171-184.

Woodward, E.G. (1980). Keratoconus. *PhD thesis, City University, London.*

Woodward, E.G. (1991). The role of rigid contact lenses in the management of keratoconus. *J Br Contact Lens Assoc* **14**: 211-217.

Wooten, B.R. and Geri, G.A. (1987). Psychophysical determination of intraocular light scatter as a function of wavelength. *Vision Res* **27**: 1291-1298.

Wright, C.E. and Drasdo, N. (1985). The influence of age on the spatial and temporal contrast sensitivity function. *Doc Ophthalmol* **59**: 385-395.

Wright, P. (1972). Superior limbic keratoconjunctivitis. *Trans Ophthalmol Soc* **92**: 555-560

Yager, D., Yuan, R. and Mathews, S. (1992). What is the utility of the psychophysical light scattering factor? *Invest Ophthalmol Vis Sci* **33**: 688-690.

Yamamoto, Y., Nakayama, C., Yokoi, N. and Kinoshita, S. (1996). Corneal thickness in keratoconus. *Invest Ophthalmol Vis Sci* **37**: 4678.

Yanoff, M. and Fine, B.S. (1989). *Ocular Pathology: A text and Atlas*, 3rd Edition, Lippencott, Philadelphia.

Yappert, M.C., Lal, S. and Borchman, D. (1992). Age dependence and distribution of green and blue fluorophores in human lens homogenates. *Invest Ophthalmol Vis Sci* **33**: 3555-3560.
Yaroslavsky, I.V., Yaroslavsky, A.N., Otto, C., Puppels, G.J., Vrensen, G.F.J.M., Duindam, H. and Greve, J. (1994). Combined elastic and Raman light scattering of human eye lenses. *Exp Eye Res* **59**: 393-400.
Yee, R.W., Matsuda, M., Schultz, R.O. and Edelhauser, H.F. (1985). Changes in the normal corneal endothelial cellular pattern as a function of age. *Curr Eye Res* **4**: 671-678.
Yue, B.Y.J.T., Baum, J.L. and Smith, B.D. (1983). Identification of collagens synthesized by cultures of normal human corneal and keratoconus stromal cells. *Biochem Biophys Acta* **755**: 318-325.
Yue, B.Y.J.T., Sugar, J. and Benveniste, K. (1984). Heterogeneity in keratoconus: possible biochemical basis. *Proc Soc Exp Biol Med* **517**: 336-341.
Zadnik, K., Mannis, M.J. and Johnson, C.A. (1984). An analysis of contrast sensitivity in identical twins with keratoconus. *Cornea* **3**: 99-103.
Zadnik, K., Mannis, M.J., Johnson, C.A. and Rich, D. (1987). Rapid contrast sensitivity assessment in keratoconus. *Amer J Optom Physiol Optics* **64:** 693-697.
Zagorski, Z. (1980). Experimental investigations on the effects of low temperature on the activity of keratocytes during healing of penetrating corneal defect. *Klin Oczna* **82**: 13-15.
Zantos, S.G. and Holden, B.A. (1977). Transient endothelial cell changes soon after wearing soft contact lenses. *Am J Optom Physiol Opt* **54**: 856-858.
Zeimer, R. and Noth, J. (1984). A new method of measuring in vivo the lens transmittance and study of lens scatter, fluorescence and transmittance. *Ophthalmic Res* **16**: 246-255.
Ziel, C.J., Gussler J.R., Van Meter, W.S., Schmeisser, E. and Litteral, G. (1990). Contrast sensitivity in extended wear of the Boston IV lens. CLAO 16: 276-278.
Zigman, S. (1971). Eye lens colour formation and function. *Science* **171**: 807-809.
Zigman, S., Groff, J., Yulo, T. and Griess, G. (1976). Light extinction and protein in the lens. *Exp Eye Res* **23**: 555-567.
Zucker, B.B. (1966). Hydration and transparency of corneal stroma. *Arch Ophthalmol* **75**: 228-231.
Zuckerman, J.L., Miller D., Dyes, W. and Keller, M (1973). Degradation of vision through a simulated cataract. *Invest Ophthalmol Vis Sci* **12**: 213-224.
Zuclich, J.A., Glickman, R.D. and Menendez, A.R. (1992). In situ measurements of lens fluorescence and its interference with visual function. *Invest Ophthalmol Vis Sci* **33**: 410-415.

Publications

Hennelly, M.L., Barbur, J.L., Edgar, D.F. and Woodward, E.G. (1997). The light scattering characteristics of the eye. *Ophthalmic Phys Opt* **17**:171.

Hennelly, M.L., Barbur, J.L., Edgar, D.F. and Woodward, E.G. (1997). Factors affecting the integrated straylight parameter in the normal eye. *Invest Ophthalmol Vis Sci* **38**: 1014.

Hennelly, M.L., Barbur, J.L., Edgar, D.F. and Woodward, E.G. (1998). Light scattering changes with age. *Ophthalmic Phys Opt* **18**: 197-203.

Edgar, D.F., Hennelly, M.L. and Barbur, J.L. (2000). Factors affecting the accuracy of light scatter measurements in human vision. *Invest Ophthalmol Vis Sci* **41**: 3.